UNIVERSITÉ DU QUÉBEC À CHICOUTIMI

MÉMOIRE PRÉSENTÉ À
L'UNIVERSITÉ DU QUÉBEC À CHICOUTIMI
COMME EXIGENCE PARTIELLE
DE LA MAÎTRISE EN INGÉNIERIE

PAR
HU CHEN

L'EFFET DU TAUX DE REFROIDISSEMENT, MODIFICATION AU STRONTIUM, TRAITEMENT THERMIQUE DU LIQUIDE ET LA MISE EN SOLUTION SUR LES CARACTÉRISTIQUES DES PARTICULES DU SILICIUM EUTECTIQUE ET LES PROPRIÉTÉS DE TRACTION DE L'ALLIAGE A356

AVRIL 2005

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EFFECT OF COOLING RATE, STRONTIUM MODIFICATION, MELT THERMAL TREATMENT AND SOLUTION HEAT TREATMENT ON THE EUTECTIC SILICON PARTICLE CHARACTERISTICS AND TENSILE PROPERTIES OF A356 ALLOY

APRIL 2005

Dedicated to my parents
谨以此献给我的父母

RÉSUMÉ

En tant qu'une des familles principales des alliages d'aluminium, les alliages Al-Si offrent une excellente coulabilité, une bonne résistance à la corrosion et des bonnes propriétés physiques et mécaniques. L'alliage A356.2 commercialement populaire, appartenant au système Al-Si-Mg, a d'excellentes caractéristiques de coulée, soudabilité, étanchéité de pression et résistance à la corrosion. L'alliage est généralement soumis à un traitement thermique (traitement T6) pour fournir de diverses combinaisons des propriétés de traction et physiques qui sont attrayantes pour plusieurs d'applications en industrie de l'automobile et de l'aérospatiale telles que des blocs de moteur, des têtes de cylindre et des roues. De tels composants critiques exigent que les pièces coulées présentent des propriétés conformes de résistance et de ductilité dans tout le matériel solidifié.

Il est bien connu que la morphologie des particules eutectiques de silicium dans les alliages Al-Si soit un facteur principal qui détermine les propriétés mécaniques de ces alliages. Dans les conditions de tel que coulé, la microstructure d'alliage contient des particules fragiles et aciculaires de silicium sous forme de plaquettes avec des côtés pointus aux extrémités. D'un point de vue mécanique, la présence de telles particules sous forme plaquettes dégradera les propriétés mécaniques parce que des efforts inhérents seront centralisés sur les côtés et les extrémités pointus, ce qui entraîne une rupture rapide. D'autre part, si les particules eutectiques de silicium sont obtenues sous une forme fine et fibreuse (silicium fibreux), une telle morphologie contribue aux meilleures propriétés de traction avec des valeurs légèrement plus élevées de résistance à la traction finale et à des valeurs de ductilité considérablement plus grandes.

En plus de la taille et de la forme des particules eutectiques de silicium, la taille de grain et le DAS (espacement de bras de dendrite) sont également importants pour les propriétés de l'alliage. Le DAS est déterminé par le taux de refroidissement. En effet, des taux de refroidissement plus élevés mènent à une taille de grain plus fine et à une plus petite valeur de DAS qui améliorent les propriétés. Tandis qu'un taux de refroidissement élevé peut également produire des particules eutectiques de silicium plus fines, leur morphologie, cependant, demeure la même (c.-à-d. aciculaire).

La modification ou le changement de la morphologie de particules de silicium d'une forme aciculaire à une forme fibreuse est habituellement provoquée en ajoutant un modificateur au métal liquide. Pour cet effet, le strontium est généralement utilisé sous forme d'alliage mère d'Al-10%Sr. Le rôle du strontium est d'affecter principalement la nucléation et la croissance de la phase de silicium en développant un habillage efficace d'impureté devant la

croissance de silicium présent dans l'alliage solidifié. Par la suite, cet habillage d'impureté produit des particules fines de silicium qui contiennent une forte densité.

Les particules fines de silicium peuvent également être produites en utilisant d'autres moyens, par exemple un taux de refroidissement élevé, traitement de mise en solution ou un traitement thermique du liquide. Un taux de refroidissement élevé a comme conséquence un degré élevé de surfusion décalant le point Al-Si eutectique de l'alliage à une plus basse température. Le taux de refroidissement élevé mène à la formation des particules plus fines de silicium comparées à un taux de refroidissement bas.

Autres moyens pour obtenir des particules fines de silicium est l'utilisation du traitement thermique du liquide, ou le processus de MTT. Dans ce cas-ci, l'utilisation de basses et de hautes températures pour l'alliage produit une structure fine de silicium. L'effet de modification est réalisé par des noyaux résultant de la dégénération de grands amas d'atomes et quelques solides réfractaires dans la basse température quand l'alliage est chauffé à hautes températures. Dans ce processus aucune addition d'élément n'est exigée. C'est une technique relativement récente qui semble être une alternative prometteuse à la modification au strontium Sr, car elle n'exige aucune addition d'élément, de ce fait ramenant le risque de porosité accrue normalement liée à l'addition du strontium au métal liquide.

L'utilisation de la surchauffe du métal liquide s'avère également un moyen pour produire l'amélioration de la structure eutectique de silicium. Dans ce cas-ci, aussi, la température élevée de la fonte aide à la dégénération des amas d'atomes, fournissant plus de noyaux pour la formation de dendrite d'α-Al fournissant un affinage de la microstructure.

Dans les alliages d'aluminium traitables thermiquement, les propriétés mécaniques sont augmentées par l'utilisation des traitements thermiques. Ces derniers qui sont appliqués sur les alliages A356 se composent de trois étapes : un traitement thermique de mise en solution (à 540 °C) pendant un temps indiqué, une trempe (dans l'eau chaude), suivie d'un vieillissement artificiel à 155 °C. La partie de traitement de mise en solution du processus affecte directement les particules de silicium et, dépendant d'un temps optimum de traitement, produit des particules sphéroïdisées de silicium. Des temps plus grands de traitement de mise en solution peuvent mener à des particules aciculaires de silicium.

Ainsi, n'importe quel facteur qui peut affecter la morphologie des particules eutectiques de silicium aura un effet sur les propriétés mécaniques des alliages Al-Si. Le but du travail actuel est d'étudier de divers moyens d'obtenir une structure eutectique fine de silicium dans l'alliage A356.2 et d'améliorer de ce fait les propriétés mécaniques de celui-ci. Les

effets du taux de refroidissement, la modification au Sr, le traitement thermique de mise en solution et le traitement thermique du métal liquide sur les caractéristiques des particules de silicium de l'alliage A356.2 (Al-7%Si-0.4%Mg) ont été étudiés. Les paramètres des particules mesurés étaient la surface moyenne, la longueur moyenne, le rapport de la rondeur et le rapport longueur/largeur en utilisant l'analyse d'image et la microscopie optique. Basé sur les résultats obtenus à partir des caractéristiques microstructurales, des propriétés de traction (la limite ultime, la limite élastique et l'allongement à la rupture) des échantillons choisis ont été examinées au moyen d'une presse INSTRON universelle pour déterminer l'effet de ces facteurs sur les propriétés mécaniques.

Les résultats ont prouvé que les alliages qui ont subi une modification au strontium Sr accompagnée d'une surchauffe et qui ont subi le processus de modification MTT fournissent très bien des particules eutectiques fines de silicium, le processus de Sr-MTT donne de meilleurs résultats de modification.

La taille et la morphologie des particules eutectiques de silicium sont affectées par le procédé de modification utilisé. Les alliages SrM, SH et SrMTT coulés montrent des particules fibreuses de silicium bien modifiées, tandis que les alliages MTT qui montrent des particules de silicium, bien que raffinées dans une certaine mesure, maintiennent toujours leur morphologie aciculaire.

Le taux de refroidissement affecte la dimension particulaire du silicium eutectique puisque un taux de refroidissement plus élevé produit des particules plus fines de silicium. Cependant, dans la marge des taux de refroidissement fournis par les extrémités froides du moule utilisé dans ce travail, le taux de refroidissement n'affecte pas la morphologie des particules de silicium.

Pendant le traitement thermique de mise en solution à 540 °C, les particules eutectiques de silicium subissent une fragmentation, une sphéroïdisation, et grossissement affectant la morphologie des particules de silicium. Le processus de sphéroïdisation est déterminé par la taille et la morphologie des particules de silicium dans les conditions tels que coulés. Les alliages subissant une modification au Sr, une surchauffe et un processus de SrMTT avec leurs particules de silicium raffinées ont besoin moins de temps de traitement de mise en solution pour le processus de sphéroïdisation que les alliages non modifiés et alliages MTT.

Une analyse des essais de traction pour les diverses coulées de l'alliage A356.2 (NM, SRM, MTT SH et SrMTT) dans la condition tel que coulé montre que le taux de refroidissement et le procédé de modification n'avez aucune influence sur la limite élastique. La limite ultime (UTS) peut être améliorée par SrM, SH, et un traitement de SrMTT. Le processus de

MTT n'a aucune influence apparente sur l'UTS. Le traitement de SrM et de SrMTT peuvent considérablement améliorer le pourcentage de l'élongation à la rupture de l'alliage A356. Les processus SH et de MTT montrent aucune amélioration significative dans le pourcentage de l'élongation. Un pourcentage d'allongement plus élevé peut être produit à un taux de refroidissement plus élevé.

L'effet du traitement thermique de mise en solution sur les propriétés de traction des diverses coulées de l'alliage A356.2 peut être résumé comme suit. La limite élastique des diverses coulées de l'alliage A356.2 est sensiblement améliorée après le traitement thermique de mise en solution de 8 h dû à la précipitation de Mg_2Si. La limite élastique demeure plus ou moins la même avec un accroissement plus ultérieur à un temps de traitement à 80 h. La limite ultime UTS est également considérablement améliorée dans les 8 premières heures du traitement thermique de mise en solution et reste alors au même niveau avec le temps augmentant jusqu'à 80h. L'amélioration est attribuée à la précipitation de Mg_2Si, à la dissolution du silicium dans la matrice d'aluminium et au changement de la morphologie de particules de silicium (sphéroïdisation). La ductilité des alliages A356.2 qui ont subi le processus de NM, SH, et MTT peut être améliorée considérablement avec le traitement thermique de mise en solution (par exemple de ~ 6% dans l'alliage non modifié et dans la condition de tel que coulé à ~ 10% après un traitement de mise en solution de 80 heures). Cependant, les alliages qui ont subi le processus SrM et SrMTT ne montrent aucune amélioration remarquable.

ABSTRACT

As one of the major families of aluminium alloys, Al-Si alloys offer excellent castability, good corrosion resistance, as well as a wide range of physical and mechanical properties. The commercially popular A356.2 alloy, belonging to the Al-Si-Mg system, has excellent casting characteristics, weldability, pressure tightness and corrosion resistance. The alloy is generally heat-treated (T6 treatment) to provide various combinations of tensile and physical properties that are attractive for several aircraft and automobile applications such as engine blocks, cylinderheads and wheels. Such critical components require that the casting parts exhibit consistent strength-ductility properties throughout the casting.

It is well known that the morphology of the eutectic silicon particles in Al-Si alloys is a key factor which determines the mechanical properties of these alloys. In the as-cast condition, the alloy microstructure contains brittle, acicular silicon particles in the form of plates with sharp sides and ends. From a mechanical point of view, the presence of such plate-like particles will degrade the mechanical properties because inherent stresses will be centralized on the sharp sides and ends and induce fracture more rapidly. On the other hand, if the eutectic silicon particles are obtained in a fine, fibrous form (fibrous silicon), such a morphology contributes to much better tensile properties with somewhat higher values of ultimate tensile strength and greatly increased values of ductility.

In addition to the size and shape of the eutectic silicon particles, grain size and DAS (dendrite arm spacing) is also important for alloy properties. The DAS is determined by cooling rate. Higher cooling rates lead to a finer grain size and a smaller value of DAS which improve the properties. While a high cooling rate can also produce finer eutectic silicon particles, their morphology, however, remains the same (i.e. acicular).

The 'modification' or change in the silicon particle morphology from acicular to fibrous is usually brought about by adding a 'modifier' to the alloy melt, for which strontium is commonly employed in the form of Al-10%Sr master alloy. The role of strontium is to primarily affect the nucleation and growth of the silicon phase by developing an effective impurity buildup in front of silicon growth fronts present in the solidifying alloy. Eventually, this impurity buildup produces the fine silicon particles which contain a high density of twins.

Fine silicon particles can also be produced using other means, *e.g.* a high cooling rate, solution heat treatment or melt thermal treatment. A high cooling rate results in a high degree of undercooling, which results in shifting the Al-Si eutectic point of the alloy to a lower temperature. The high cooling rate leads to the formation of finer silicon particles compared to a low cooling rate.

Another means of obtaining fine silicon particles is through the use of melt thermal treatment, or the MTT process. In this case, the mixing of low and high temperature melts of the alloy produce a fine silicon structure. The modification effect is achieved by nuclei resulting from the degeneration of big atom clusters and some refractory solids in the low temperature melt when it is heated by the high temperature melt. In this process no element addition is required. This is a relatively recent technique that appears to be a promising alternative to Sr modification, as it requires no element addition, thus reducing the risk of increased porosity normally associated with the addition of strontium to the alloy melt.

The use of melt superheat is also found to produce refinement of the eutectic Si structure. In this case, also, the high melt temperature assists in the degeneration of atom clusters, providing more nuclei for α-Al dendrite formation, and a resulting refinement of the microstructure.

In heat-treatable aluminum alloys, the mechanical properties are enhanced by the use of heat treatments. Heat treatment of A356 alloys consists of three steps: solution heat treatment (at 540°C) for a specified time, quenching (in warm water), followed by artificial 155°C aging. The solution treatment part of the process directly affects the silicon particles and, depending upon an optimum treatment time, produces spheroidized silicon particles. Larger solution treatment times lead to coarsening of the Si particles.

Thus, any factor that can affect the morphology of the eutectic silicon particles will have an effect on the mechanical properties of Al-Si alloys. The aim of the present work was to investigate various means of obtaining a fine eutectic silicn structure in A356.2 alloy and thereby improve the alloy mechnical properties. The effects of cooling rate, Sr modification, solution heat treatment and melt thermal treatment on the silicon particle characteristics of A356.2 (Al-7%Si-0.4%Mg) alloy were studied. The particle characteristics measured were the *average particle area*, *average particle length*, *average particle roundness* and *average particle aspect ratio*, using image analysis and optical microscopy. Based on the results obtained from the microstructural characteristics, tensile properties (yield strength, ultimate tensile strength and percentage elongation) of selected samples were tested, using an Instron Universal MT machine, to determine the effect of these factors on the mechanical properties.

The results showed that Sr modification, superheat, and Sr-modification-MTT processed castings provide fine eutectic Si particles, the SrMTT process giving the best modification results .

Both size and morphology of the eutectic silicon particles are affected by the modification process used. The SrM, SH and SrMTT castings show well modified fibrous Si particles, whereas the MTT casting exhibits Si particles that, although refined to a certain extent, still retain their acicular morphology.

Cooling rate affects the eutectic Si particle size in that a higher cooling rate produces finer Si particles. However, within the range of cooling rates provided by the end-chill mold used in this work, the cooling rate does not affect the morphology of the Si particles.

During solution heat treatment at 540°C, the eutectic Si particles undergo fragmentation, spheroidization, and coarsening, affecting the Si particle morphology. The spheroidization process is determined by the size and morphology of the Si particles in the as-cast condition. The Sr-modified, superheat and SrMTT processed castings with their refined Si partcles require much less solution treatment time for the spheroidization process to take place that do the non-modified (NM) and MTT castings.

An analysis of the tensile test data for the various A356.2 alloy castings (NM, SRM, SH MTT and SrMTT) in the as-cast condition shows that both cooling rate and modification process have no influence on the yield strength. UTS can be improved by SrM, SH, and SrMTT treatment. The MTT process has no apparent influence on the UTS. Both SrM and SrMTT treatment can greatly improve the percentage elongation of A356 alloy castings. SH and MTT processes do not show any significant improvement in the percentage elongation. Higher percentage elongation can be produced at higher cooling rate.

The effect of solution heat treatment on the tensile properties of the various A356.2 alloy castings can be summed up as follows. The yield strength of the various A356.2 alloy castings is significantly improved after 8 h solution heat treatment due to the precipitation of Mg_2Si. The yield strength remains more or less the same with further increase in solution treatment time to 80 h. The UTS is also greatly improved within the first 8 h of solution heat treatment and then remains at the same level as solution time increases up to 80h. The improvement is attributed to Mg_2Si precipitation, dissolution of Si within the Al-matrix, and change in the Si particle morphology (spheroidization). The ductility of the NM, SH, and MTT processed A356.2 alloy castings can be improved considerably with solution heat treatment (*e.g.* from ~6% in the non-modified casting in the as-cast condition to ~10% after 80 h solution treatment). However, that of the SrM and SrMTT processed castings shows no remarkable improvement.

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INTRODUCTION

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INTRODUCTION

As one of the major families of aluminium alloys, Al-Si alloys offer excellent castability, good corrosion resistance, as well as a wide range of physical and mechanical properties. In addition, Al-Si alloys are also characterized by their low specific gravity, low melting point, and negligible gas solubility with the exception of hydrogen which has considerable solubility in molten aluminum at high temperature.

The commercially popular A356.2 alloy, belonging to the Al-Si-Mg system, has excellent casting characteristics, weldability, pressure tightness and corrosion resistance. The alloy is generally heat-treated (T6 treatment) to provide various combinations of tensile and physical properties that are attractive for several aircraft and automobile applications such as engine blocks, cylinderheads and wheels. Such critical components require that the casting parts exhibit consistent strength-ductility properties throughout the casting.

It is well known that the morphology of the eutectic silicon particles in Al-Si alloys is a key factor which determines the mechanical properties of these alloys. In the as-cast condition, the alloy microstructure contains brittle, acicular silicon particles in the form of plates with sharp sides and ends. From a mechanical point of view, the presence of such plate-like particles will degrade the mechanical properties (e.g., the tensile and impact properties) because inherent stresses will be centralized on the sharp sides and ends and induce fracture more rapidly. On the other hand, if the eutectic silicon particles are obtained in a fine, fibrous form (fibrous silicon), such a morphology contributes to much better tensile properties with somewhat higher values of ultimate tensile strength and greatly increased values of ductility. The 'modification' or change in the silicon particle morphology from acicular to fibrous is usually brought about by adding a 'modifier' to the alloy melt, for which strontium is commonly employed in the form of Al-10%Sr master alloy. The role of strontium is to primarily affect the nucleation and growth of the silicon phase by developing an effective impurity buildup in front of silicon growth fronts present in the solidifying alloy. Eventually this impurity buildup produces the fine silicon particles which contain a high density of twins.

Fine silicon particles can also be produced using other means, e.g. a high cooling rate, solution heat treatment or melt thermal treatment. A high cooling rate results in a high degree of undercooling, which results in shifting the Al-Si eutectic point of the alloy to a lower temperature. The high cooling rate leads to the formation of finer silicon particles compared to a low cooling rate.

Another means of obtaining fine silicon particles is through the use of melt thermal treatment, or the MTT process. In this case, the mixing of low and high temperature melts of the alloy produces a fine silicon structure. The modification effect is achieved by nuclei degenerated from the big atom clusters and some refractory solids in the low temperature melt when it is heated by the high temperature melt. In this process no element addition is required.

In heat-treatable alloys, the mechanical properties are enhanced by the use of heat treatments. Heat treatment of A356 alloys consists of three steps: solution heat treatment (at 540°C) for a specified time, quenching (in warm water), followed by artificial aging (at 150°C). The solution treatment part of the process directly affects the silicon particles and, depending upon an optimum treatment time, produces spheroidized silicon particles. Larger solution treatment times lead to coarsening of the Si particles.

Basically speaking, any factor that can affect the morphology of the eutectic silicon particles will have an effect on the mechanical properties of Al-Si alloys. The aim of the present work was to study the effect of various combinations of the above four factors i.e., cooling rate, Sr modification, solution heat treatment and MTT on the silicon particle characteristics of A356.2 (Al-7%Si-0.4%Mg) alloy, the particle characteristics measured being the *average particle area*, *average particle length*, *average particle roundness* and *average particle aspect ratio*. Based on the results obtained from the microstructural characteristics, tensile properties (yield strength, ultimate tensile strength and percentage elongation) of selected samples were tested to determine the effect of these four factors on the mechanical properties.

1.1 OBJECTIVES

The present research work was undertaken to investigate various means of obtaining a fine eutectic silicon structure in A356.2 alloy and thereby improve the alloy mechanical properties. The main objectives of the study were as follows:

i) Investigate the effects of cooling rate, strontium modification, melt thermal treatment (MTT process) and solution heat treatment on the eutectic silicon particle characteristics in A356.2 alloy;

ii) Study the effect of the above parameters on the alloy tensile properties (yield strength, ultimate tensile strength and percentage elongation);

iii) To date, there are very limited studies reporting on the effect of the MTT process on the modification of eutectic silicon particles in A356 alloys. The data collected in this study will help to bridge the existing gap in the literature in this area.

CHAPTER 2

LITERATURE REVIEW

CHAPTER 2

LITERATURE REVIEW

2.1 ALUMINUM-SILICON CASTING ALLOYS

Aluminum casting alloys with silicon as a major alloying element are an important class of alloys, widely employed due to their superior casting characteristics compared to other aluminum alloys, as well as their high corrosion resistance, low thermal expansion coefficient, weldability, and elevated mechanical properties. Today, Al-Si alloys are used extensively in the automobile industry for engine components including blocks, cylinder heads, pistons, intake manifolds and brackets, and are replacing cast iron components because of their light weight. [1,2]

One of the main features of Al-Si alloys is their excellent castability. This refers to the high fluidity of the molten alloy and its ability to flow into and fill the areas of a mold before it becomes too solid to flow any further. This feature of high fluidity is characterized by one thermal property of Al-Si alloys: the heat of fusion. It is known that aluminum has a high heat of fusion, i.e., a lot of heat must be absorbed by the mold and its surroundings in the course of solidifying aluminum (more, in fact, than any other of the commonly-cast metals). However, the heat of fusion of silicon is even higher, and several times greater than that of aluminum (*cf.* 55.55 kJ mol^{-1} with 10.79 kJ mol^{-1} for Al). In this case, alloying silicon into aluminum significantly increases the heat that must be removed from the Al-Si alloy melt for it to solidify. The more heat that must be removed, the longer the time it will take, and the further the alloy can flow, *i.e.*, the higher its fluidity. Although the fluidity of Al-Si alloys can be increased by increasing the Si content, however, when the Al-Si alloys contain 18-20% or more silicon, the formation of primary silicon crystals in the melt may mechanically impede the flow. That is why the silicon content of most Al-Si alloys is controlled to within 18%, with only a few exceptions (*e.g.*, 392 and 393 alloys). [1]

With the addition of certain elements to Al-Si alloys, a wide range of physical and mechanical properties including high corrosion resistance, good weldability, low shrinkage/thermal expansion, and high tensile properties can be achieved in different Al-Si alloys. However, not every element can be an alloying element of aluminum, as it must have a considerable solubility in aluminum, especially in the solid state.

Table 2.1 shows the solubility of various elements in aluminum. In practice, only a few elements with sufficient solid solubility such as silicon, zinc, magnesium, and copper can be used as alloying additions.

In Al-Si alloys with silicon contents of 11-13%, an Al-Si eutectic can be formed during solidification. Such alloys are named as Al-Si eutectic alloys (*e.g.*, 336 and 413 alloys). The two other groups of Al-Si alloys are the Al-Si hypoeutectic alloys with silicon content between 5 and 10% (*e.g.*, 319 and 356 alloys) and Al-Si hypereutectic alloys with silicon content between 14 and 20% (*e.g.*, 390 and 393 alloys), as shown in Figure 2.1.

Table 2.1 Solubility of various elements in binary aluminum alloys [2]

Element	Temperature(a) °C	°F	Liquid solubility wt%	at.%	Solid solubility wt%	at.%
Ag	570	1060	72.0	60.9	55.6	23.8
Au	640	1180	5	0.7	0.36	0.049
B	660	1220	0.022	0.054	<0.001	<0.002
Be	645	1190	0.87	2.56	0.063	0.188
Bi	660(b)	1220(b)	3.4	0.45	<0.1	<0.01
Ca	620	1150	7.6	5.25	<0.1	<0.05
Cd	650(b)	1200(b)	6.7	1.69	0.47	0.11
Co	660	1220	1.0	0.46	<0.02	<0.01
Cr	660(c)	1220(c)	0.41	0.21	0.77	0.40
Cu	550	1020	33.15	17.39	5.67	2.48
Fe	655	1210	1.87	0.91	0.052	0.025
Ga	30	80	98.9	97.2	20.0	8.82
Gd	640	1180	11.5	2.18	<0.1	<0.01
Ge	425	800	53.0	29.5	6.0	2.30
Hf	660(c)	1220(c)	0.49	0.074	1.22	0.186
In	640	1180	17.5	4.65	0.17	0.04
Li	600	1110	9.9	30.0	4.0	13.9
Mg	450	840	35.0	37.34	14.9	16.26
Mn	660	1220	1.95	0.97	1.82	0.90
Mo	660(c)	1220(c)	0.1	0.03	0.25	0.056
Na	660(b)	1220(b)	0.18	0.21	<0.003	<0.003
Nb	660(c)	1220(c)	0.01	0.003	0.22	0.064
Ni	640	1180	6.12	2.91	0.05	0.023
Pb	660	1220	1.52	0.20	0.15	0.02
Pd	615	1140	24.2	7.5	<0.1	<0.02
Rh	660	1220	1.09	0.29	<0.1	<0.02
Ru	660	1220	0.69	0.185	<0.1	<0.02
Sb	660	1220	1.1	0.25	<0.1	<0.02
Sc	660	1220	0.52	0.31	0.38	0.23
Si	580	1080	12.6	12.16	1.65	1.59
Sn	230	450	99.5	97.83	<0.01	<0.002
Sr	655	1210	...	...	...	...
Th	635	1180	25.0	3.73	<0.1	<0.01
Ti	665(c)	1230(c)	0.15	0.084	1.00	0.57
Tm	645	1190	10.0	1.74	<0.1	<0.01
U	640	1180	13.0	1.67	<0.1	<0.01
V	665(c)	1230(c)	0.25	0.133	0.6	0.32
Y	645	1190	7.7	2.47	<0.1	<0.03
Zn	380	720	95.0	88.7	82.8	66.4
Zr	660(c)	1220(c)	0.11	0.033	0.28	0.085

(a) Eutectic reactions unless designated otherwise. (b) Monotectic reaction. (c) Peritectic reaction.

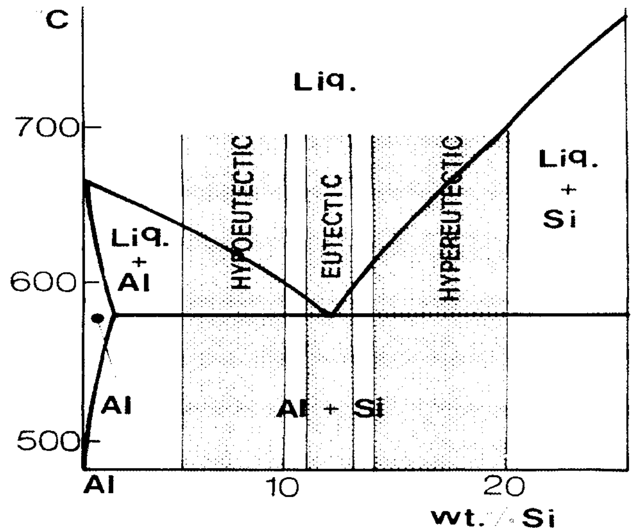


Figure 2.1 Part of the Al-Si phase diagram showing composition ranges of various Al-Si alloy types. [3]

From Figure 2.1 it can be seen that the solidification process of Al-Si hypoeutectic alloys includes:

1) Formation of the α-aluminum dendrite network;

2) The aluminum-silicon eutectic reaction to produce the Al-Si eutectic; and

Precipitation of secondary eutectic phases, such as Mg_2Si and Al_2Cu also takes place depending on whether the alloy contains magnesium and copper, e.g., such as in the case of Al-Si-Mg, Al-Si-Cu, and Al-Si-Cu-Mg alloys.

According to the three-digit designation system of the Aluminum Association,[4] Al-Si base alloys belong to the 3XX and 4XX series of aluminum casting alloys, as shown in Table 2.2 below.

Table 2.2 Classification of aluminum casting alloys [4]

Series	Alloy family
1XX	99.0% min Al
2XX	Al-Cu
3XX	Al-Si-Mg, Al-Si-Cu, Al-Si-Cu-Mg
4XX	Al-Si
5XX	Al-Mg
6XX	Unused
7XX	Al-Zn
8XX	Al-Sn
9XX	Unused

In Al-Si alloys, Mg and Cu are the two most important alloying additions. Within Al-Si alloys, Al-Si-Mg, Al-Si-Cu, and Al-Si-Cu-Mg are the three major alloy systems in the 3XX series, for which A356.2, A319.2, and B319.2 are typical examples. The main function of Mg and Cu is to aid in Mg_2Si and Al_2Cu precipitation, which can improve the alloy mechanical properties upon heat treatment.

At the same time, because of the presence of some impurity elements such as Fe and Mn, some intermetallic phases also precipitate during solidification. The iron intermetallics Al_5FeSi and α-$Al_{15}(Mn,Fe)_3Si_2$ are two phases often seen in Al-Si alloys. The β-Al_5FeSi phase tends to form thin platelets which appear as needles in cross-section. These platelets are very hard and brittle and have a relatively low bond strength with the matrix.[5] The β-

iron phase also increases porosity by blocking feeding channels between solidifying α-Al dendrites.

Among Al-Si alloys, hypoeutectic alloys such as 319 (Al-6.5%Si-3%Cu) and 356 (Al-7%Si-0.3Mg) offer good castability and corrosion resistance, while 380 alloy (Al-8.5%Si-3.5%Cu) is popularly used in die casting for the silicon provides good casting properties and the alloy can be strengthened by adding small amounts of Cu, Mg or Ni. Eutectic alloys such as 413, 443 and 444 alloys provide high corrosion resistance, good weldability and low specific gravity. Hypereutectic alloys such as 390 alloy which contain high silicon levels have outstanding wear resistance, a lower thermal expansion coefficient, and very good casting characteristics.

Table 2.3 shows the characteristics of some major Al-Si alloys, where the characteristics are rated on a scale of 1 to 5, from best to worst.

Table 2.3 Characteristics of aluminum-silicon casting alloys[6]

Alloy	Casting Method	Resistance To Tearing	Pressure Tightness	Fluidity	Shrinkage Tendency	Corrosion Resistance	Machinability	Weldability
319.0	S,P	2	2	2	2	3	3	2
332.0	P	1	2	1	2	3	4	2
355.0	S,P	1	1	1	1	3	3	2
A356.0	S,P	1	1	1	1	2	3	2
A357.0	S,P	1	1	1	1	2	3	2
380	D	2	1	2	-	5	3	4
390	D	2	2	2	-	2	4	2
413.0	D	1	2	1	-	2	4	4
443.0	P	1	1	2	1	2	5	1

S: sand casting; P: permanent mold casting; D: high pressure die casting
Rating: 1 Best, 5 Worst

2.2 A356 TYPE Al-Si-Mg ALLOYS

The Al-Si-Mg alloy system has excellent casting characteristics, weldability, pressure tightness, and corrosion resistance. With heat treatment, Al-Si-Mg alloys can provide a wide range of physical and mechanical properties. The heat treatment includes the processes of solution heat treatment, quenching, and natural or artificial aging. Such alloys are commonly used in automobile components such as engine blocks and wheels. [2]

Among Al-Si-Mg alloys, A356.2 alloy is a commercially popular alloy, used for its excellent mechanical properties and high strength-to-weight ratio. Its chemical composition is given in Table 2.4.

Table 2.4 Chemical composition of A356.2 alloy

AA Designation	Si %	Mg %	Fe %	Cu %	Mn %	Zn %
A356.2	6.5-7.5	0.30-0.45	0.13-0.25	0.10	0.05	0.05

The excellent mechanical properties of A356.2 alloy can be attributed to the effects of Si and Mg after heat treatment of the alloy. Solution heat treatment at 540°C followed by quenching and natural or artificial aging allows for the formation of interdendritic non-equilibrium precipitates of Mg_2Si and changes in the Si particle characteristics.[7, 8] In general, A356.2 alloy contains 0.3 to 0.45% Mg which can induce age hardening through the precipitation of Mg_2Si. The higher the Mg content, the more the age hardening that can be achieved. However, when the Mg content exceeds 0.7%, no further hardening is observed. Increase in Mg content up to 0.7% has been reported to result in higher yield strength or lower ductility and fracture toughness.[9]

The Si particle characteristics, especially the morphology, also influence the mechanical properties, where a change from an acicular to a fibrous morphology improves the properties, in particular, the ductility. In this regard, the molten metal processing (melt treatment) and casting techniques, and the type of heat treatment used are the different factors by which the form and size of the silicon particles can be controlled.[7,10]

2.3 SOLIDIFICATION OF A356 ALLOY

Although stable equilibrium solidification seldom exists in a practical casting process, the study of equilibrium systems is still very valuable because it constitutes a limiting condition from which actual solidification conditions can be estimated.[10] In a real casting process, the extent of deviation from equilibrium conditions has a significant effect on the actual microstructure observed.

Solidification of hypoeutectic Al-Si alloys can be characterized by a short nucleation event, the subsequent growth of equiaxed dendrites until they impinge onto each other at the dendrite coherency point, the growth and coarsening of secondary dendrite arms, and a final eutectic precipitation in the case of a binary alloy. In the case of A356 (Al-Si-Mg) alloy, precipitation of a secondary eutectic Mg_2Si phase takes place in the final stages of solidification, following the Al-Si eutectic reaction.

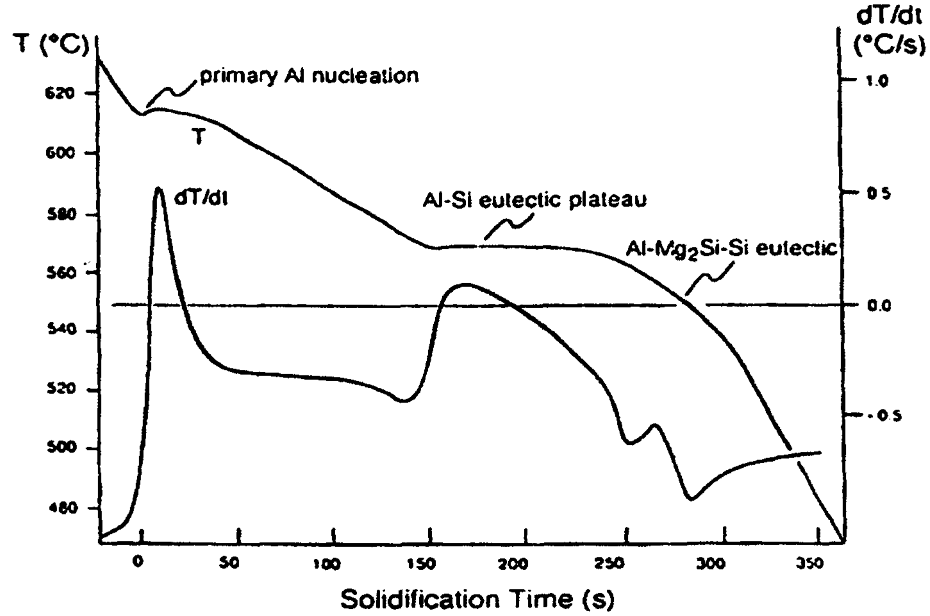
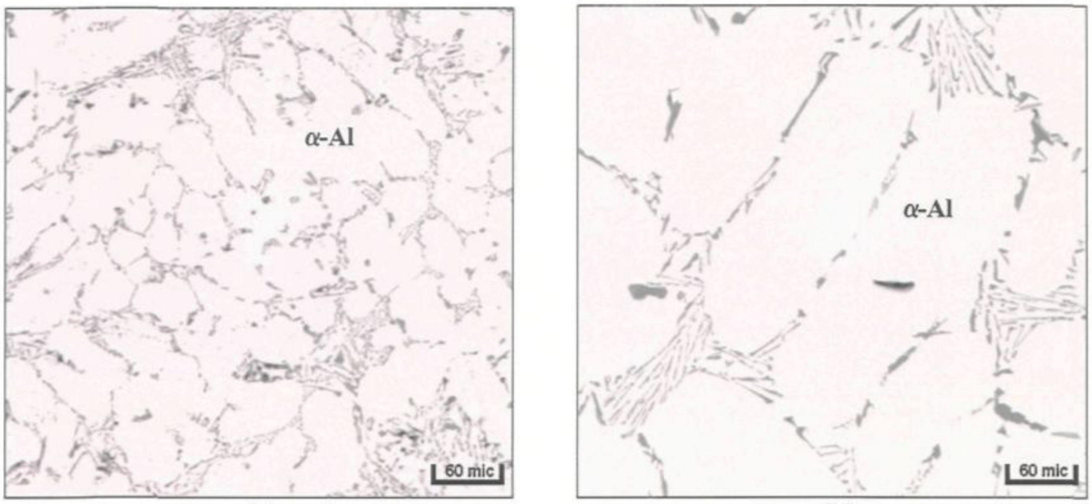


Figure 2.2 Cooling curve of A356 alloy[14]

Figure 2.2 shows the cooling curve and its first derivative (dT/dt) obtained from the thermal analysis of A356 alloy. The cooling curve indicates the precipitation sequence in A356 alloy at different stages of solidification process, *viz.*, formation of the α-Al dendrite network, followed by the Al-Si eutectic reaction and the precipitation of Mg_2Si towards the end of solidification. The dT/dt curve delineates the peaks corresponding to each reaction.

2.3.1 Formation of α - Al Dendrite Network

During solidification, precipitation of the α-Al phase from the liquid melt takes place in the form of dendrites. With subsequent growth, these dendrites impinge onto each other at the dendrite coherency point, followed by the growth and coarsening of secondary dendrite arms. Figure 2.3 provides examples of the dendrites observed in A356 alloy samples obtained under high and low cooling rate conditions.



(a) (b)

Figure 2.3 Morphology and size of α-Al dendrites observed in A356.2 alloy under (a) high cooling rate, and (b) low cooling rate conditions.

The secondary dendrite arm spacings (SDAS) is popularly used to indicate the size of the α-Al dendrites and hence provide an estimation of the fineness of the microstructure. Many studies[11,12,13,15,16] have pointed out that the SDAS is basically controlled by the cooling rate, since the cooling rate dictates the speed at which mass diffusion occurs.[14] It takes time for the Al atoms to diffuse to the dendrites from the liquid. Thus, the higher the cooling rate, the less time it will take for the Al atoms to diffuse, and the smaller will be the SDAS, as shown in Figure 2.4.

The following equation is commonly used to describe the effect of cooling rate on the size of the α-Al dendrites:[15,16]

$$\lambda = BR^{-\alpha}$$

where λ is the dendrite cell dimension, B and α are constants, and R = dT/dt is the average cooling rate during solidification of the primary α-Al dendrite cells. This equation is supported by several published experimental results, some of which are plotted in Figure 2.4.[11,12,13,15,16]

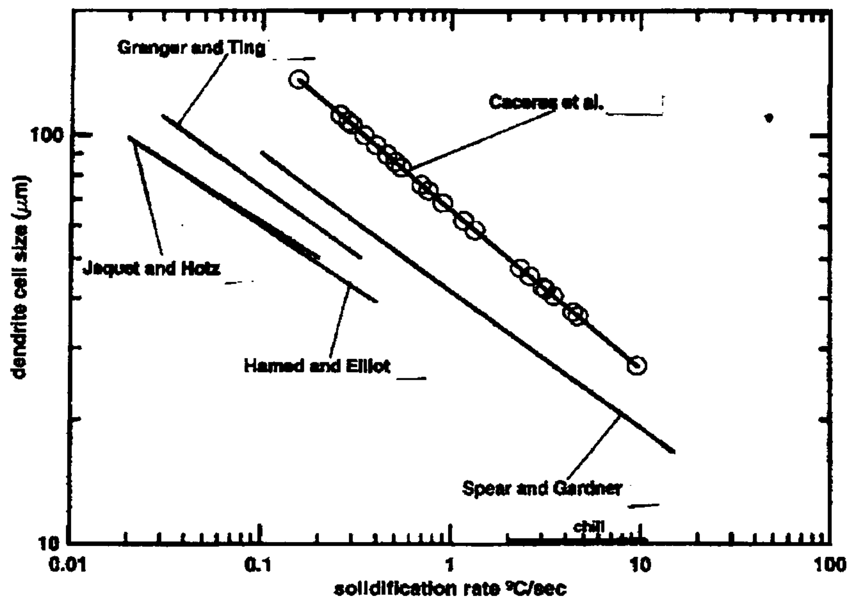


Figure 2.4 Dendrite cell size as a function of cooling rate.[11,12,13,15,16]

The fineness of the microstructure is also determined by the grain size. A grain refers to a family of α-Al dendrites which originate from the same nucleus. While a high cooling rate reduces the dendrite arm spacing, it also refines the grain size. This effect is called chilling grain refinement. Grain refinement can also be achieved by the addition of certain elements such as Ti and B into the melt. This is known as chemical grain refinement. In this process, the grain refiner is added to the melt in the form of a master alloy or flux, to provide an enhanced number of nuclei for the nucleation of new α-Al crystals. In the present study, grain refinement of the A356.2 alloy employed was carried out using Al-5%Ti-1%B master alloy.

The SDAS is an important parameter that controls the alloy tensile properties. The smaller the dendrite cell size, the higher the tensile properties. A high cooling rate which results in a small dendrite arm spacing can improve the tensile properties of A356 alloy. Similarly, small grain sizes achieved with the addition of grain refiner will also improve the tensile properties.

2.3.2 Formation of the Al-Si Eutectic

During solidification of A356 alloy, as the melt temperature drops down to 577.6°C, which is widely accepted as Al-Si eutectic temperature,[17] the Al-Si eutectic reaction takes place, as shown in Figure 2.1 and Figure 2.2. The eutectic reaction occurs at 577.6°C, at a Si level of ~ 12%.

$$\text{A356 alloy liquid} \rightarrow Al_{eut} + Si_{eut}$$

During the eutectic reaction, the liquid alloy is completely transformed to nearly pure Si and Al in solid solution. The solid solution of Al can contain up to 1.5 wt.% Si at the eutectic temperature. However, the solubility of silicon in aluminum decreases with temperature, *e.g.*, to 0.05 wt.% at 300°C.[18] The Al-Si eutectic nucleates on the primary aluminum dendrites and grows into the interdendritic regions during the reaction. From the Al-Si binary phase diagram, it can be estimated that A356 (Al-7%Si-0.4%) alloy contains approximately 50% Al-Si eutectic.

2.3.3 Mg_2Si Precipitation

Towards the end of solidification, the Mg_2Si will precipitate from the supersaturated solid solution of Mg and Si in aluminum. The final characteristics of the Mg_2Si is determined by the cooling rate. Mg_2Si precipitated at low cooling rates will be present as coarse incoherent non-hardening particles, as shown in Figure 2.5. On the other hand, at high cooling rates, Mg and Si atoms can be frozen in solid solution to form a supersaturated solid solution (SSS) of Mg and Si in aluminum. Mg and Si atoms in the SSS state are ready to be heat treated for age hardening, which will be elaborated in section 2.7.1.

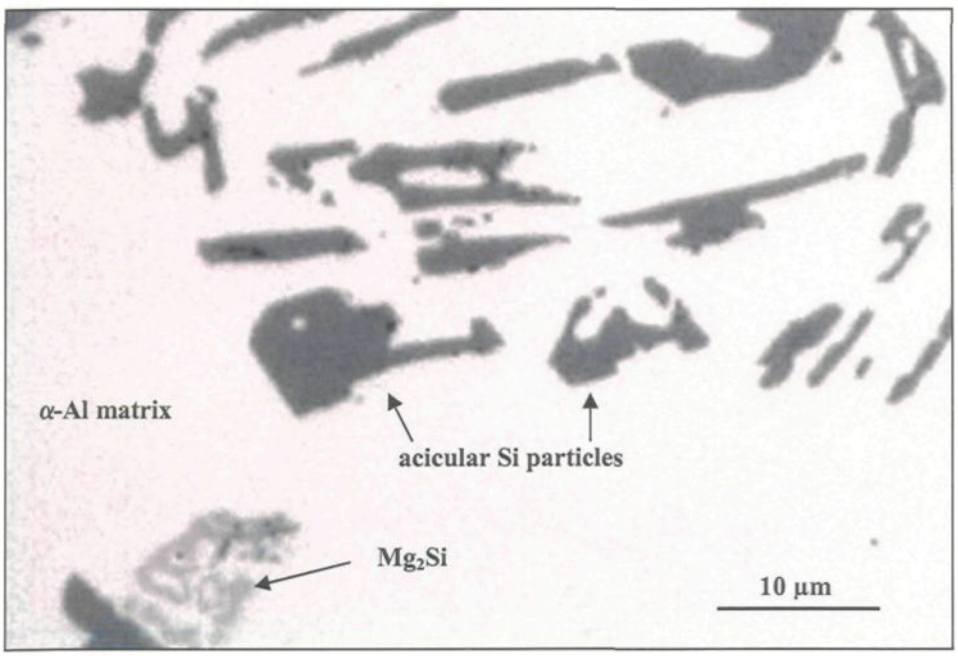


Figure 2.5 Optical microstructure showing precipitation of Mg_2Si particles in an Al-Si-Mg alloy at low cooling rate.

2.4 MODIFICATIOIN OF Al-Si ALLOYS

From the time (1921) that Pacz[19] discovered that Al-Si alloys containing 5 to 15%Si could be treated with alkali fluoride (*viz.*, sodium fluoride) to improve their ductility and machinability, the study of modification has attracted many researchers.[20,21,27] Early studies dealt primarily with the use of sodium (Na) as the modifying agent.

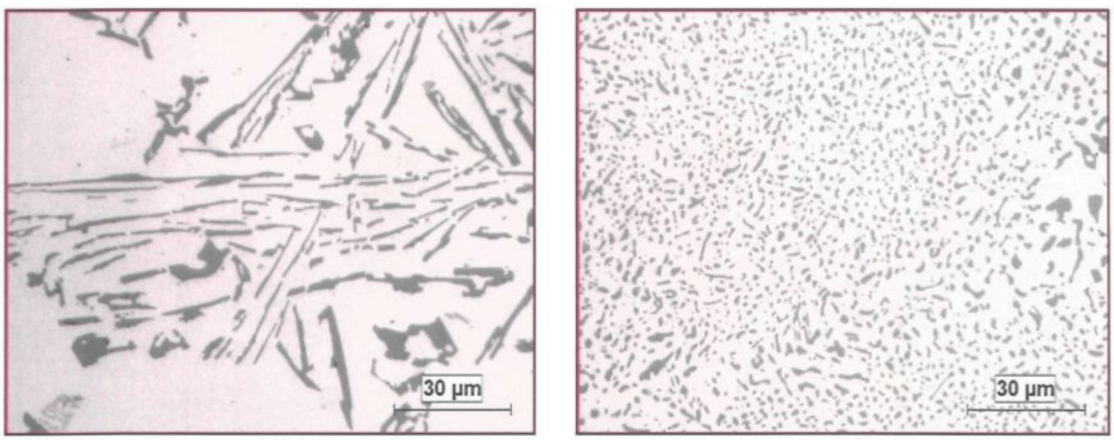
In the 1970s, Hess and Blackmun[22] reported on the potential of strontium (Sr) as a better and more reliable alternative for modification purposes. This was the starting point of the numerous investigations that followed through the next two decades on the effect of Sr as a modifier of Al-Si alloys in terms of both the enhancement in mechanical properties obtained, as well as the increased porosity observed in the Sr-modified alloys.

Today, modification is one of the melt treatments commonly carried out for Al-Si alloys where, through the addition of a 'modifier', the eutectic silicon morphology is changed from its brittle, acicular plate-like form to a fibrous form that improves the alloy properties.

Several elements are known to cause eutectic silicon modification. Group IA and Group IIA elements of the Periodic Table, rare earth elements (*e.g.*, La, Ce), As, Sb, Se and Cd have all been reported to exert a modification effect.[23,26,27] However, only Na, Sr and Sb have been used in general. Among them, antimony (Sb), due to its toxic effects, is not used in North America. Due to its low boiling point, the 'fading' or poor retention of sodium in the melt once added, leaves Sr as the modifier of choice in present-day foundry operations.

The amount of each modifier element needed depends on the alloy composition, with a higher silicon content requiring a larger addition of the modifier. Sodium is generally used in the range of 0.005 to 0.01wt%. Strontium is used in the amount of ~ 0.02 wt% to modify hypoeutectic alloys such as A356 (with 7%Si), while up to 0.04 wt% may be needed for eutectic alloys such as 413 containing about 12 wt%Si.

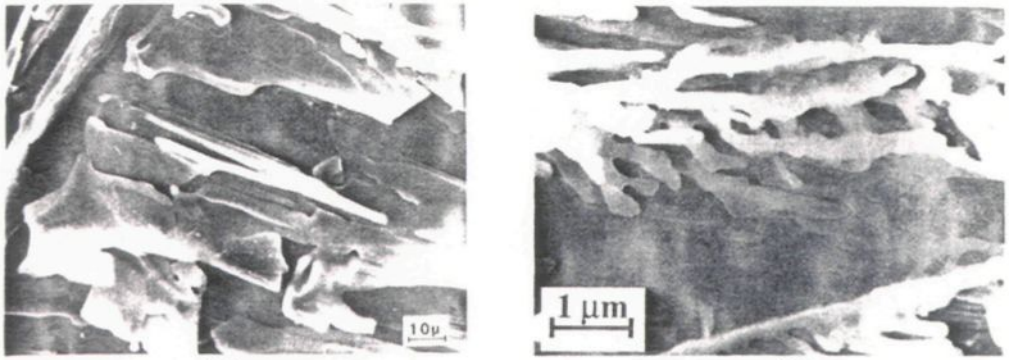
Figure 2.6 shows how, with the addition of Sr-modifier to the melt, the unmodified acicular eutectic Si plates become modified into fine particles, exhibiting a fibrous morphology.



(a) (b)

Figure 2.6 Optical micrographs showing the eutectic Si morphology in as-cast A356 alloy samples in: (a) unmodified, and (b) 200ppm Sr-modified condition.

As can be seen, in the unmodified state (a), the eutectic Si particles are present in the form of acicular flakes with a low density. By density is meant the number of Si particles observed per unit area or field. However, with the addition of 200 ppm Sr, these flakes are modified and refined into well-distributed fine fibres with a high density (b). This is demonstrated more clearly by the SEM images of Figure 2.7.



(a) (b)

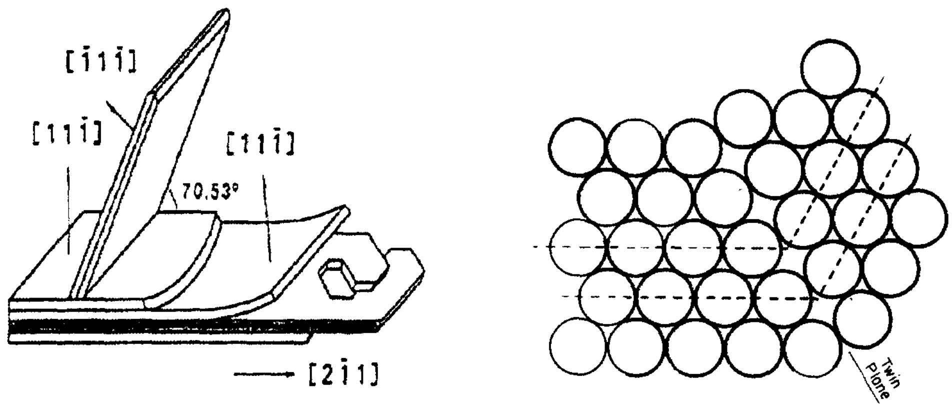
Figure 2.7 SEM images of : (a) eutectic Si flakes; (b) eutectic Si fibres.[26]

Apart from the use of modifiers (*viz.*, chemical modification), the eutectic silicon can also be modified through solution heat treatment or the use of high cooling rates (*i.e.*, quench modification). As full modification is difficult to achieve by increasing the solidification rate of the casting alone, Al-Si alloys are generally modified chemically, using modifying agents.[23]

Superheating the Al-Si alloy melt is also known to refine the eutectic silicon.[42] More recently, the melt thermal treatment (MTT) process has been reported as a promising alternative method of modification of Al-Si alloys, by Japanese and Chinese researchers.[24,38,39,41,42]

2.4.1 Mechanism of Eutectic Silicon Modification

With respect to the Al-Si eutectic reaction, the silicon phase plays a critical role in the modification process. In the unmodified state, the silicon particles assume a flake-like morphology when they grow at solidification rates of 5-100 μms^{-1}, and at temperature gradients of the solid-liquid interface of 50 -150°Ccm^{-1}.[25] The shape of the silicon particles (or flakes) can be described in terms of the facets on the close-packed {111} faces of the diamond cubic structure, generally combined with a few twins on the same planes. Transmission electron microscopic examination also shows that silicon flakes have < 211 > preferred growth direction. These aspects are shown in the schematic diagram of Figure 2.8 (a),[26] while Figure 2.8 (b) shows how twinning occurs in a crystal.[27]



(a) (b)

Figure 2.8 (a) Schematic model of eutectic Si flakes with twin configuration shaded,[26] (b) Twinning in a crystal showing the continuity of the atom planes across the twin plane.[27]

Crystallization of silicon takes place by the addition of atoms to form steps which move across the solid-liquid interface. These steps originate at twins across the {111} planes, as shown in Figure 2.9. By the means of a twin-plane reentrant (TPRE) growth mechanism, the reentrant edge at the growth tip formed by the twin planes tends to retain silicon atoms from the melt and promotes growth along the <112> direction. The modified silicon, although imperfect crystallographically, is highly twined with a rough microfaceted structure. This type of growth of the modified silicon allows free and easy branching to occur, to form the fibrous structure. The twin spacing is typically around 0.4-1.0 μm.

Both conventional and high resolution transmission electron microscopy (TEM and HRTEM) studies on Al-Si alloys have shown that chemically modified eutectic Si contains a much higher twin density than the unmodified eutectic.[26]

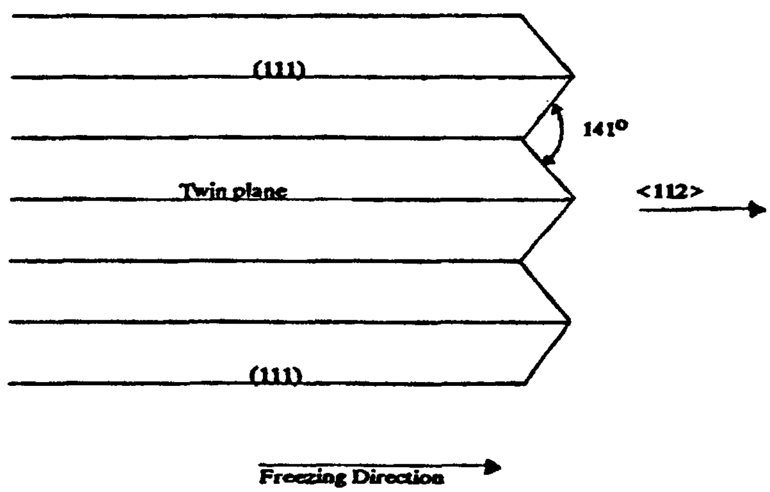


Figure 2.9 Schematic of twin planes and resultant grooves at the solid-liquid interface during the growth of an unmodified Si particles.[28]

According to Shamsuzzoha *et al.*,[29] modifying agents such as Sr or Na lead to an impurity build up in front of the silicon growth front. It is this impurity buildup that affects the growth of the eutectic Si particles during solidification by retarding the growth of the faceted eutectic Si over the nonfaceted α-Al phase to give enough time for coupled eutectic Si to grow. During the process of retarding eutectic Si growth, the impurity buildup induces a TPRE-assisted zigzag growth mechanism to promote a high twin density in the eutectic Si in Al-Si alloys treated by chemical modification.[25]

2.5 METHODS OF EUTECTIC SILICON MODIFICATION

In general, modification of Al-Si alloys can be classified into two types: quench modification and chemical modification. In the former, no additional element is added to the melt and the eutectic Si flakes are refined under high cooling rates (growth rates of 1 $mm \cdot s^{-1}$ or higher). In the case of chemical modification, with low level additions of certain chemical elements, the eutectic Si flakes are modified into branched fibres, while primary Si particles (polygonal in shape) assume more nearly spherical shapes. The chemical element addition or "modifier" or "modifying agent" can be Na, Sr, Ca, Ba or selected rare earth metals (La, Ce, Pr, Eu, Yb).[23]

Recently, the melt thermal treatment or MTT process has also been reported to refine the Al-Si eutectic in Al-Si alloy. In this process, low and high temperature melts of the alloy are mixed to produce refinement of the eutectic silicon. The use of melt superheat is also known to refine the eutectic silicon particles.

2.5.1 Quench Modification

Under rapid cooling rates, eutectic silicon particles can be refined from the large and coarse flakes formed under slow cooling conditions. This is referred to as quench modification. The information obtained from TEM observations indicates that the twin density in quench-modified fibres is very low, and some fibres even appeared to be twin plane-free.[27] Such investigations have revealed that quench modified fibres actually have the same characteristics of flakes refined by a large undercooling. Thus, in the case when the Al-Si eutectic is quench modified, flake to fibre morphology transition is not related to a massive increase in the twin density in eutectic Si as is observed in the case of chemical modification.

According to Khan *et al.*,[30] the transition of the eutectic Si particle morphology from flake to quench-modified fibrous is determined by the growth velocity, V, in that both the undercooling and interparticle spacing are function of V. As Figure 2.10 shows, the interparticle spacing decreases as the growth velocity increases,[29] which means that any factor that increases the growth velocity will produce a finer microstructure. At the same time, the increase in undercooling with increase in growth velocity helps in promoting the transition of the Si particles from flake to quench-modified fibrous form.

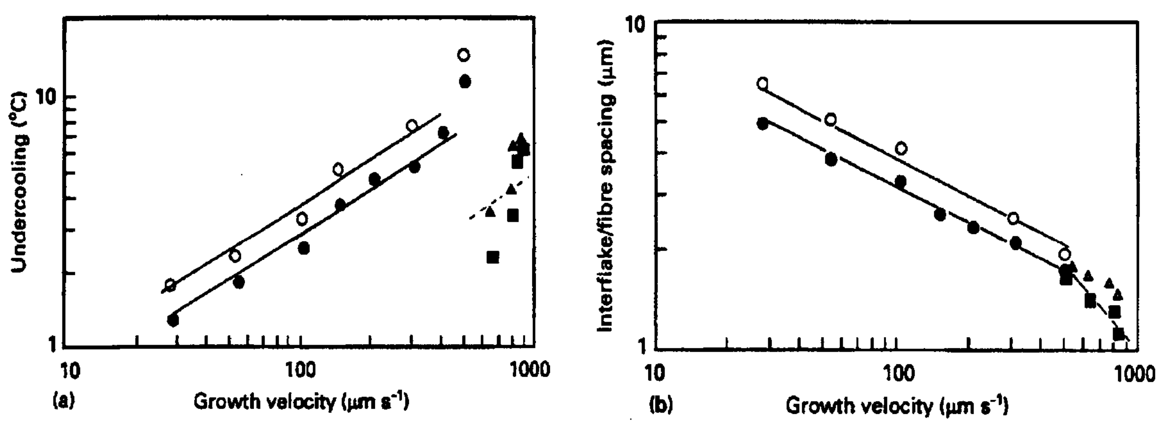


Figure 2.10 Undercoolings (a) and interparticle spacings (b) for unmodified (○,●) and quench modified (■,▲) Al-Si eutectic plotted as function of growth velocity for different temperature gradients: (●,■) 122°C cm^{-1}, (○,▲) 76°C cm^{-1}.[30]

2.5.2 Chemical Modification

With the addition of a low concentration of a modifying agent to an Al-Si alloy melt, the eutectic Si flakes can be modified into branched fibres which contain a high density of twins. An effective modifying agent or modifier should be evaluated against the following criteria:

- Size ratio of modifier atom to Si atom
- Melting point
- Vapour pressure
- Oxidation potential

The essential requirement for a modifier to induce twinning in eutectic Si crystals is that the ratio of the modifier element atom size to that of the Si atom must be in the range of 1.54 - 1.85. According to Lu and Hellawell[27], the ideal value of this ratio is around 1.646. From this point of view, many elements can be used as modifiers, *e.g.*, Ca and La, as shown in Table 2.5. Actually, these elements have been reported to have a modification effect on Al-Si alloys.[23,27] However, sodium and strontium are the two most popularly used commercial modifiers on account of some other important factors, as indicated in Table 2.5.

A modifier with a low melting point can promote its rapid dissolution in the Al-Si alloy melt which is usually held around 1000K. Thus, the dissolution of sodium with a melting point of 371K is much easier than that of strontium which melts at 1042K. Calcium and lanthanum are even more difficult to dissolve even though their atom ratios (1.68 and 1.59) are closer to the ideal value than that of strontium (1.84).

Table 2.5 Properties of possible modifiers[27]

Element	Atomic Radius, r (Å)	r/r_{Si}	Melting Point (K)	Vapour Pressure at 1000K (atm)	-ΔG oxide (kj mol^{-1} at 1000K)	$K_{oxidation}$
Ba	2.18	1.85	998	5×10^{-5}	482	20
Sr	2.16	1.84	1042	1×10^{-3}	480	15
Eu	2.02	1.72	1095	1.8×10^{-4}	500	-
Ca	1.97	1.68	1112	2.6×10^{-4}	509	400
Yb	1.93	1.65	1097	5.6×10^{-3}	500	1500
La	1.87	1.59	1193	10^{-6}	487	-
Na	1.86	1.58	371	0.2	367	2.7×10^{-5}
Ce	1.83	1.56	1071	10^{-16}	497	-
Pr	1.82	1.55	1204	10^{-13}	524	-
Nd	1.82	1.55	1283	10^{-11}	452	-

Vapor pressure also affects the choice of modifier. While a high vapour pressure is helpful for dissolving the modifier into the melt more rapidly, it can also causes the element to boil off and be lost from the melt, producing a 'fading' effect. Thus, sodium, which has the highest vapour pressure (0.2 atm at 1000K), fades very easily compared to other elements.

In addition to vapour pressure, oxidation potential is another important factor which can lead to fading.[23] The equilibrium constant $K_{oxidation}$ in Table 2.5 represents the oxidation tendency of the reaction,

$$x\,Al_2O_3 + y\,\text{Modifier} \rightarrow 2x\,Al + 3\,\text{Modifier}_xO_y$$

An element with a high value of K tends to be oxidized more easily than those with low K values. Although Na is very easily oxidized when exposed to air, its oxidation tendency in Al-Si alloy melts is very low. Other elements such as Ca and Yb have a high tendency for oxidation in the melt and hence are not effective modifiers. In comparison, the oxidation of Sr is very slow and so does not affect its efficiency as a modifier.

Through a comparison of eutectic Si particle characteristics observed in 200 ppm Sr-modified permanent and sand mold castings of A356 alloys, Paray and Gruzleski[5] highlighted the importance of chemical modification in situations where the Si particles cannot be refined by increasing the solidification rate (as in the case of sand castings).

Combining the above criteria, among all the elements shown in Table 2.5, only sodium and strontium have been used as effective modifiers for commercial application. [31,32] A third element, antimony, is often used as a modifier in European foundries. Unlike Na or Sr, Sb modifies the eutectic Si into a lamellar rather than a fibrous structure. The modification is permanent and has less gas pick-up and porosity formation tendency.[33] However, antimony does not work well at low cooling rates and is incompatible with other modifiers. In addition, the recycling of metal containing Sb is very difficult. More importantly, antimony is regarded as a health hazard and its commercial application is banned by law in North America.

While sodium is capable of producing very fine eutectic Si fibres within a very short time, there are several factors that limit its application. First of all, it is usually available in the form of pure metal, stored in kerosene as it is very easily oxidized in air. Thus, its addition to the melt is quite problematic, and its concentration in the melt very hard to control. Secondly, due to its high vapour pressure, it fades very quickly, providing only a short-term modification effect. Thirdly, it is sensitive to porosity and has adverse effects in terms of oxidation and agressivity against mold coatings or electrical resistances.[33]

Compared to sodium, while strontium does not have an immediate modification effect and has a tendency to cause porosity (which is not preferable for the mechanical properties), it has its own advantages. Due to its low vapor pressure and less tendency for oxidation, the loss rate of strontium is distinctly lower than that of sodium. Thus strontium can provide a very durable modification effect. Strontium-modified melts can be cast and remelted and will still exhibit a modified structure when re-cast. Also, strontium is very easy to store without any special requirements. It is available in the form of master alloys which makes its addition to the melt very convenient. Strontium can be used in many types of castings including sand mold and permanent mold casting.

In practical application, strontium is added to the Al-Si alloy melt in the form of master alloys, Al-10%Sr and Al-16%Si-10%Sr being the two most commonly used master alloys, as they are economical and very convenient to use, with excellent recovery and no fuming.[34]

Master alloys may be obtained in various shapes, *e.g.*, waffle form or rods. After the master alloy is added to the melt, a certain holding time is required to achieve optimum modification. For master alloy in waffle form, about 30 to 45 min are required, whereas in the case of rods, only 15 to 20 min are sufficient to achieve maximum modification[35]

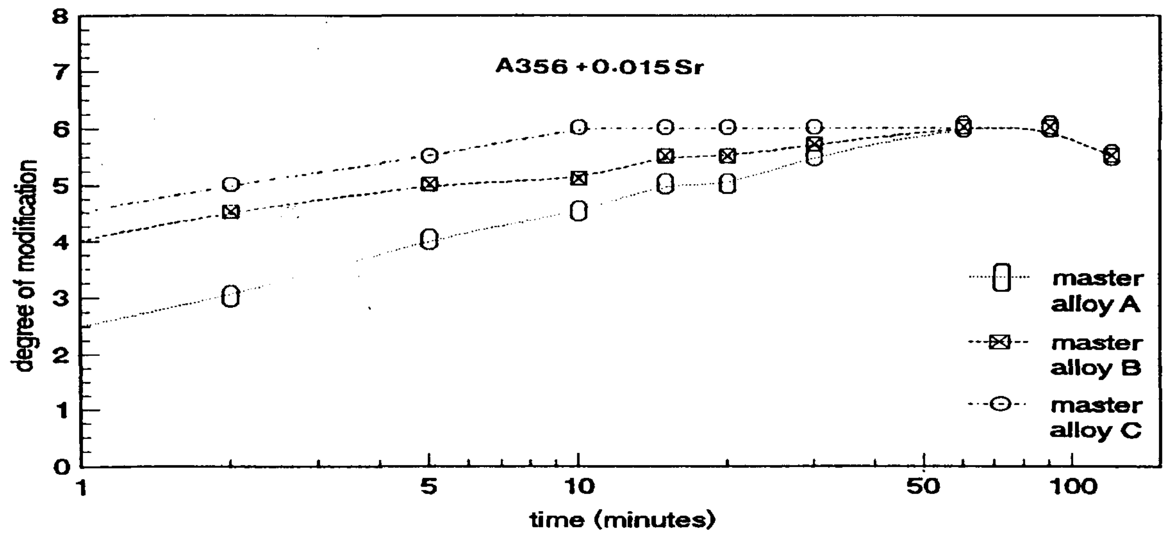


Figure 2.11 Effect of holding time on degree of modification achieved in a 150ppm Sr-modified A356 alloy using different Al-Sr master alloys.[36]

Chai and Bäckerud[36] conducted a study on the effect of holding time on the degree of modification achieved in 150 ppm Sr-modified A356 alloys using different Al-Sr master alloys. The degree of modification is based on a rating of 1 to 6, covering unmodified, lamellar, undermodified, well-modified and overmodified structures.[28] Figure 2.11 shows the results of their study, while details of the master alloys used are given in Table 2.6.

Table 2.6 Compositions of master alloys listed in Figure 2.11.[36]

Master alloys	Composition (wt%)				Al_4Sr^* (μm)
	Sr	Fe	Si	Al	
A	10.92	0.19	0.07	remain	400*100
B	3.60	0.15	0.06	remain	130*10
C	9.78	0.17	0.06	remain	10*1

* Size of Al_4Sr particles present in the master alloy

From Figure 2.11 it can be seen that about 10-20 min are required to achieve maximum modification. According to Chai and Bäckerud,[36] it is the size of the Al_4Sr

particles in the master alloy that affect the degree of modification. A master alloy with finer Al_4Sr particles will produce a higher degree of modification within a few minutes, like the C master alloy does. In the present work, the Al-10%Sr master alloy was employed to modify the A356.2 alloy melts.

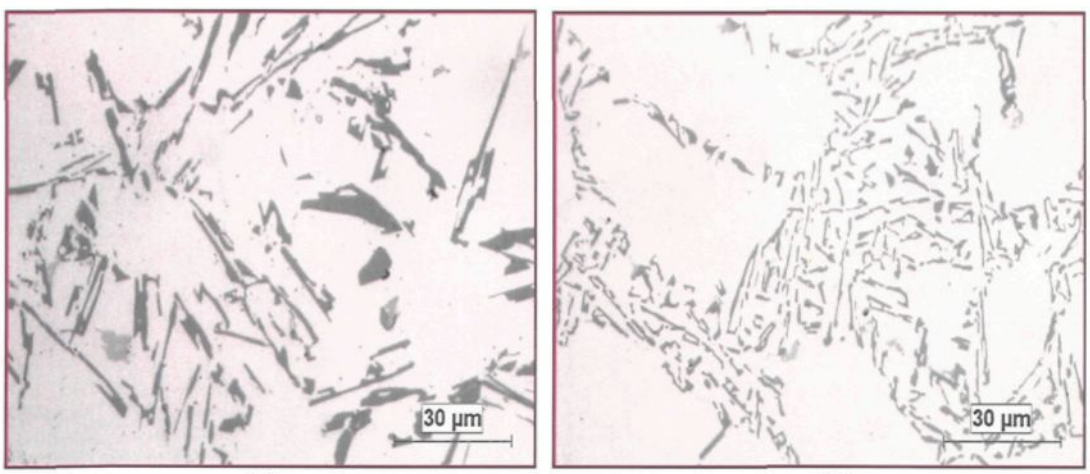
2.5.3 Melt Thermal Treatment

Melt Thermal Treatment (MTT), which was first reported by Valanbun in the 1960s,[37] has received much attention from Japanese and Chinese researchers in recent years.[24,38,39,41,42] To a certain degree, it appears to be a promising alternative to chemical modification in that it can reduce some of the negative influences of chemical modification such as increased porosity. Microstructure analysis of MTT processed Al-Si alloy castings show that the resulting microstructure is refined significantly, resulting in a considerable increase in the tensile strength-to-elongation ratio.

In the MTT process, a low temperature melt (LTM) and a high temperature melt (HTM) are mixed in preset weight proportions, stirred, and cast. When the temperature of the LTM is just above the liquidus, the melt contains a lot of atom clusters and refractory heterogeneous phases. The bonding force of these clusters is much lower than that of the solid phases. The effects of heating with the addition of the HTM and stirring enable these larger clusters to be easily broken into smaller ones which disperse in the melt uniformly, acting as the nuclei. As the temperature of the clusters is higher than that of the solid phase, the growing rate of these cluster nuclei will be slower than that of the solid phase, and the secondary dendrites will also grow slowly, decreasing the dendrite arm spacing.

Essentially, the LTM contains the nuclei, while the HTM provides instant thermal energy for nuclei multiplication.[39,40]

Figure 2.12 shows the microstructure of eutectic Si particles observed in A356.2 alloy without and after MTT processing. It can be seen that in the non-modified state, the silicon particles are present in the form of coarse acicular flakes after solidification, as shown in Figure 2.12 (a). After MTT processing, the Si flakes are refined into finer and more fibrous particles, as shown in Figure 2.12 (b). However, so far little study has been reported on the research of the twin plane content in the Si particles formed in MTT processed Al-Si alloys.

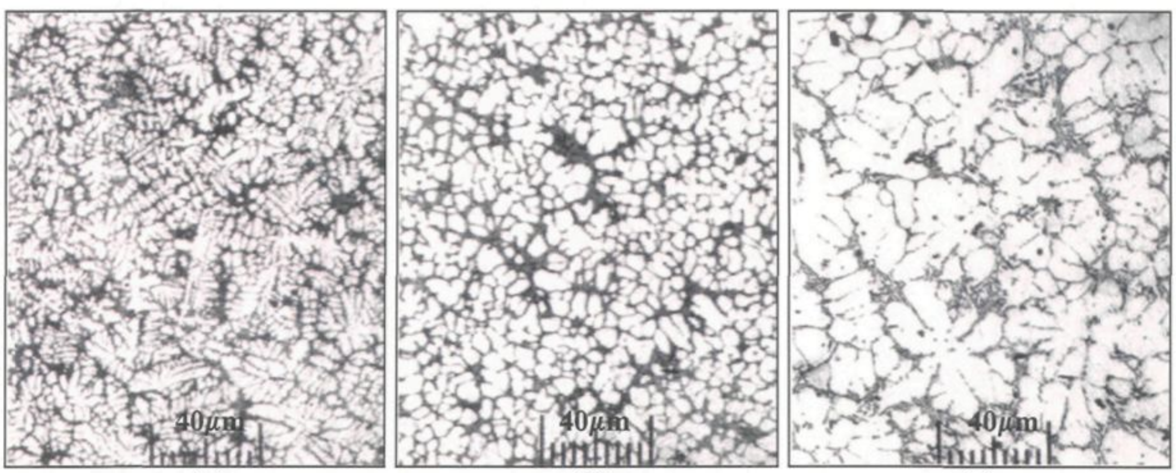


(a) (b)

Figure 2.12 Effect of MTT on eutectic Si in A356.2 alloy, as cast: (a) without MTT treatment; (b) MTT treated (2kg LTM at 600˚C mixed with 4kg HTM at 900˚C), cast at 720˚C.

There are three factors which are critical to the modification effect of the MTT process: the LTM structure, the holding time from the time of mixing the HTM into the LTM until casting, and the cooling rate of the mixed melt.[41]

The structure of the LTM determines the solidification structure of MTT-processed alloys. If the primary α-Al phase of the LTM has a tree-like dendritic structure in the case when the LTM is not stirred, the dendrite size will become smaller after the MTT process, but the morphology of the dendrites will still remain tree-like, as shown in Figure 2.13(a). On the other hand, if the dendritic structure of the LTM is broken into a rosette-like form with stirring, as shown in Figure 2.13(b), the resulting solidification structure of the MTT treated melt will also be in non-dendrite, rosette-like or spherical morphology, as shown in Figure 2.13 (c).[41]



(a) (b) (c)

Figure 2.13 Solidification structure of A356: (a) unstirred LTM, 600°C; (b) stirred LTM, 600°C; and (c) final structure by mixing HTM (850°C) into stirred LTM (600°C).[41]

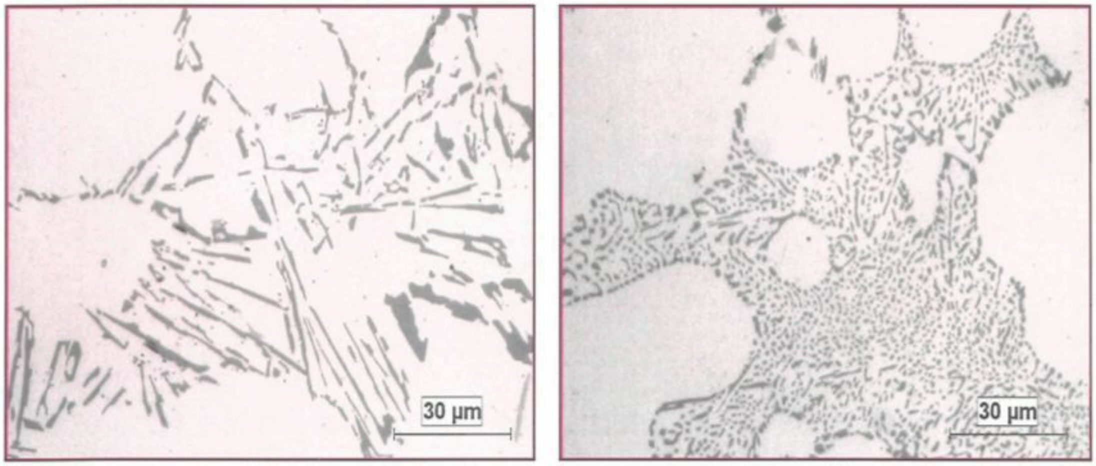
There is a holding time between the mixing of the LTM and HTM melts and pouring. During this period, the gas entrapped in the melt will escape, which can lower the gas content in the solidified alloys and thus improve the soundness of the casting. However, on the other hand, the effect of the MTT process fades as the holding time increases. The combination of these two factors results in a critical holding time at which the tensile properties can reach their peak values. The study by Wang *et al.*[41] shows the critical time is 60 seconds (see section 2.8.4, Figure 2.28).

Cooling rate can also affect the refining effect of the MTT process. There is a cooling rate range for which the MTT process can improve the tensile properties most effectively. According to Wang *et al.* [41], this range lies between 0.6 and 8.5 Ks^{-1}.

2.5.4 Melt Superheat

In addition to the MTT process, the effect of melt superheat on the eutectic Si structure in A356.2 alloy was also studied in this work. When A356 alloy is heated to temperatures above 800°C, the amount of clusters and crystalline particles in the melt decrease to a very low level. If the A356 melt is solidified at a high cooling rate from the superheated condition, the solidification structure will contain very fine Si particles, as shown in Figure 2.14.

According to Jie *et al.*,[42] if the heat treatment temperature is kept below 800°C, there is no obvious effect on the refinement of the Si particles in A356 alloy. However, over 800°C, the Si particles are significantly refined. At melt temperatures of 900°C, the refinement of the Si particles by superheat treatment is comparable to that obtained with 100 ppm Sr modification. Jie *et al.*[42] have contributed this refinement effect of superheat to the existence of Mg in the A356 alloy, as they did not find any such effect in Al-Si binary alloys (*i.e.*, containing no Mg).



(a) (b)

Figure 2.14 Microstructures of eutectic Si in A356.2 alloy, obtained from melts: (a) at 750°C; (b) superheated at 900°C for 20 minutes.

2.6 OTHER FACTORS AFFECTING EUTECTIC SILICON MODIFICAION

In order to achieve optimum modification, a number of other factors must be taken into consideration. Both the chemical composition of the alloy and the solidification rate will determine the structure of the eutectic Si in the as-cast condition, *i.e.*, in the non-modified state. The original size of the Si particles will determine the amount of modifier addition required to bring about proper modification. Obviously, coarser Si particles will require a higher modifier level to achieve a well-modified eutectic structure. Improper additions could result in undermodification or overmodification.

2.6.1 Chemical Composition

In the case of Al-Si-Mg alloys, Si and Mg are the main alloying elements. The Si content will determine the amount of modifier required. Thus, for example, to achieve the same degree of modification, an A413 alloy (with 12%Si) will require a higher addition of modifier than will an A356 alloy containing 7%Si only.

In those Al-Si-Mg alloys containing a high level of Mg, such as A332 alloy (1.0% Mg), Mg also has a slight refining or modification effect on the non-modified acicular Si particles, resulting in an eutectic structure that is a mixture of fibrous, lamellar and acicular particles. In A356 alloy, however, where the Mg content is only 0.4%, the Mg does not affect the Si particles. Nevertheless, it does affect the modification process (using Sr) as, due to the formation of the complex intermetallic compound $Mg_2SrAl_4Si_3$, which forms prior to the Al-Si eutectic, the modification effect of Sr is reduced, resulting in a partially modified eutectic Si structure rather than a fully modified one. [43]

Phosphorus, an inevitable impurity in Al-Si alloys, can also reduce the effect of modification by reacting with the modifier.[44] When strontium is added to A356 alloy, the reaction between the phosphorus and strontium is the main reason for the strontium fading that results. As shown in Figure 2.15, phosphorus has little effect on the degree of modification during the first 10 minutes after the addition of strontium to the melt.[36] However, since the melt must be held for a period of time (normally more than 10 minutes) to render the strontium effective, the effect of modification will be distinctly reduced. In this case, with 50 ppm phosphorus present in an A356 alloy containing 150 ppm strontium, the modification degree after 60 minutes holding time is reduced to 3 for the C master alloy, and to as low as 2 with the A and B master alloy[36] (see Table 2.6 for details of these master alloys). This problem can be solved by increasing the Sr level of the melt.

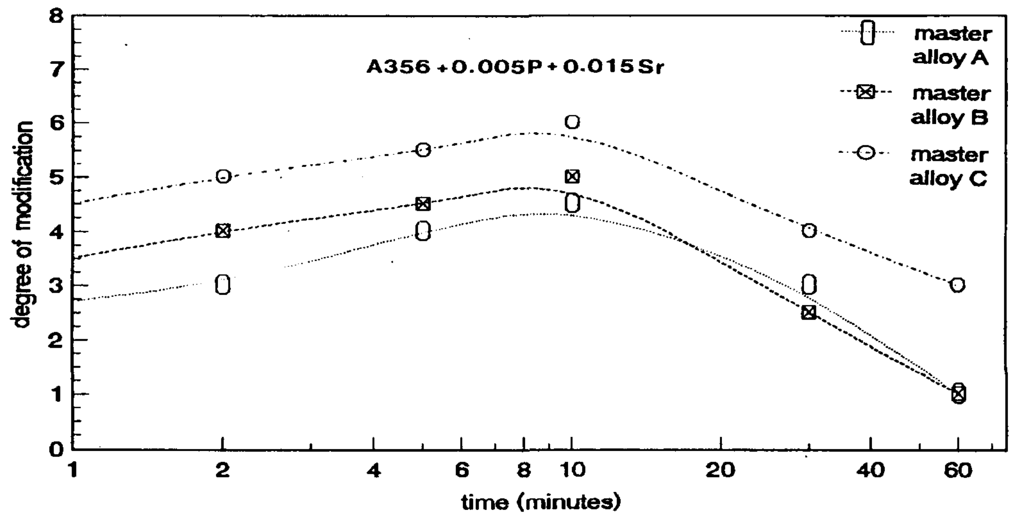


Figure 2.15 Effect of phosphorus on modification in A356 alloy.[36]

2.6.2 Solidification Rate

As the alloy microstructure and its constituents, including the eutectic Si particles, can be refined under rapid cooling rates, a high solidification rate will also enhance the effect of chemical modification. On the other hand, a very slow solidification rate could degrade the modification effect even in the presence of a modifier level sufficient enough to produce a fine fibrous eutectic Si structure. According to Pan *et al.*,[45] with 200 ppm Sr, a fully modified structure can be achieved in a casting at a high cooling rate (0.75°C/s), while only partial modification is obtained with a low cooling rate (0.34°C/s).

Paray and Gruzleski[5] quantified the effect of solidification rate on strontium modification in A356 alloy, using permanent-mold and sand-mold castings, representative of high and low solidification rates. Table 2.7 shows the Si particle parameters measured in the two cases.

Table 2.7 Silicon particle size analysis for the effect of solidification rate on modification.[5]

Parameter	**Permanent-mold casting (modified by 200ppm Sr)**	**Sand-mold casting (modified by 200ppm Sr)**
Particles/mm²	64866	48156
Area (μm^2)	0.24 ± 0.21	2.11 ± 2.95
Perimeter ((μm)	2.19 ± 1.14	5.84 ± 4.29
Average diameter (μm)	0.60 ± 0.26	1.64 ± 1.08
Aspect ratio	1.74 ± 0.51	1.79 ± 0.57

It can be seen that for the same level of strontium (200 ppm), the permanent mold casting produces much finer particles than the sand mold casting. However, the aspect ratio of the Si particles is not affected by the solidification rate, *i.e.*, solidification rate does not affect the Si particle shape as does Sr modification.

Based on various experimental results reported in the literature,[35,46,47,48] it is suggested that about 50-150 ppm Sr should be sufficient for relatively thin-section permanent mold castings, but at least 150-300 ppm Sr is required to achieve full modification in heavy sand mold castings that solidify at a low solidification rate.

2.6.3 Undermodication and Overmodification

In chemical modification, the use of improper amounts of the modifier can lead to either undermodification or overmodification.

With an insufficient modifier addition, the eutectic Si will exhibit a mixture of modified Si fibres and unmodified Si flakes, as shown in Figure 2.16.

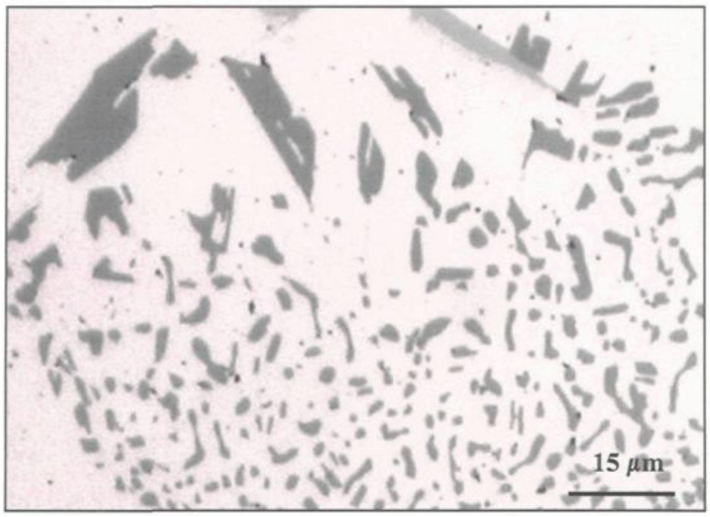


Figure 2.16 Undermodified eutectic Si particles in A356 alloy modified with 200 ppm Sr, as-cast condition.

When a modifier level in excess of that required is used, changes in the eutectic Si termed "overmodification" will occur, as shown in Figure 2.17. When Sr is used as the modifying agent, the overmodified eutectic Si appears larger than that in fully modified state. Overmodification can be caused by two phenomena: (a) the coarsening and joining of refined Si particles, and (b) the formation of different kinds of intermetallic particles containing strontium, such as Al_4SrSi_2, Al_2SrSi_2, and Al_3SrSi,[45,46] which will deplete the melt of the Sr needed to modify the Si particles in the regions where these intermetallics occur.

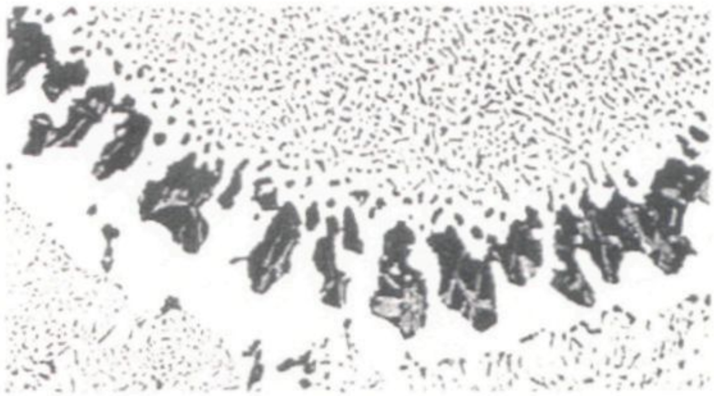


Figure 2.17 Internal structure of Si particles in Al-Si alloy overmodified by 200ppm Na.[46]

Both undermodifiation and overmodification exert a deleterious effect on the mechanical properties of Al-Si alloys. Thus a proper level of modifier is essential to achieve the required enhancement in properties.

2.6.4 Porosity

Porosity is one of the main problems associated with the use of strontium as a modifier. An increase in porosity is usually observed with the addition of strontium. As hydrogen is the only gas which has a considerable solubility in aluminum in the liquid state, the gas porosity observed in a casting is attributed to the hydrogen present in the melt. Shrinkage porosity, on the other hand, results from the reduction in volume (shrinkage) accompanying solidification. It has been suggested that the increase in porosity in Sr-modified alloys may be attributed to an increase in the hydrogen level of the alloy melt with the Sr addition.

Many studies have been carried out in this context. Hurley and Atkinson[35] have shown that the hydrogen level in Sr-modified A356 alloy does not increase until the temperature of the melt exceeds 1375 K (1101.85°C), as shown in Figure 2.18. As the melt temperature for most Al-Si alloys is kept below 1000°C, the increase in porosity is not expected to be caused by the increase in hydrogen content.

According to Argo and Gruzleski,[49] strontium addition results in the redistribution of the porosity throughout the casting: an increase in the microshrinkage and a decrease in the macroshrinkage (or piping), the total shrinkage remaining unchanged. The exact reasons for this redistribution of microshrinkage are still not clear. Emadi and Gruzleski[50] have proposed two possibilities: changes in interdendritic feeding or in the physical properties of the liquid metal/alloy.

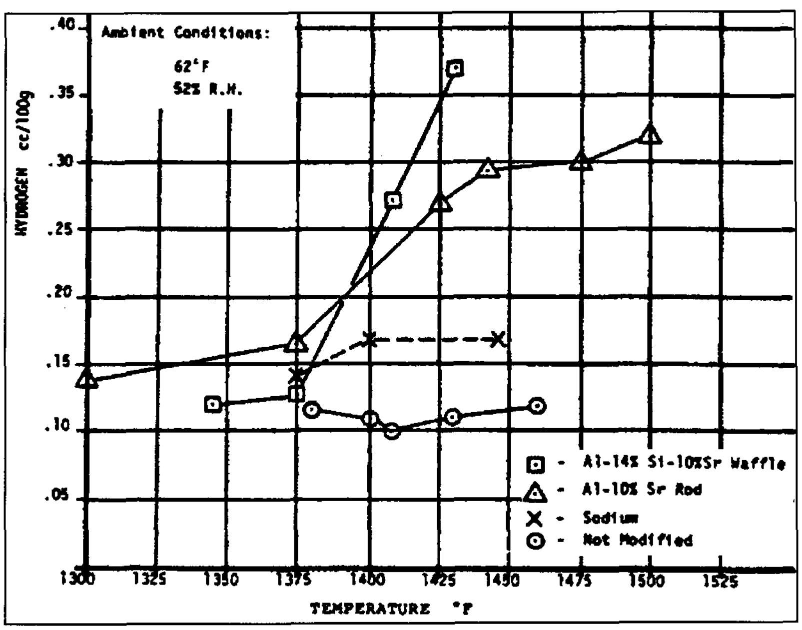


Figure 2.18 Gas content vs. holding temperature.[35]

According to Bian *et al.*,[51] strontium modification results in a change in the porosity morphology. In unmodified Al-10%Si alloys, the porosity is present in long, fissured, irregular form. With the addition of strontium, however, the porosity has a more rounded, regular and smooth shape, as shown in Figure 2.19. They suggest that the change in the morphology characteristics may be caused by the change in surface tension, inclusion content, and eutectic solidification with the addition of strontium.

(a) (b)

Figure 2.19 Porosity observed in reduced pressure castings of Al-10%Si alloys in: (a) unmodified, and (b) Sr-modified conditions.[51]

The problem of porosity in Sr-modified Al-Si alloys can easily offset the benefits that modification brings to the mechanical properties, particularly with respect to the ductility. Effective action should be taken to reduce the gas content, such as degassing after strontium addition, redesigning the gating and riser of the mold, controlling the hydrogen level in the liquid melt, and the use of chilling and directional solidification. In addition, new processing methods, such as hot isostatic pressing, are reported to be very efficient in reducing the porosity problem in Sr-modified alloys.[28]

2.7 EFFECT OF HEAT TREATMENT ON EUTECTIC SILICON PARTICLES

The presence of Mg in A356 alloy renders it a heat-treatable alloy, *viz.*, one whose mechanical properties can be enhanced with the use of a suitable heat treatment. Any heat treatment process involves three steps: (i) solution heat treatment, (ii) quenching, and (iii) natural or artificial aging. The improvement in properties is brought about through the precipitation of Mg_2Si within the alloy matrix during the aging process.

2.7.1 Role of Solution Heat Treatment

The main purpose of solution heat treatment is to dissolve as much Mg and Si into solid solution in the matrix, homogenize the casting, and change the morphology of the eutectic Si particles.[52]

Figure 2.20 shows that the solubility of Mg and Si in the Al-rich α-phase decreases with temperature. Therefore, in order to dissolve as much as Mg and Si into solid solution, the temperature of solution heat treatment must be as close as possible to the eutectic temperature. At the same time, this temperature should never exceed the melting point in order to avoid any local melting at the grain boundaries which can irreversibly reduce the mechanical properties. In most cases, for A356 and A357 alloys, the temperature of solution heat treatment is controlled at $540 \pm 5^{\circ}C$ to achieve a solubility of about 0.6% Mg in the solid solution.[7]

In the as-cast A356 alloy, the segregation of solute elements (Mg, Si) may affect the mechanical properties. As the solubility of Si increases with temperature, the Si content will be highest in the center of the α-Al dendrites which form first during the solidification

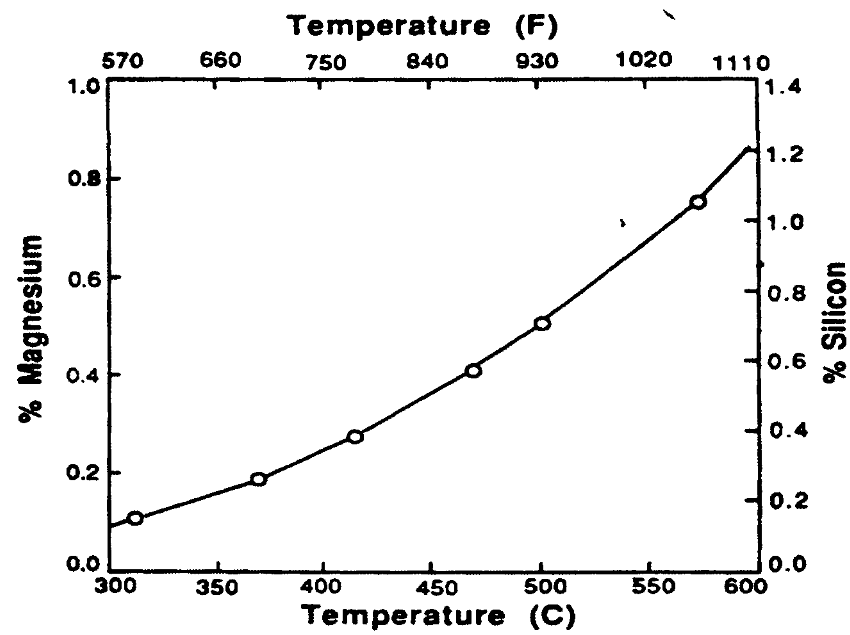


Figure 2.20 Equilibrium solubility of Mg and Si in solid aluminum when both Mg_2Si and Si are present.[7]

process. The Mg content, on the other hand, increases slightly from the center of the dendrite to the edge. However, these segregations are not very strong and can be eliminated within 30 min at 550°C, without any impact on modification.

During the solution heat treatment, the morphology of the eutectic Si particles changes with increase in the solution treatment time. This change includes three stages: fragmentation, spheroidization, and coarsening. Fragmentation occurs in the initial stages of solution heat treatment, when the Si particles start necking and then break into segments.[53] Then the Si particles are gradually spheroidized to a more rounded shape. Following spheroidization, with further solution treatment, the Si particles begin to increase in size, *i.e.* they undergo coarsening.[54] Both spheroidization and coarsening are driven by surface energy, while the alloy system tries to reduce the surface area to a minimum.

It has been found that the change in morphology of the Si particles is more dependent on the solution heat treatment temperature rather than the solution time.[55] In addition, the initial as-cast Si structure also has a great influence on the change in morphology that can take place during solution heat treatment. Fine as-cast Si particles need less solution treatment time to spheroidize,[56] as shown in Figure 2.21. Highly spheroidized eutectic Si particles are observed in the modified alloy after only 8 h solution time, whereas in the unmodified alloy, the eutectic Si is still present mainly in flake morphology. The higher spheroidization rate achieved in the modified eutectic Si particles can be explained on the basis of the different interfacial instabilities in the two cases: Compared to the unmodified Si particles, the modified eutectic Si particles are more interfacially instable and tend to break down into fragments and then spheroidize.

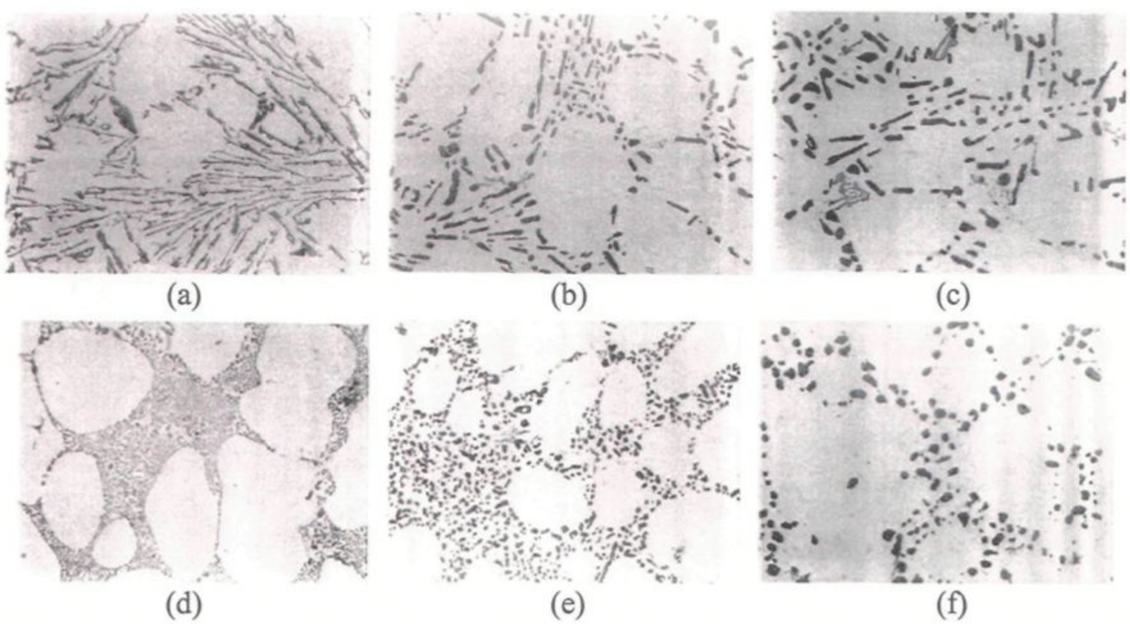


Figure 2.21 Microstructures showing eutectic Si particles observe in A356.2 alloy samples solution heat treated at 540°C. Unmodified alloy: (a) as-cast; (b) 2 h; (c) 8 h, and Sr-modified alloy: (d) as-cast; (e) 2 h; (f) 8 h.[7]

On the other hand, the growth rate of unmodified eutectic Si particles during solution heat treatment is higher than that of modified particles. Growth rates of 0.024 $\mu m^3/h$ and 0.01 $\mu m^3/h$ have been reported by Parker *et al.*[57] and Meyer[58] in the two cases, respectively. In the unmodified case, the large diversity in the size and shape of Si particles provides a greater driving force in the coarsening process.

2.7.2 Role of Quenching

Following solution heat treatment, the alloy is quenched; the purpose of quenching is to form a supersaturated solid solution of Mg_2Si in the alloy at a low temperature. The cooling rate must be very high to prevent any Mg_2Si precipitation from the solid solution. To obtain a high cooling rate, the quenching media must have sufficient volume and heat extracting capacity. Water is the most common quenching media, and for very thin parts, oil or air can also be employed. In addition, the quench interval is also critical, especially in the temperature range where Mg_2Si has the maximum precipitation rate. For A356 alloy, between 250 to 400°C, Mg_2Si can precipitate from the solid solution in 45 to 60 seconds,[8] which means the quench interval in this temperature range must be shorter than 45 seconds to produce a fully solid solution.

However, the cooling rate cannot be too high as it will cause distortion of the casting and induce residual stresses. In the case of water quenching, the temperature of water is normally controlled between 25°C to 100°C to provide a proper cooling rate.

2.7.3 Role of Aging

After solution heat treatment and quenching, A356 alloy castings are aged, typically at 155 to 175°C for 4 to 6 hours, for further enhancement of the mechanical properties through the process of age or precipitation hardening. The purpose of aging is to precipitate Mg_2Si from the solid solution in the following sequence:

$$\text{SS } \alpha \text{ phase} \rightarrow \text{GP zones} \rightarrow \beta' \rightarrow \beta$$

where SS α phase refers to the supersaturated α-Al phase; GP zones or Guinier-Preston zones, correspond to an early stage of the precipitates, characterized by an enrichment of solute atoms (Mg, Si) on the lattice sites of the α-Al matrix;[59] β' has a composition of Mg_2Si but appears in the form of rods that are semi-coherent with the α-Al matrix; and β is the final precipitate of Mg_2Si in the form of platelets which are coherent with the aluminum matrix at room temperature.

The whole aging process in A356 alloy begins with the decomposition of the SS α phase with a clustering of silicon atoms. This clustering leads to the formation of needle-shaped GP zones in the α-Al matrix, about 0.1 nm in diameter and 10 nm in length, and oriented along <100>. As the aging time increases, the GP zones grow to form the rod-like semi-coherent phase β', with an f.c.c. structure and long axis parallel to the <100> direction. With further increase in aging time, the equilibrium phase β (Mg_2Si) forms, with an f.c.c. structure, and a lattice parameter of the 0.639 nm. In addition, large Si particles are also formed if the alloy contains excess silicon.

The precipitation rate of Mg_2Si is dependent on the Si content. If the Si content is higher than that stoichiometrically necessary for the formation of Mg_2Si, the excess Si, even in small amount, can result in a much higher precipitation rate. In A356 alloy, there is about 1.35% excess Si, which can reduce the solid solubility of Mg_2Si, but can also lead to an increase in the solvus temperature at a given Mg_2Si level. Therefore, at any given temperature, a greater degree of supersaturation can be achieved and a finer dispersion of precipitates will be obtained.[8]

In addition to Si, Mg and Ti are two other alloying elements in A356 alloy which can influence the aging process. A higher Mg content can result in a greater supersaturation of Mg in the α-Al matrix, leading to a higher tendency for Mg_2Si precipitation. On the other hand, with the aid of electron microprobe and TEM analysis, Apelian *et al.*,[7] found that the presence of Ti, in the form of needle-shaped $TiAl_3$ in A356 alloy, delays the precipitation of Mg_2Si.

As a result of precipitation hardening, the mechanical properties of A356 alloy are improved. The aging temperature and aging time are two primary variables used to control the effect of precipitation hardening. Different hardening effects can be obtained with different combinations of aging temperature and aging time, as shown in the Time-Temperature-Transformation (TTT) curve of in Figure 2.22. According to the TTT curve, if the aging temperature is 300°C, it takes only 10 s for Mg_2Si to start precipitating, and after less than 2 min the maximum hardness is achieved. However, if the aging temperature is lowered down to 200°C, it takes about 2 min for the onset of Mg_2Si precipitation, and around 16-20 minutes to reach the peak hardness value. Generally speaking, it has been observed that increasing the aging temperature by 10°C is equivalent to enhancing the aging time by a factor of two.[8]

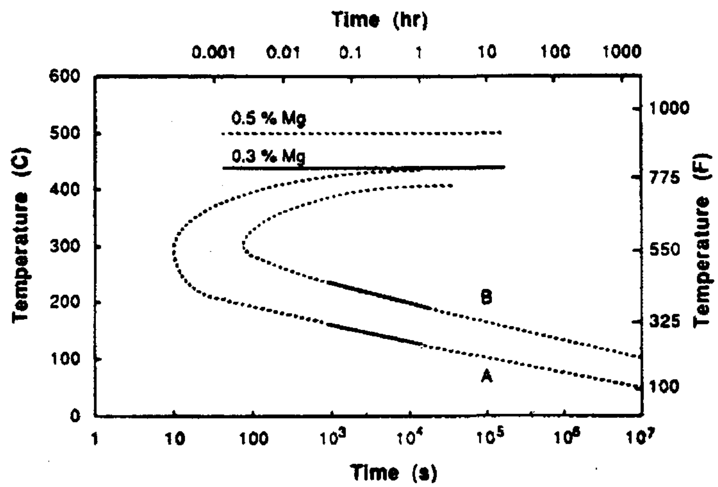


Figure 2.22 Proposed TTT curve for A356 alloy with 0.3%Mg: A) Onset of Mg_2Si precipitation; B) Curve of maximum hardness.[7]

If A356 castings which have been solution heat treated and quenched are stored at room temperature, the strength properties will be found to decrease. This decrease is attributed to a phenomenon known as natural aging, in order to distinguish it from the artificial aging process mentioned above. Figure 2.23 provides an example of how the hardness varies with natural aging in T6-treated A356 alloy.

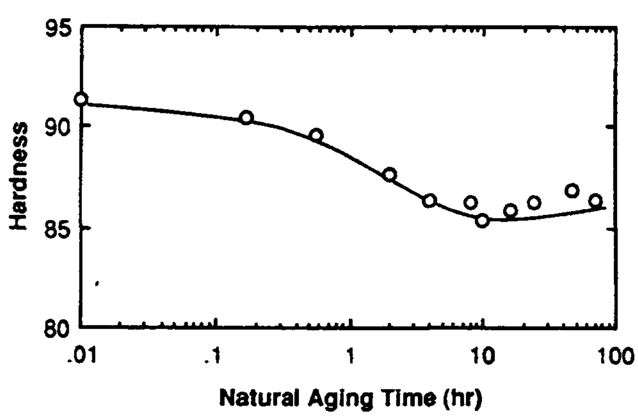


Figure 2.23 Effect of natural aging on T6 hardness (Rockwell F) of A356.[8]

Natural aging is not caused by Mg_2Si precipitation since, according to the TTT curve, over 1000 h are required at room temperature for Mg_2Si to start precipitating, whereas the phenomenon of natural aging can be observed only after 10 h, as shown in Figure 2.23. Apelian *et al.*[7] attribute natural aging to the interaction of vacancies and solute elements that constitute the precipitating phase. However, the effect of natural aging can be minimized by adding small amounts of Cu, Sn, In, or Cd into the castings or a short, high-temperature treatment prior to artifical aging. Storing the casting at a low temperature can also reduce the effect of natural aging on the strength properties.

2.8 TENSILE PROPERTIES

The tensile properties of an alloy are evaluated in terms of the yield strength (YS), ultimate tensile strength (UTS), and percentage elongation (% El) or ductility.

The tensile properties of A356 alloy castings are controlled by the fineness of the microstructure (*i.e.*, the dendrite arm spacing), Mg_2Si precipitation, and the eutectic Si particle characteristics, as well as by the presence of other intermetallics, inclusions and porosity in the casting. In view of the fact that all the parameters studied in this work, *viz.*, cooling rate, Sr modification, superheat, MTT process, and solution heat treatment affect the eutectic Si particle characteristics, the tensile properties will also be affected, correspondingly, by these factors.

The tensile properties can be calculated from the engineering stress-strain curve shown in Figure 2.24.[60] The stress, or the average longitudinal stress, in the tensile specimen is given by,

$$S = P / A_0$$

where S stands for stress, P is the longitudinal load on the specimen, and A_0 is the original cross-section area of the specimen.

The yield strength (YS) is the stress when the elongation of the specimen reaches 0.2% under load. The ultimate tensile strength (UTS), or tensile strength in short, is the maximum stress the curve reaches during the tensile testing process. Percentage elongation (%El) is calculated by the equation,

$$\%El = \sigma / L_0$$

where σ is the elongation measured and L_0 is the original length of the specimen.

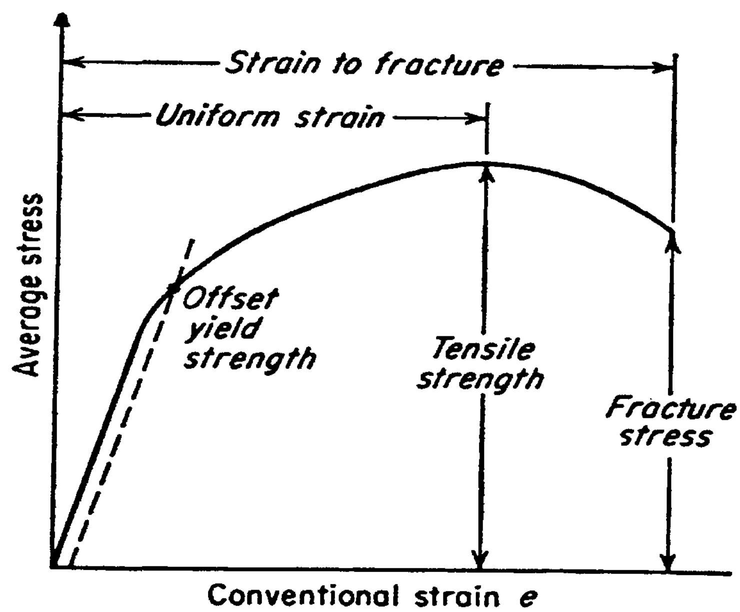


Figure 2.24 The engineering stress-strain curve.[60]

2.8.1 Effect of Eutectic Si Particle Size and Morphology

The fracture mechanism during tensile testing takes place via three stages: particle cracking, microcrack formation and growth, and local linkage of microcracks.[61] When a longitudinal load is applied to the specimen and plastic deformation occurs, the increasing internal stress induces cracking the Si particles as also in the Fe-rich intermetallics. The initial cracks in the eutectic Si particles form intraparticle microcracks which keeps growing. As strain continues, more and more intraparticle cracks are formed. When the volume fraction of cracked particles reaches a critical value, cracks in certain orientations are linked up very rapidly, resulting in fracture. According to Wang *et al.*,[62] fracture occurs when the cracked particles reach approximately 45 % volume fraction (or 20 % number fraction).

Wang *et al.*[62] also studied the effect of Si particle size and shape on the tensile properties of A357 alloy (Al-7%Si-0.55%Mg). As shown in Figure 2.25, for two applied stains, ϵ_f, of 0.010 and 0.035, the cracking tends to occur in particles of larger sizes and high aspect ratio. For example, at the strain $\epsilon_f = 0.035$, all particles larger than 20 μm have cracked while none of those smaller than 4 μm have cracked. This tendency does not change with the applied strain. In other words, the larger, elongated particles are first to crack, followed by the smaller and rounder ones.

Thus, through the use of various modification processes and solution heat treatment, the eutectic Si particle characteristics of an alloy can be suitably altered so that it exhibits improved tensile properties.

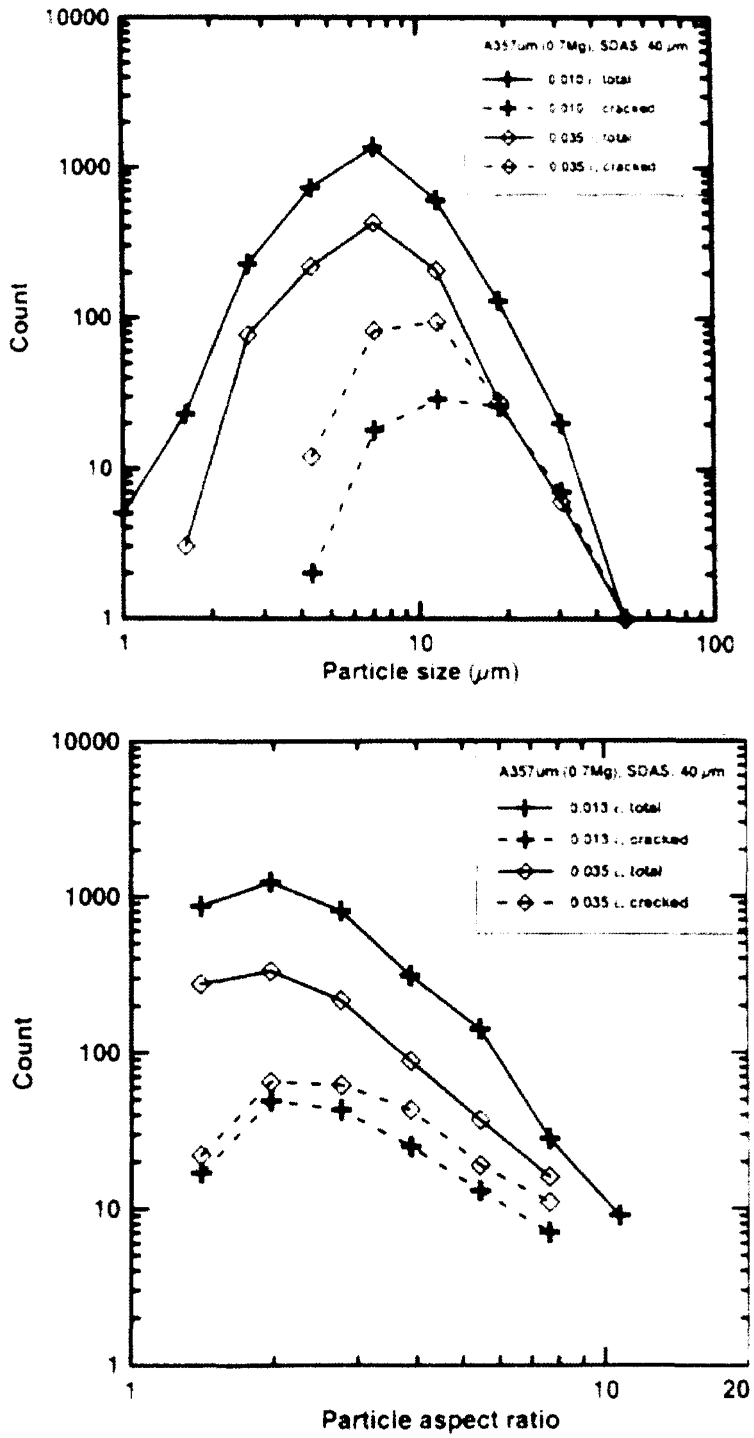


Figure 2.25 The distribution of all (solid lines) and cracked (dashed lines) Si particles as a function of (a) particle size and (b) particle aspect ratio (shape) for the non-modified A357 alloy at two levels of applied strain, ϵ_f.[62]

2.8.2 Effect of Cooling Rate

As discussed in section 2.6.2, a high cooling rate can produce finer and fibrous eutectic Si particles. Since a refinement of the eutectic Si structure can improve the tensile properties (especially the ductility), A356 alloy castings obtained at high cooling rates will exhibit higher tensile properties.

Table 2.8 shows the results of the study carried out by Paray and Gruzleski[5] on the effect of cooling rate on the tensile properties of A356 alloy. The cooling rate in permanent-mold casting is much higher than that in sand-mold casting. It can be seen that with the higher cooling rate, the YS and UTS of the permanent-mold casting are increased about 10% and 40%, respectively. Also, the standard deviation values indicate that the tensile properties are more homogeneous in the permanent-mold castings. The biggest improvement appears in the ductility, where the percentage elongation increases to about 2.5 times that observed in the sand-mold casting. The improvement in properties is attributed to the change in morphology of the eutectic Si particles achieved with the high cooling rate.

Table 2.8 Effect of cooling rate on tensile properties of unmodified A356 alloy, as-cast.[5]

Tensile Properties	Permanent-mold casting	Sand-mold casting
UTS (MPa)	219 ± 8	157 ± 12
YS (MPa)	109 ± 1	99 ± 12
El %	6.2 ± 1.6	2.4 ± 0.5

2.8.3 Effect of Strontium Modification

The effect of strontium modification on the tensile properties of A356 alloy has been investigated by many researchers. Closset[63] reported that the percentage elongation of Sr-modified low pressure 413 alloy castings is greatly upgraded, while the tensile strength is also improved, but to a lesser extent. Mahmoud and Toshiro[64] compared the mechanical properties of unmodified and Sr-modified Al-Si alloys cast in steel and graphite molds. Their results, as depicted in Figure 2.26, also show that tensile properties, particularly ductility, can be improved with strontium modification, *i.e.* by modifying the morphology of the eutectic Si particles from acicular to fibrous.

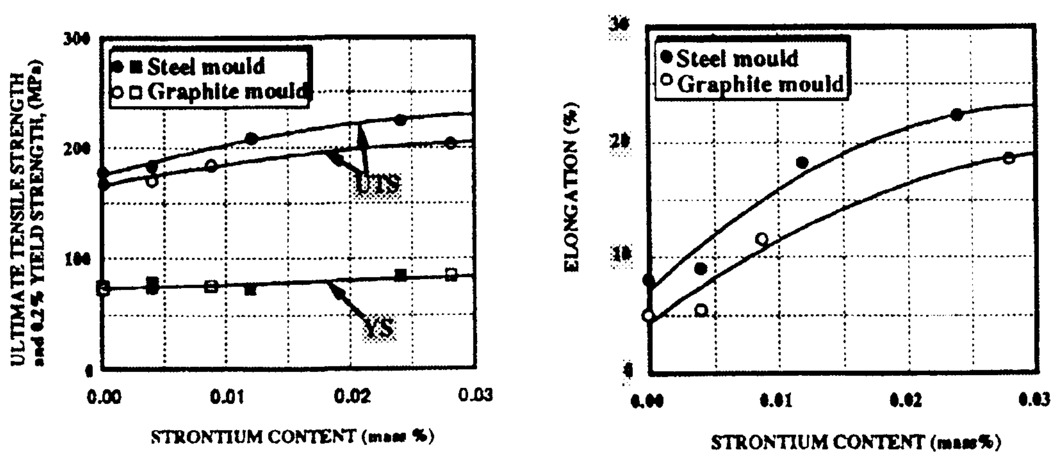


Figure 2.26 Influence of solidification rate and Sr level on the tensile properties of eutectic Al-Si alloy.[64]

Figure 2.26 shows the effect of various strontium modification level on tensile properties under different solidification rate. It can be seen that with 200ppm strontium, YS is slightly increased while UTS has a very remarkable improvement, and the percentage elongation is increased from 8.03% in the unmodified alloy to 22.2% in the 240 ppm strontium modified alloy, that is, by almost three times.[64] In addition, the modification is not affected significantly by the cooling rate (*i.e.* under either the high (steel mold) or low (graphite mold) solidification rates).

In their studies of investment-mold A356 alloy castings, Closset and Fay[65] also found that even at low solidification rates, Sr modification worked well in improving the mechanical properties.

2.8.4 Effect of Superheat and MTT Processes

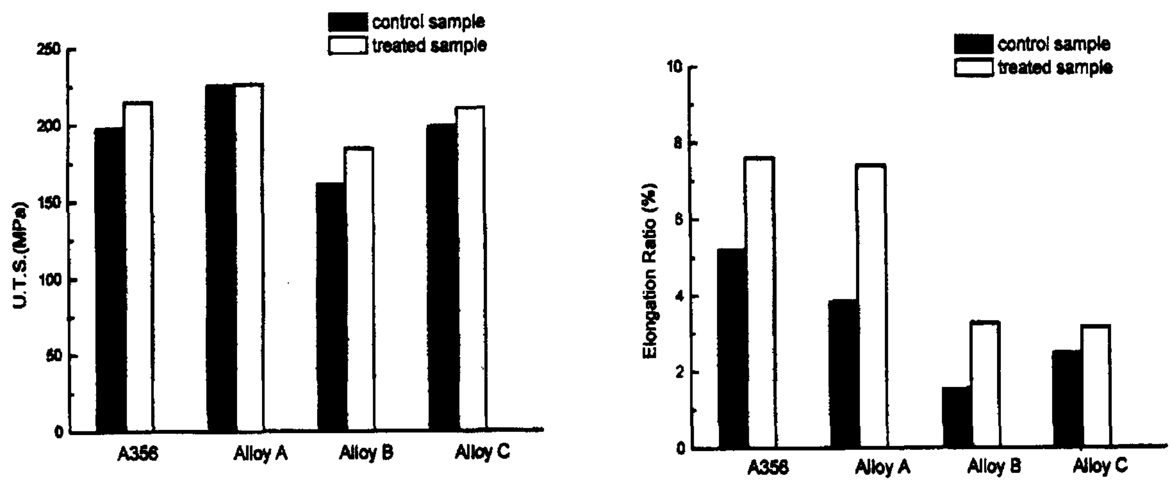
Tensile properties of A356 alloy can also be improved by superheating the alloy melt. Table 2.9 shows the results of the study carried out by Jie *et al.*[42] on A356 alloys, where it can be seen that the tensile properties increase with the melt superheat temperature until they reach maximum strength (340 MPa UTS) and ductility (8.5%) at 845°C, after which, the tensile properties begin to decline, as the melt superheat is increased to a higher temperature.

Table 2.9 Effect of superheat treatment on tensile properties of A356 alloy.[42]

Superheat Temperature (°C)	Ultimate Tensile Strength (MPa)	Yield Strength (MPa)	Percentage Elongation (%El)
720	305	260	5.0
810	330	280	3.0
845	340	270	8.5
945	330	275	7.0

To date, there are very few studies in the literature that report on the effect of melt thermal treatment (MTT) on the tensile properties of A356 alloy. The investigations by

Wang and coworkers[39,41,42] are probably the only references to be found. Wang *et al.* [41] studied the effect of the MTT process on the mechanical properties of hypoeutectic A356 alloys, Figure 2.27, where, compared to the control sample (poured at 720°C without any treatment), MTT processed alloys exhibit a slightly higher UTS but a remarkably increased ductility, where A, B and C are A356 alloys containing, respectively, 3.2%Cu, 0.75%Fe, and 1%Mg levels compared to the base alloy (Al-7.1%Si-0.4%Mg-0.096%Fe-0.052%Cu).



(a) (b)

Figure 2.27 Effect of MTT process on tensile properties of Al-Si alloys: (a) UTS; (b) El%.[41]

Wang *et al.*[41] also investigated the effect of holding time, *viz.* the time from mixing the HTM into the LTM to pouring, on the tensile properties, as shown in Figure 2.28. It can be seen that the UTS increases sharply in the first 20 seconds, gradually reaches its peak value after a holding time of 60s, then drops down rapidly as the holding time is further increased.

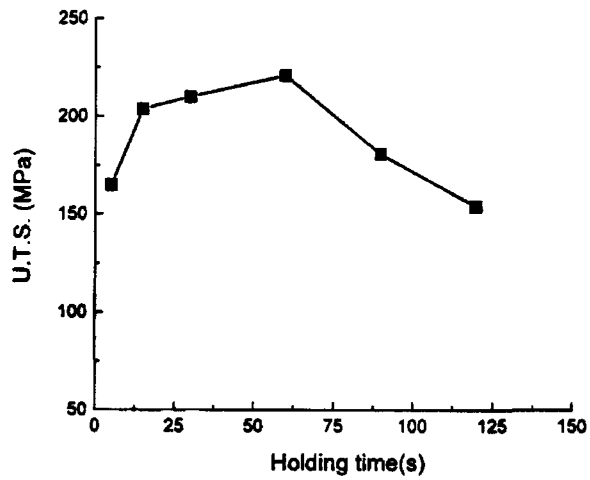


Figure 2.28 Effect of holding time on UTS of A356 alloy treated by MTT process.[41]

2.8.5 Effect of Solution Heat Treatment

The effect of solution heat treatment on the tensile properties of A356 alloy has been investigated by many researchers.[7,8,66,67,68,69] Their studies show that the tensile properties of A356 alloy can be significantly improved after solution heat treatment, followed by artificial aging. This improvement can be attributed to the changes in the eutectic Si particle size and shape that occur during the solution heat treatment and the precipitation of Mg_2Si during artificial aging.

Temperature and time are the two main parameters of solution heat treatment. Shivkumar *et al.*[67] reported that increasing solution heat treatment temperature from 540°C to 550°C can enhance the tensile properties of ASTM B 108 test bars of A356 alloy cast in permanent mold. However, they also pointed out that the solution treatment temperature should be controlled under 560°C since solution treatment at temperatures higher than 560°C will cause grain boundary melting and have a detrimental effect on the tensile properties. An investigation of the effect of solution time on the tensile properties of Al-Si-Mg/SiC_p composite castings carried out by Samuel and Samuel[68] showed that the effect of solution treatment (at 520°C) on the tensile properties was observed during the first 4 h, and thereafter little improvement was observed as the solution time continued to increase, even when the solution temperature was increased from 520°C to 550°C.

Tsukuda *et al.*[69] conducted an investigation on the effect of solution heat treatment temperature and time on the tensile properties of A356 alloy. Their results are presented in Figure 2.29. It can be seen that both UTS and %El improve with solution time at solution temperatures of 520°C and 530°C, while the YS decreases somewhat with increase in solution time. Peak properties are obtained at 540°C in 2 h solution time, but then show a slight decrease as the solution time is extended. While the changes in UTS and YS are relatively small from one solution temperature/time to the next, the percentage elongation shows much greater variations in comparison. Overall, the best tensile properties are obtained at 540°C/2 h.

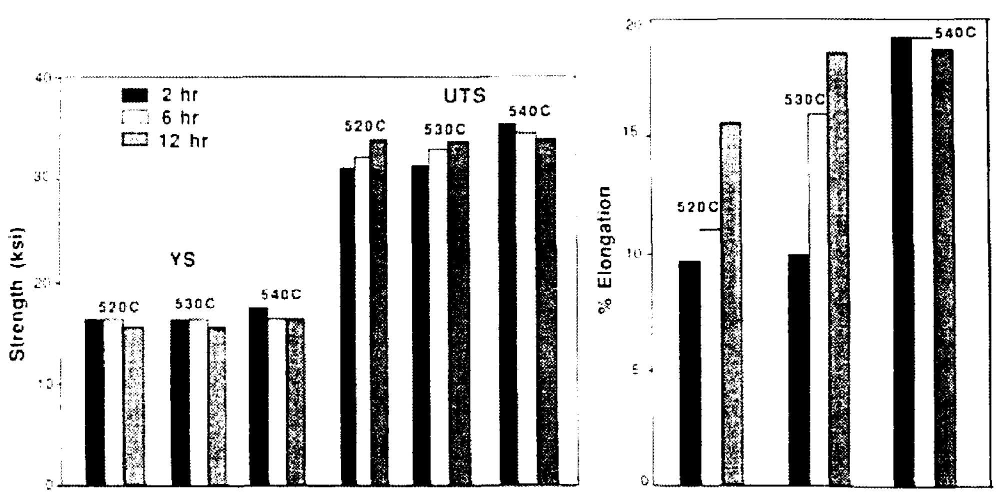


Figure 2.29 Effect of solution heat treatment temperature and time on tensile properties of A356 alloy.[69]

Following solution heat treatment and artificial aging, the tensile properties of A356 alloy can be greatly improved to desirable levels. This effect is attributed to the precipitation of Mg_2Si within the α-Al matrix. Tsukuda *et al.*[70] studied the effect of artificial aging temperature and time on the tensile properties of A356 alloy. Their results are presented in Figure 2.30. It can be seen that increasing either aging temperature (from 120°C to 180°C or aging time (up to 12 h) increases the YS and UTS, but reduces the ductility. Aging at 180°C/6h provides high strength, whereas aging at 140°C/4h gives a high elongation. According to Shivkumar *et al.*,[8] with an increase in aging time, YS and UTS reach a peak value after 10 h aging while %El reaches a minimum value. Further increase in the aging time is found to reduce the YS and UTS, with a corresponding increase in %El.

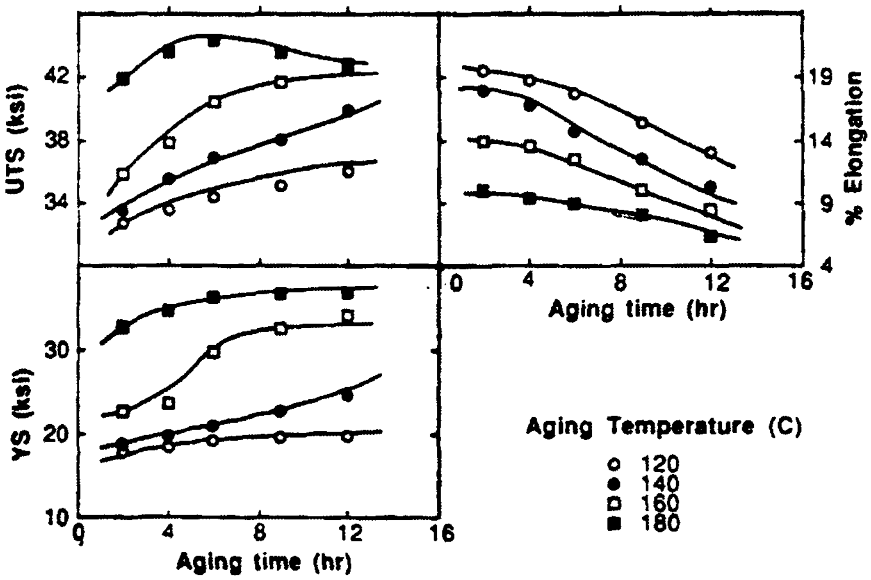


Figure 2.30 Effect of aging temperature and time on tensile properties of A356 alloy solution heat treated at 540°C for 9 hr and quenched at 15°C before aging.[70]

2.8.6 Quality Index

Drouzy *et al.*[71] brought forth the concept of quality index, Q, in the mid of 1970s. Instead of using ductility alone, the utilization of quality index, Q, is based on the considerations of the relationships between UTS, YS and %El. The quality index, Q, is defined as

$$Q = UTS + k \log \%El$$

with an unit of MPa and k a coefficient (equal to 150 MPa for the Al-7%Si-Mg alloys). Therefore, for A356.2 alloys studied in the present work, the quality index, Q, can be defined as

$$Q\ (MPa) = UTS\ (MPa) + 150\ (MPa) \log \%El$$

The quality index, together with yield strength, YS, can be represented by two sets of iso-lines (iso-YS and iso-Q) in a UTS-%El diagram. The effect of various casting and heat-treatment variables on the quality index, Q, as well as on yield strength, YS, has been summarized by Gruzleski and Closset,[28] as shown in Figure 2.31. Some parameters (*e.g.* Mg content and aging condition) have an influence on YS but not on Q. On the other hand, soundness of the casting, modification process, cooling rate, and solution heat treatment can affect the quality index, Q. Generally speaking, sounder, well-modified, and solution heat-treated castings possess a higher quality index, Q.

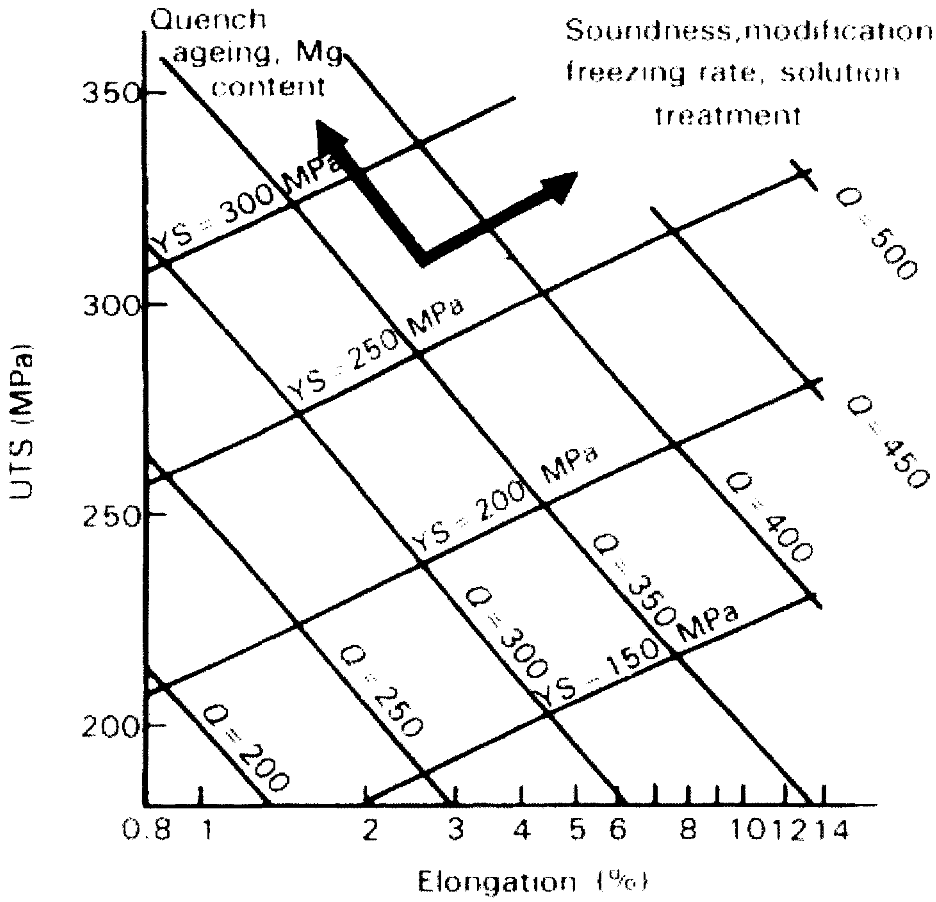


Figure 2.31 Relationship between UTS, El, YS and Q for an Al-7%Si-Mg alloy.[28]

CHAPTER 3

EXPERIMENTAL PROCEDURE

CHAPTER 3

EXPERIMENTAL PROCEDURE

The A356.2 aluminum casting alloy used in the present study was received in the form of 12.5 kg ingots. Table 3.1 lists the chemical composition of the as-received ingots.

Table 3.1 Chemical composition of as-received A356.2 ingot.

Ingot Type	Si %	Mg %	Fe %	Cu %	Mn %	Zn %	Ti %	Pb %	Al %
A356.2	6.78	0.33	0.11	0.02	0.04	0.04	0.08	0.03	bal.

The A356.2 alloy ingots were cut into smaller pieces, cleaned, dried and melted in a 7-kg capacity SiC crucible, using an electrical resistance furnace. The melting temperature was kept at 750°C ± 5°C.

3.1 MELT TREATMENT PROCEDURES

For preparing castings corresponding to various melt treatments and melt conditions, 6-kg charges of A356.2 alloy were melted in each case. The melts were grain refined, using 55 g of Al-5%Ti-1%B master alloy per 6 kg charge of metal. Degassing was carried out using pure dry argon, injected into the melt by means of a graphite rotary degassing impeller. The degassing time/speed were kept constant at 30 min/150 rpm.

For the preparation of Sr-modified castings, after degassing, the melt was modified using Al-10%Sr master alloy, where 12 g of the master alloy were added (to the 6 kg charge) to provide a Sr level of 200 ppm. The melt was stirred carefully and held for about 20 min to ensure proper dissolution of the strontium into the melt, followed by degassing for another 10 min before pouring.

For the preparation of castings using superheated melts, the melt temperature was increased to 900°C. The melt was held at this temperature for 20 min and then poured into the mold. The preparation of the castings using the melt thermal treatment (MTT) process will be described in section 3.2.1, separately.

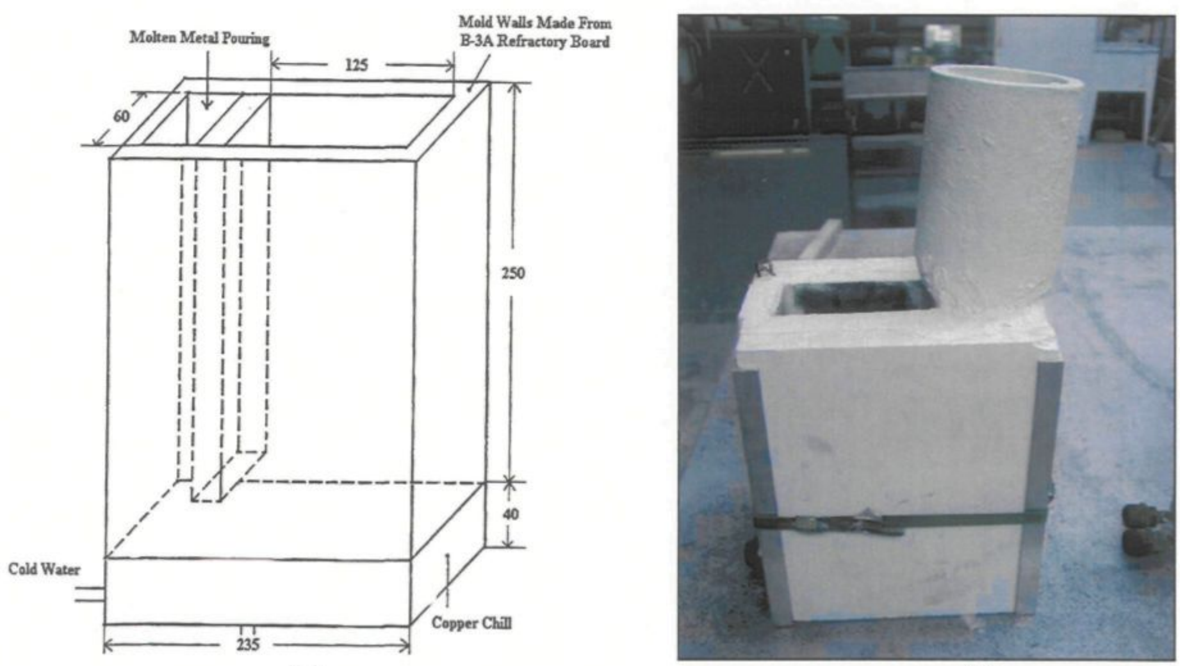
Figure 3.1 shows the two furnaces that were employed for preparing melts at 750°C and 900°C, respectively. Sampling for chemical analysis were taken from each of the melts corresponding to the different casting types.

(a) (b)

Figure 3.1 Furnaces used for preparing melts at (a) 750°C, and (b) 900 °C (superheating and MTT process).

3.2 CASTING PROCEDURES

Castings were prepared using a rectangular end-chilled mold, as shown in Figure 3.2. The four walls of the mold are made of refractory material, while the bottom consists of a water-chilled copper base, to provide directional solidification. A schematic diagram of the mold (64 x 127 x 254 mm) is shown in Figure 3.2(a), while Figure 3.2(b) shows the actual mold configuration. This kind of mold is designed to provide a range of cooling rates along the height of the casting above the chill end.



(a) (b)

Figure 3.2 The end-chilled mold used to prepare the castings in the present study: (a) schematic diagram (all dimensions are in mm); and (b) actual mold configuration.

The mold was preheated at 225°C for at least 2-3 h to remove all moisture. The molten metal was poured into the mold through ceramic foam filter discs fitted into the riser to avoid oxides and inclusions from entering the mold. The water (that circulates in the copper chill) was turned on as soon as the liquid metal had filled the mold to about 3 cm.

Such an arrangement produced ingot blocks with solidification rates that decreased with increasing distance from the chill end, giving microstructures that exhibited secondary dendrite arm spacings (SDAS) from 15 to 85 μm along the height of the cast block.

3.2.1 Melt Thermal Treatment (MTT) Process

For preparing castings using the MTT process, a 6-kg charge of A356.2 alloy was melted at 750° (in the furnace corresponding to Figure 3.1(a)), grain refined and degassed using the same procedures described previously. Following this, 4 kg of the melt were transferred to the other furnace (Figure 3.1(b)), already preheated to 750°C. The temperature of the first furnace was then lowered to 600°C, while that of the second was increased to 900°C. The corresponding low temperature melt (LTM) and high temperature melt (HTM) were held at their respective temperatures for 20 min, followed by 15 min of degassing. The HTM melt was then poured into the LTM melt, the mixture stirred carefully, followed by pouring into the end-chilled mold.

For the preparation of Sr-modified grain-refined castings using the MTT process, the same procedure was followed, except that the initial 6-kg melt was modified using 10 g of Al-10% Sr master alloy to give a Sr level of 100 ppm, followed by degassing for another

10-15 min. After that 4 kg of the modified melt were transferred to the other furnace and the same procedures followed of preparing the LTM and HTM melts, mixing them and then pouring the melt into the end-chilled mold.

3.2.2 Preparation of Castings Corresponding to Various Melt Treatments

A number of castings were prepared corresponding to each one of the melt conditions and treatments described in the previous section, to provide a sufficient number of castings for carrying out solution heat treatment for times ranging from 2 h to 80 h, and the corresponding metallography samples and tensile test specimens. Table 3.2 summarizes the details corresponding to all the castings that were prepared. The chemical compositions of the corresponding melts are given in Table 3.3, obtained from spectroscopic analysis.

Table 3.2 Details of the various A356.2 end-chill castings prepared for the present work

Casting Type	Melt Condition /Treatment	Charge	Additions to Charge	Melt/Pouring Temperature	No. of Castings Prepared
NM	As-received (non-modified) + grain refined	6kg	55g Al-5% Ti-1% B	750°C	10
SrM	Grain refined + Sr-modified	6kg	55g Al-5% Ti-1% B 12g Al-10% Sr	750°C	10
SH	Grain refined + Superheated (900°C)	6kg	55g Al-5% Ti-1% B	900°C	6
MTT	MTT process-treated Non-modified + grain refined LTM (600°C) HTM (900°C)	6kg (2kg) (4kg)	 55g Al-5% Ti-1% B	670°C	6
SrMTT	MTT process-treated Grain refined + Sr modified LTM (600°C) HTM (900°C)	6kg (2kg) (4kg)	□ 55g Al-5% Ti-1% B 3g Al-10% Sr	670°C	6

Table 3.3 Chemical composition of various types of melts.

Casting type	Casting No.	Si %	Mg %	Sr%	Ti %	Al %
NM	1	5.99	0.3219	< 0.0000	0.1762	bal.
	2	6.99	0.3849	0.0002	0.1694	bal.
	3	6.58	0.3225	< 0.0000	0.1601	bal.
	4	6.54	0.3575	0.0001	0.1690	bal.
	5	6.39	0.3571	0.0005	0.1826	bal.
	6	6.00	0.3445	< 0.0000	0.1709	bal.
SrM	1	6.17	0.3039	0.0220	0.1353	bal.
	2	6.26	0.3027	0.0204	0.1505	bal.
	3	6.51	0.3069	0.0213	0.1684	bal.
	4	6.60	0.2194	0.0202	0.1532	bal.
	5	6.05	0.2396	0.0204	0.1500	bal.
	6	6.33	0.2367	0.0203	0.1474	bal.
SH	1	6.44	0.3237	0.0007	0.0145	bal.
	2	6.17	0.2839	0.0002	0.1273	bal.
	3	6.05	0.3214	0.0005	0.1583	bal.
	4	6.25	0.2998	0.0002	0.1358	bal.
	5	6.63	0.3172	0.0004	0.1440	bal.
	6	6.47	0.3282	0.0002	0.1401	bal.
MTT	1	6.23	0.3085	0.0001	0.1435	bal.
	2	6.03	0.3281	0.0002	0.1560	bal.
	3	6.15	0.3177	0.0001	0.1345	bal.
	4	5.89	0.3244	0.0002	0.1614	bal.
	5	6.35	0.3130	0.0001	0.1406	bal.
	6	7.66	0.2471	0.0012	0.1391	bal.
SrMTT*	1	7.10	0.2962	0.0096	0.2053	bal.
	2	7.12	0.3214	0.0118	0.1878	bal.
	3	6.64	0.2992	0.0170	0.2401	bal.
	4	7.04	0.3246	0.0161	0.2361	bal.
	5	6.98	0.3069	0.0153	0.2260	bal.
	6	6.91	0.3255	0.0126	0.2099	bal.

*100 ppm Sr (and not 200 ppm Sr) was used for the SrMTT melt to determine whether in using the MTT process, a lesser amount of Sr would suffice to obtain a well-modified eutectic structure

3.2.3 Sectioning of End-Chill Castings for Sample Preparation

The end-chill castings that were prepared corresponding to the various melt treatments and processes were sectioned to obtain blanks that were subsequently sectioned to provide samples for solution heat treatment, metallography and tensile testing.

Figure 3.3 shows a schematic diagram of an end-chill casting (all dimensions are in mm). Three specimens blanks were sectioned from each of the prepared castings, at heights of 10, 50 and 100 mm from the chill end, and corresponding to average secondary dendrite arm spacings (SDAS) of 37, 62 and 78 μm, respectively, as shown in Table 3.4.

The SDAS values were determined by measuring the secondary dendrite arm spacings from the corresponding metallography samples using an optical microscope-image analyzer system. At least 40 measurements were made for each sample and the average value taken to represent the SDAS value for the corresponding level, as shown in Table 3.4.

It is to be noted that, for the metallography and solution treatment samples, the blanks were sectioned such that their surfaces corresponded exactly to the 10, 50 and 100 mm levels. These were the surfaces that were subsequently polished for microstructural examination. In the case of the tensile test specimens, the specimen blanks were sectioned such that the centrelines of the blanks corresponded to the 10, 50 and 100 mm levels (as shown in Figure 3.3), in order to be able to correctly compare the microstructures with the tensile properties.

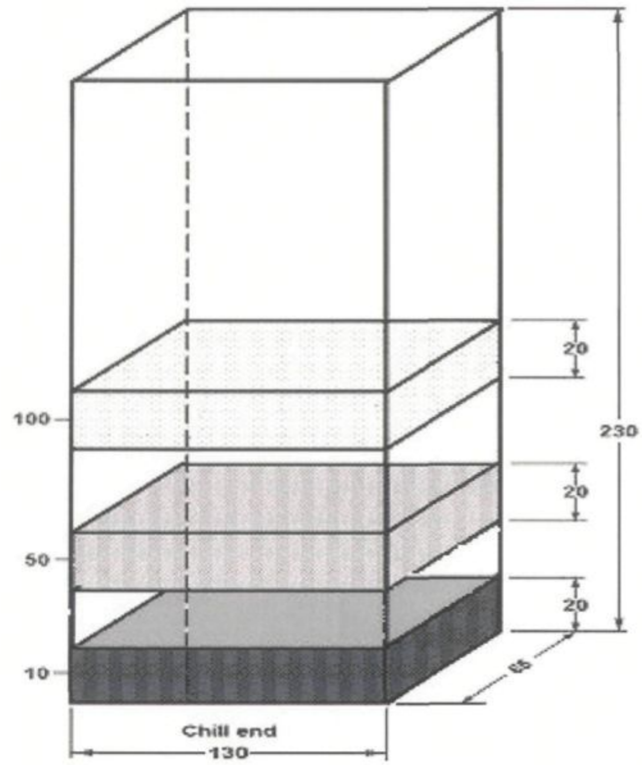


Figure 3.3 Schematic diagram of the end-chill casting (all dimensions are in mm).

Each of the three specimen blanks obtained per casting were further sectioned into 21 parts and numbered, following the sequence shown in Figure 3.4.

Table 3.4 SDAS values obtained at various levels of the end-chill casting

Level #	Distance From the Chill End (mm)	SDAS (μm)
1	10	37
2	50	62
3	100	78

1	**2**	**3**	**4**	**5**	**6**	**7**
8	**9**	**10**	**11**	**12**	**13**	**14**
15	**16**	**17**	**18**	**19**	**20**	**21**

Figure 3.4 Sectioning of specimen blank for preparation of samples for solution heat treatment and metallography.

3.3 SOLUTION HEAT TREATMENT

Two castings per casting type were used to obtain 42 samples for solution heat treatment for each of the three levels of the casting. Following the sectioning scheme of Figure 3.4, the first sample section (section 1) was kept aside as representing the as-cast condition for that level/casting type. The remaining 40 samples were solution heat treated at 540°C for times ranging from 2 h to 80 h in increasing intervals of 2 h, giving 40 solution treatment conditions.

Thus, each of the three levels per casting type provided 2 as-cast samples and 40 solution heat treated samples, giving a total of 3 x 42 = 126 samples per casting type.

The solution heat treatment was carried out in a Blue M Electric furnace at 540°C, with a temperature control of ± 5°C, for the 40 solution times. The samples were quenched in warm water (60°C).

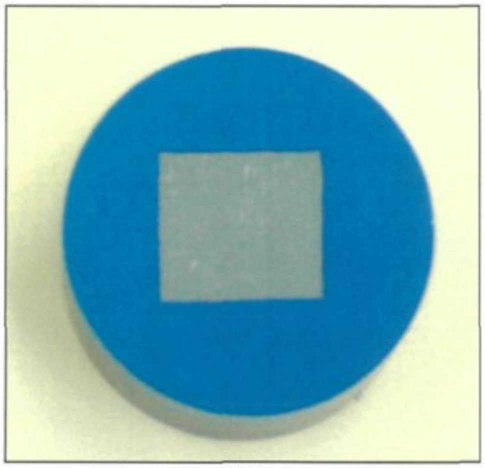
3.4 METALLOGRAPHY

The as-cast and solution heat treated samples (126 per casting type) were mounted in bakelite and polished to a fine finish (1 μm diamond suspension). Figure 3.5 shows the mounting press and polishing machine that were employed for this purpose. An example of a typical metallography sample is shown in Figure 3.6(a).

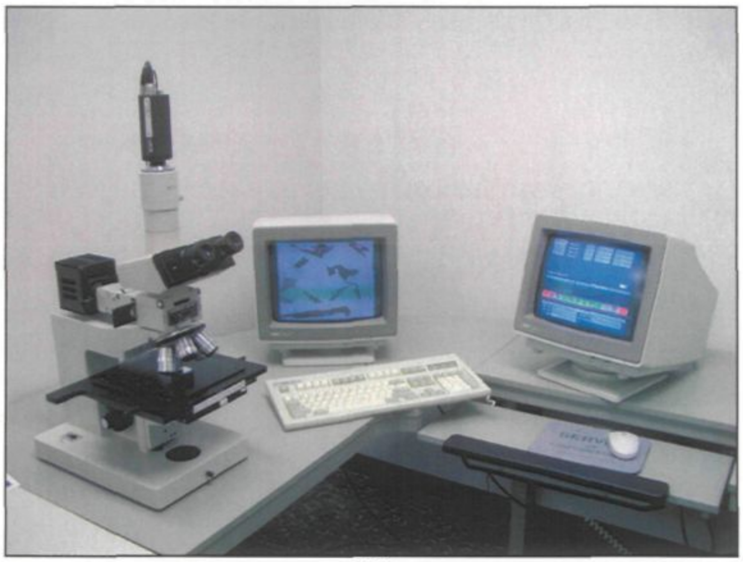
(a) (b)

Figure 3.5 (a) PRONTOPRESS-2 mounting machine;
(b) BUEHLER ECOMET 4 polishing machine.

The polished samples were examined using an Olympus BH-UMA optical microscope. The secondary dendrite arm spacings (SDAS) and eutectic Si particle characteristics were measured and quantified using a Leco 2001 image analyzer in conjunction with the optical microscope, as shown in Figure 3.6(b).



(a)



(b)

Figure 3.6 (a) Prepared sample for microstructural analysis; (b) Optical microscope and image analyzer system used for microstrutural analysis.

For the SDAS measurements, at least 40 measurements were made per sample, and the average taken to represent the SDAS value for that sample.

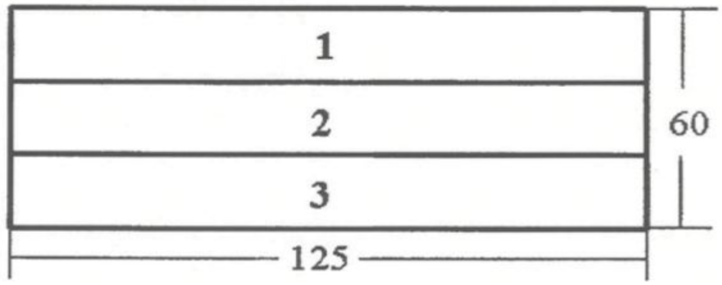
The eutectic Si particle characteristics were examined for determining the particle size and morphology corresponding to each casting type and solution heat treatment condition. The average Si particle area, length, roundness and aspect ratio were measured, where the area and length parameters estimated the size of the Si particles, while the roundness and aspect ratio parameters provided an indication of the spheroidization (roundness) of the Si particles.

For these measurements, 40 fields were examined for each sample, such that the entire sample surface was traversed in a regular, systematic manner, and the Si particle characteristics noted for each field. The measurements were carried out at 500 X magnification for the non-modified (NM) castings, and at 1000 X for the other (*viz.,* SrM, SH, MTT and SrMTT) castings.

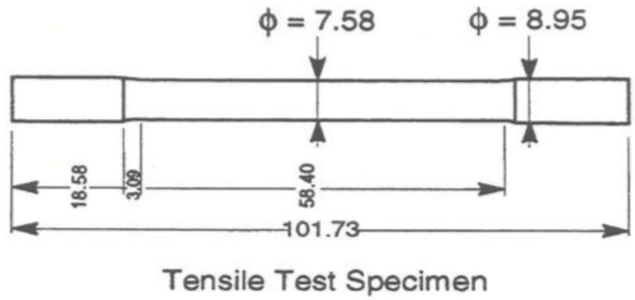
3.5 TENSILE TESTING

To prepare samples for tensile testing, specimen blanks were sectioned from each casting at the three levels of 10, 50 and 100 mm above the chill end, such that the centre line of each blank corresponded to these levels, as mentioned previously in section 3.2.3.

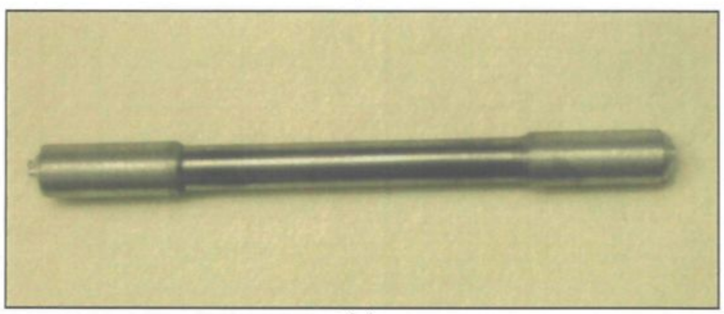
Each specimen blank was then sectioned into three, as shown in Figure 3.7(a), to provide three rectangular bars. These bars were solution heat-treated at 540°C for 0(as-cast condition), 8, 40 and 80 h, then machined to form the tensile test specimens, in keeping with the dimensions shown in Figure 3.7(b). An example of the actual specimen is shown in Figure 3.7(c). After machining, the tensile specimens were aged at 155°C for 5 h before the tensile testing was carried out. Four specimens were tested corresponding to each casing type/level/solution heat treatment condition.



(a)



(b)



(c)

Figure 3.7 (a) Blank sectioning scheme for preparing tensile test specimens;
(b) Tensile test specimen dimensions (in mm);
(c) Actual tensile test specimen.

The tensile testing was carried out using an Instron Universal Testing machine, as shown in Figure 3.8. The tests were conducted at room temperature at a strain rate of 2×10^{-4} m/s.

Figure 3.8 Instron Universal Mechanical Testing machine.

CHAPTER 4

AS-CAST MICROSTRUCTURE

CHAPTER 4

AS-CAST MICROSTRUCTURE

4.1 INTRODUCTION

Microstructures showing the eutectic Si particle characteristics obtained in the as-cast condition for the various casting types produced are presented in this chapter. Optical micrographs obtained from the three levels in each A356.2 alloy casting type (taken at 500 X magnification) reveal the changes in the eutectic Si particle characteristics with the change in the dendrite arm spacing, *viz.*, the effect of cooling rate on the former.

The Si particle characteristics were measured using a Leco 2001 image analyzer in conjunction with the optical microscope that was used to obtain the optical micrographs. Four parameters were measured: the average Si particle area, length, roundness and aspect ratio. These provided an estimation of the changes in size (area/length) and morphology (roundness/aspect ratio) of the Si particles, and hence that of the effectiveness of the modification process corresponding to a specific casting type (*i.e.*, Sr modification, superheat, MTT and SrMTT processes).

As will be shown in the following sections, the Sr modification, superheat and SrMTT processes produced a well-modified and fibrous eutectic Si morphology, whereas the MTT process alone produced a moderate refinement in the Si particles but no change in their morphology.

4.2 QUALITATIVE ASPECTS OF THE EUTECTIC Si PARTICLE CHARACTERISTICS IN THE AS-CAST CONDITION

The optical micrographs taken from the various A356.2 alloy casting types are presented in this section. To simplify the discussion, the five casting types studied will be referred to by their casting codes as shown in Table 4.1.

Table 4.1 Casting codes for the different A356.2 alloy castings produced.

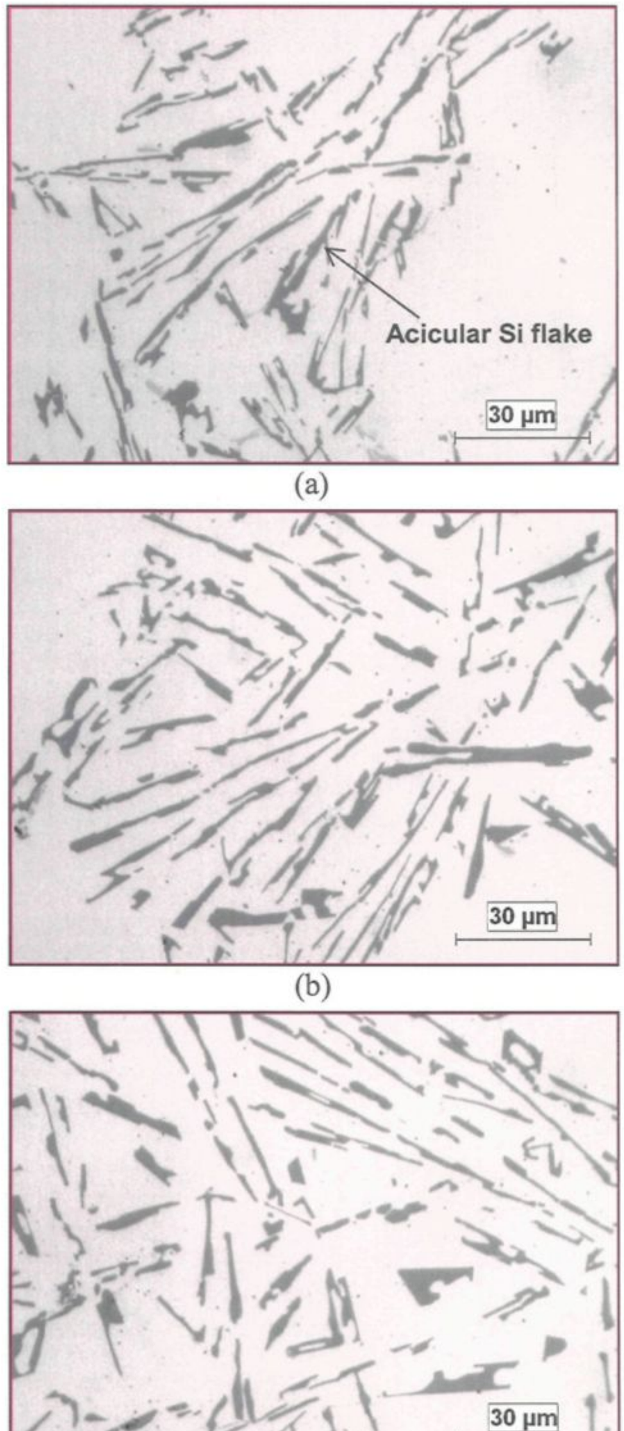
Casting Code	Casting Type
NM	Non-modified
SrM	200 ppm Sr-modified
SH	900°C Melt Superheat
MTT	Melt Thermal Treatment (MTT)
SrMTT	MTT process + 100 ppm Sr-modified*

* 100 ppm Sr (and not 200 ppm Sr) was used to determine whether in using the MTT process, a lesser amount of Sr would suffice to obtain a well modified eutectic structure

4.2.1 Effect of Cooling Rate

Figures 4.1 through 4.5 show the eutectic Si particle characteristics displayed by the A356.2 alloy castings corresponding to the five casting types. Each figure displays the microstructures obtained at levels 1, 2 and 3 of each casting, corresponding to DASs of 37 μm, 62 μm, and 78 μm, respectively.

As can be seen from Figure 4.1, the non-modified NM casting displays the typical acicular Si particles. Some amount of refinement due to cooling rate is observed in Figure 4.1(a) compared to Figures 4.1(b) and (c). In effect, the dendrite arm spacings of levels 2 and 3 are not that far apart and hence their microstructures would be more similar than different, particularly when compared to that of level 1, with a dendrite arm spacing almost half that of the others.

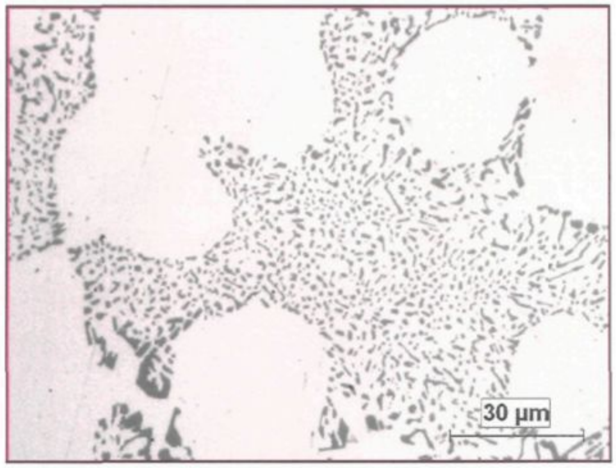


(a)

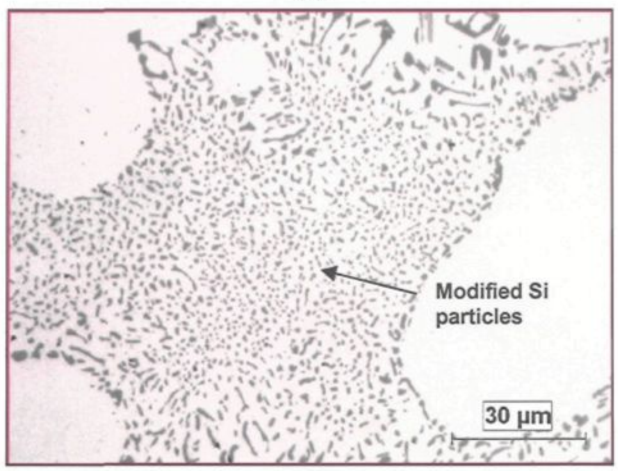
(b)

(c)

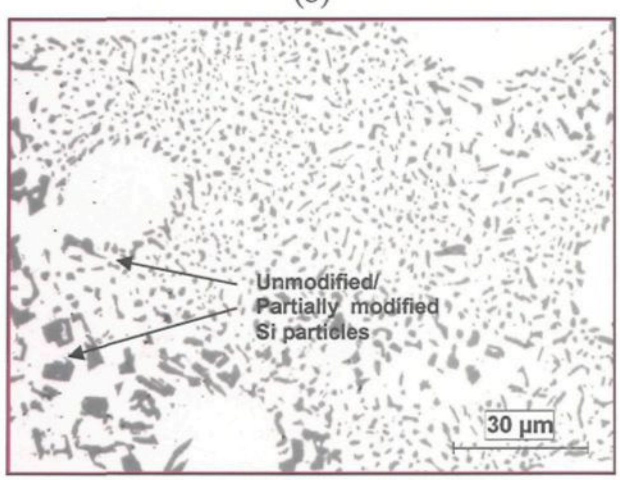
Figure 4.1 Optical micrographs showing the eutectic Si particle characteristics observed in as-cast samples of the NM (non-modified) A356.2 alloy casting: (a) level 1, DAS 37 μm; (b) level 2, DAS 62 μm; (c) level 3, DAS 78 μm.



(a)



(b)



(c)

Figure 4.2 Optical micrographs showing the eutectic Si particle characteristics observed in as-cast samples of the SrM (200 ppm Sr-modified) A356.2 alloy casting: (a) level 1, DAS 37 μm; (b) level 2, DAS 62 μm; (c) level 3, DAS 78 μm.

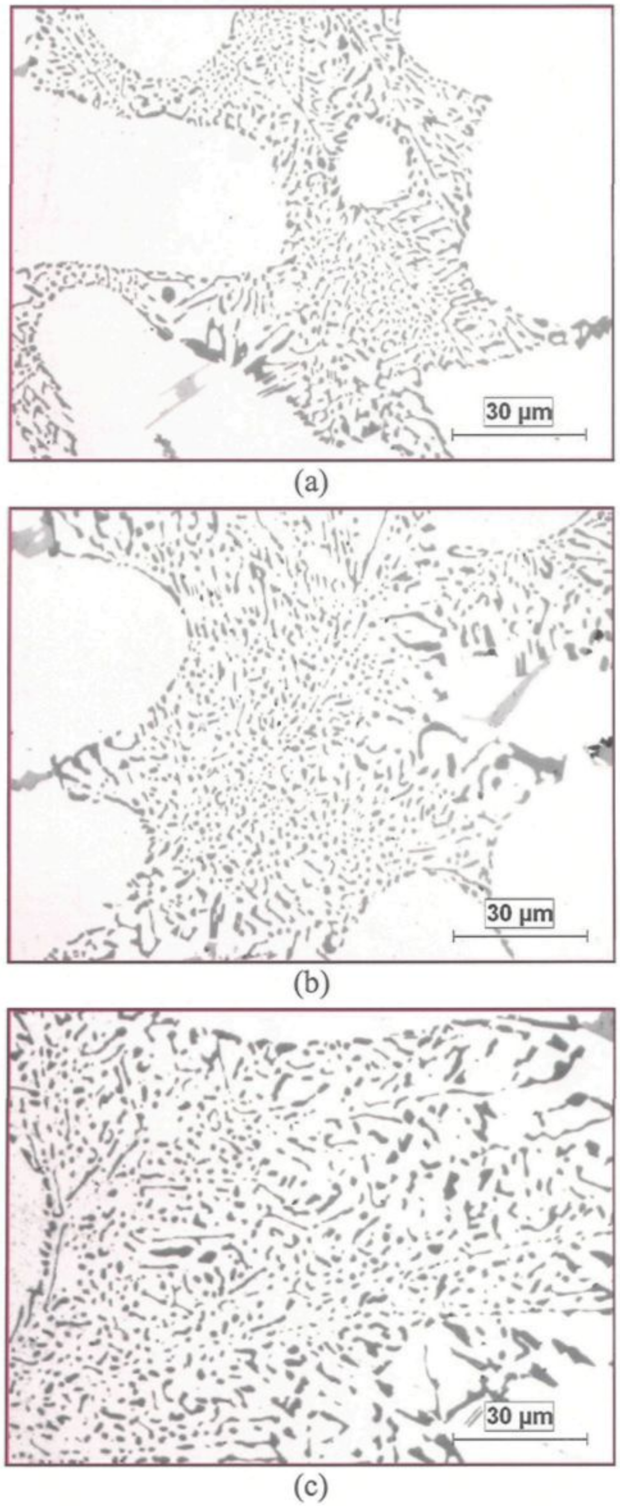
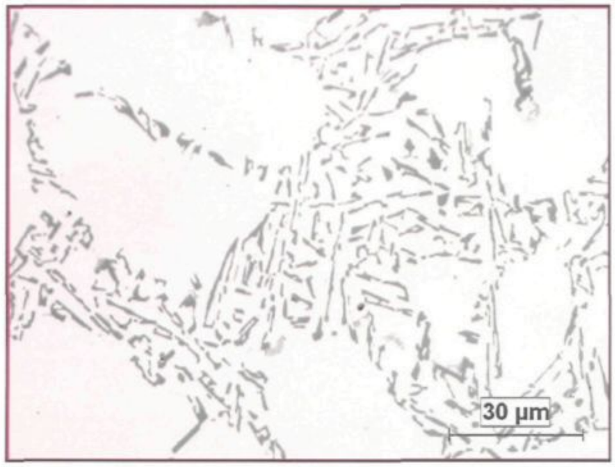
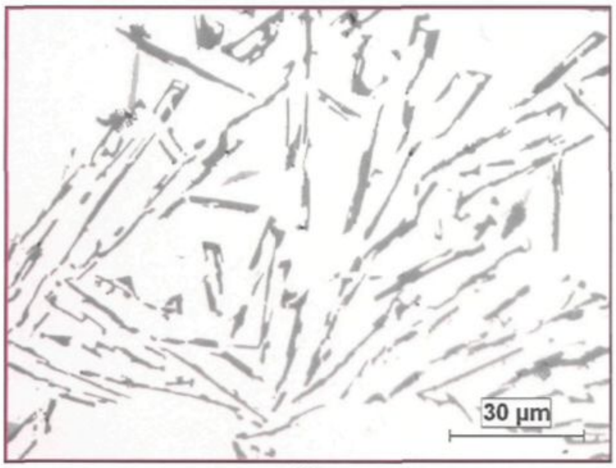


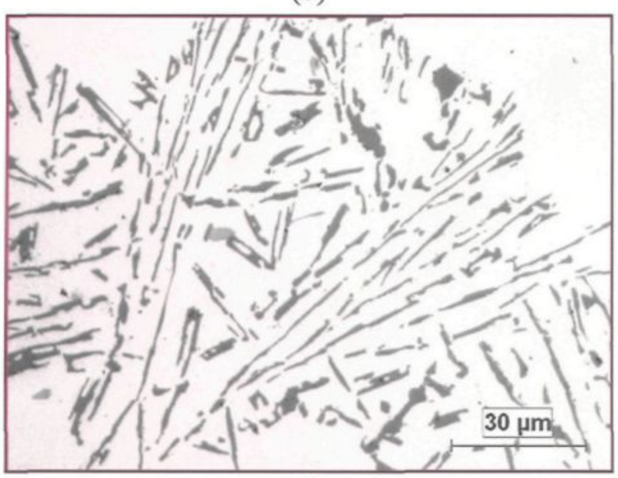
Figure 4.3 Optical micrographs showing the eutectic Si particle characteristics observed in as-cast samples of the SH (superheated) A356.2 alloy casting: (a) level 1, DAS 37 μm; (b) level 2, DAS 62 μm; (c) level 3, DAS 78 μm.



(a)

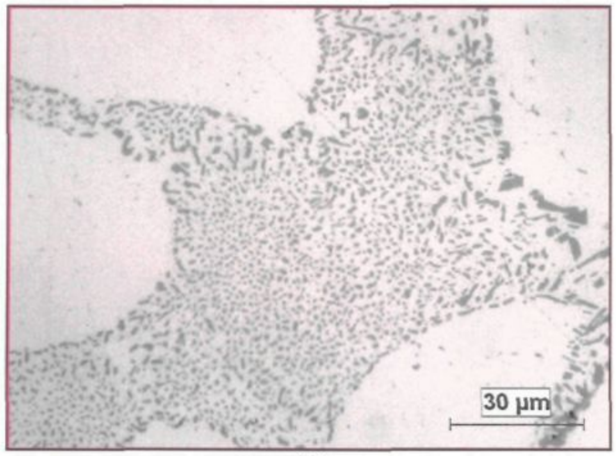


(b)

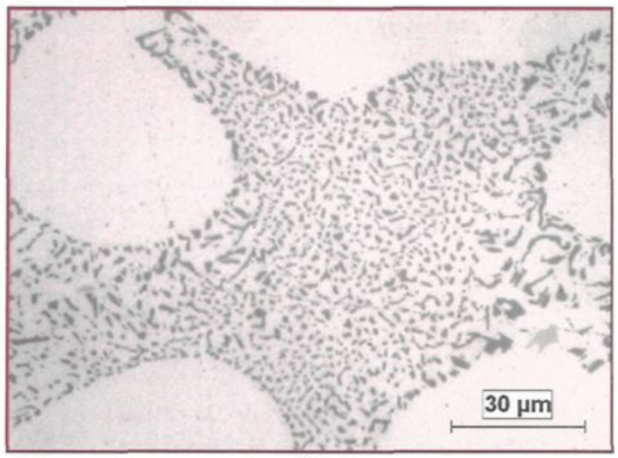


(c)

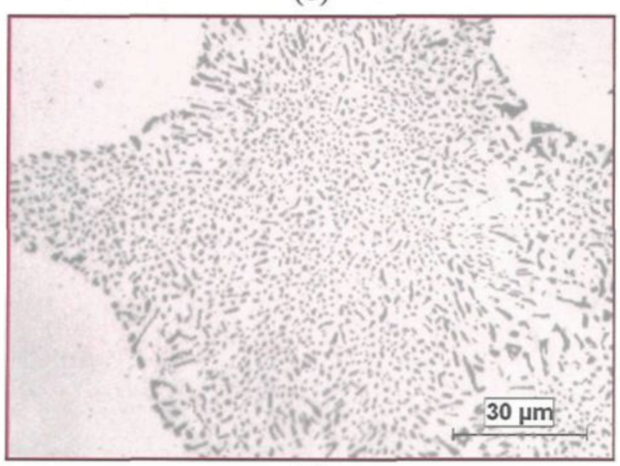
Figure 4.4 Optical micrographs showing the eutectic Si particle characteristics observed in as-cast samples of the MTT processed A356.2 alloy casting: (a) level 1, DAS 37 μm; (b) level 2, DAS 62 μm; (c) level 3, DAS 78 μm.



(a)



(b)



(c)

Figure 4.5 Optical micrographs showing the eutectic Si particle characteristics observed in as-cast samples of the SrMTT (100 ppm Sr-modified + MTT processed) A356.2 alloy casting: (a) level 1, DAS 37 μm; (b) level 2, DAS 62 μm; (c) level 3, DAS 78 μm.

Tolui and Hellawell[72] and Hogan and Song[73] have reported that the Si interparticle spacing decreases with increase in cooling rate and *vice versa*. This is evidenced to some extent in Figure 4.1.

With the introduction of 200 ppm Sr to the melt, the eutectic Si particles are completely transformed from long, acicular plates to well-modified fibrous particles, as shown in Figure 4.2. The very fine size of the particles results in a significant increase in the Si particle density. The observation of a well-modified eutectic structure in A356.2 alloys with Sr addition is well reported in the literature (see, for example, Pan *et al.*[45] and Crosley and Mondolfo[20]).

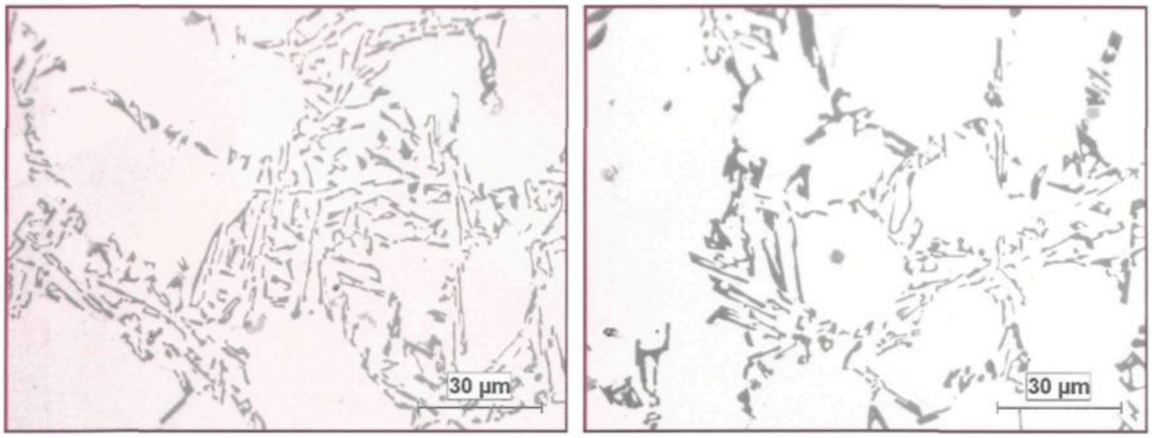
In Figures 4.2(a) and 4.2(c), while the eutectic Si regions are well modified, a certain number of unmodified or partially modified Si particles are always observed situated close to the α-Al dendrites. This phenomenon is a result of the distribution of Si concentration within the α-Al dendrites. The areas close to the dendrites contain higher Si concentrations, requiring more strontium to become fully modified. However, due to the high cooling rate produced by the end-chill mold, there is less time for the strontium to be distributed to these areas and thus there is not enough strontium available to fully modify the eutectic Si particles, leaving them partially modified or unmodified.

Figure 4.3 shows that superheating of the melt has a remarkable refining effect on the eutectic Si in A356.2 alloy. This effect can be attributed to the dissolution of atom clusters present in the melt at the superheat temperature. According to Pople and Sidorov,[74] if the superheat temperature is high enough for the atom clusters to dissolve fully in the melt, the cooling rate should have no effect on the eutectic Si particle characteristics in the microstructure. However, by comparing Figures 4.3(a), (b) and (c), it can be seen that the size of the eutectic Si particles increases somewhat as the cooling rate decreases, so it can be concluded that the 900°C melt superheat temperature used in the present study is not high enough to achieve the same results. Therefore, in the present case, the microstructure of the eutectic Si particles is determined by both the superheat temperature and the cooling rate.[75]

Figures 4.4 and 4.5 compare the effects of melt thermal treatment (MTT) on the microstructures of castings obtained from unmodified and Sr-modified A356.2 alloy melts, respectively. Although the eutectic Si particles are refined in the MTT-processed casting of the unmodified alloy, they still retain their acicular morphology, see Figure 4.4. This observation was also reported by Wang *et al.*[39] Combination of Sr-modification and the MTT process results in very fine eutectic Si regions, where the acicular, larger-sized Si particles that were observed at the edges of the α-Al dendrites in Figure 4.2 (for the Sr-modified alloy) appear to have been minimized considerably in the SrMTT casting, Figure 4.5.

In this regard, it ought to be mentioned that, in the MTT casting obtained from the non-modified A356.2 alloy, the refining (or modifying) effect was not homogeneous over the sample surface. As Figure 4.6 shows, the eutectic Si particles in (a) are comparatively well refined, while those in (b) are a mix of refined and unrefined Si particles. Both micrographs were taken from the MTT casting-level 1 sample, at a magnification of 500 X.

This irregularity in modification may be caused by the inhomogeneous transfer of thermal energy when the LTM and HTM melts are mixed; on account of this, atom clusters



(a) (b)

Figure 4.6 Optical micrographs corresponding to two fields of observation in the MTT casting-level 1 sample, showing (a) well-refined, and (b) inhomogeneously refined eutectic Si regions.

that are not broken into smaller nuclei will eventually result in the formation of larger Si particles upon solidification.

As mentioned previously, there appears to be very little literature that reports on the MTT process in the context of the modification of Al-Si alloys. To the best of our knowledge, the studies of Wang and coworkers[39,41,42] are probably the only references to be found. The present study extended the work of Wang *et al.*[39,41,42] to investigate the combined effect of Sr addition and the MTT process on the modification effect in A356.2 alloy by modifying the alloy melt with 100 ppm Sr before subjecting it to the melt thermal treatment process.

As Figure 4.5 clearly shows, the combination of Sr+MTT process produces the best results as far as obtaining a well-modified eutectic is concerned. The uniformity of the eutectic Si particle size throughout the eutectic regions is remarkable. Compared to the 200 ppm Sr-modified case (SrM casting, Figure 4.2), hardly any large Si particles are observed at the periphery of the α-Al dendrites.

It is to be mentioned here that, for the SrMTT casting, only 100 ppm Sr was used, to determine if a lesser amount of Sr than that usually employed for obtaining a well-modified eutectic structure in Al-Si alloys would suffice to obtain the same level of modification after the MTT process was carried out on the Sr-modified alloy melt. As will be shown in Section 4.3, quantification of the eutectic Si particle characteristics (using image analysis) showed that the SrMTT casting samples provided the smallest Si particle sizes, followed by the SrM and then the SH (superheated melt) casting samples.

4.2.2 Comparison of Modification Methods in Relation to Cooling Rate

The level of modification observed in the different A356.2 alloy castings corresponding to the non-modified (NM), Sr-modified (SrM), 900°C superheated melt (SH), MTT processed (MTT), and Sr-modified-MTT processed (SrMTT) castings are compared in Figure 4.7 for samples obtained from level 1 and level 3 of each casting, corresponding to DAS values of 37 μm and 78 μm, respectively.

As can be seen, well-modified fibrous Si particles are produced with Sr-modification, melt superheat and Sr-modification+MTT processes, the latter producing the finest particles, while the use of the MTT process alone is seen to only refine the Si particles but not change their acicular morphology. The effect of cooling rate is clearly apparent for the MTT-processed casting samples (Figures 4.7(g) and 4.7(h)), and also evident to some extent in the NM , SrM and SH casting samples. The extremely fine Si particles in the case of the SrMTT casting render it difficult to distinguish the effect of cooling rate when comparing Figures 4.7(i) and 4.7(j).

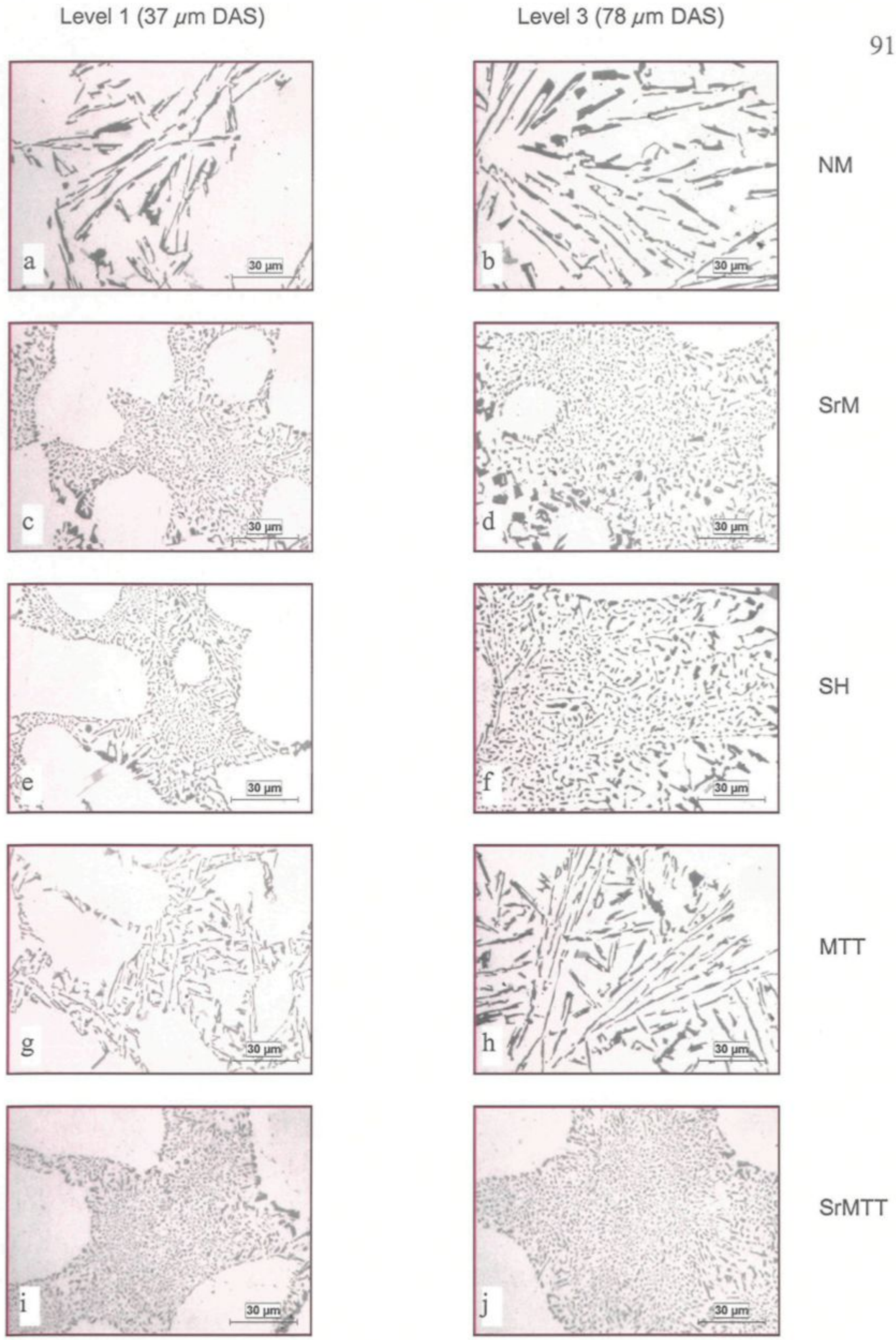


Figure 4.7 Comparison of modification in different A356.2 alloy samples obtained from: (a, b) NM, (c, d) SrM, (e, f) SH, (g, h) MTT, and (i, j) SrMTT castings in the as-cast condition, and corresponding to levels 1 and 3 in each case.

4.3 QUANTITATIVE ASPECTS OF THE EUTECTIC Si PARTICLE CHARACTERISTICS IN THE AS-CAST CONDITION

A quantitative evaluation of the eutectic Si particle characteristics was carried out using image analysis. As described in the experimental procedures in Chapter 3, measurements of the silicon particle area, length, roundness and aspect ratio were taken over 40 fields, in covering the sample surface area in a regular, systematic manner. From these measurements, the average value and standard deviation (SD) were obtained in each case. The results corresponding to the different casting types and levels are presented and discussed in this section.

4.3.1 Effect of Cooling Rate and Modification Method

The effect of cooling rate on the Si particle characteristics in Al-Si alloys has been investigated by many researchers.[76, 77, 78, 79] In the present study, the A356.2 alloy melts subjected to different modification methods were cast into end-chilled molds that provided a range of cooling rates in the same casting, along the height of the casting block. Three cooling rates were selected for study, at heights or levels of 10, 50 and 100 mm above the chill end and corresponding to DAS values of 37, 62, 78 μm, respectively. As the A356.2 alloy melts were modified before being cast, in examining the effect of cooling rate, the effects of the modification method used in each case would also be incorporated automatically.

Table 4.2 summarizes the results of the eutectic Si particle characteristics obtained for different samples in the as-cast condition. It can be seen that the cooling rate has a moderate to significant influence on the Si particle size in that the particle size increases as the cooling rate is decreased. The moderate effect is observed in the case of the non-modified alloy casting, where a gradual increase in the average Si particle area and length values are observed on going from level 1 to level 3. In comparison, the other four (modified) castings show a significant influence of the cooling rate, although this may not be that evident in the case of the SrMTT casting samples compared to the MTT casting samples, on account of the very fine particle sizes obtained in the former. Similar results have been reported by Mancheva *et al.*[77] who observed that the average Si particle area in AlSi7Mg castings improved from 0.9 μm^2 to 0.4 μm^2 when the cooling rate was increased from 14.8 to 72.4 K/s.

While the cooling rate affects the Si particle size, Table 4.2 shows that the shape of the Si particles is not affected by the change in cooling rate. Both the average roundness and average aspect ratio values (and their standard deviations) remain more or less the same from one level to the next. This is to be expected, since these parameters relate to the morphology rather than the size of the Si particles, with roundness values close to 100 and an aspect ratio of 1.0 representing completely spherical particles. As can be seen, the acicular particles of the non-modified alloy display low roundness values (less than 50%) and high aspect ratios (2.6 to 3.3), whereas the SrM, SH and SrMTT castings have much higher roundness values (75–77%) and comparatively lower aspect ratios (~1.8). The standard deviations obtained for these two parameters are also approximately similar for the SrM, SH and SrMTT castings (~20 and ~0.7, respectively), indicating that these parameters are influenced by the modification process rather than the cooling rate.

In contrast to the modified castings discussed above, the MTT casting samples exhibit roundness and aspect ratio values that are comparable to, but somewhat lower than, those obtained for the non-modified alloys, indicating that the Si particles, although refined, still retain their acicular morphology. Also, the standard deviations observed for these two parameters for the MTT and NM casting samples are higher (~28 and ~1.35 to 1.7, respectively), compared to those noted for the SrM, SH and SrMTT modified castings.

Similar results corresponding to the NM and SrM castings in the present work were obtained by Paray and Gruzleski.,[5] in their studies on non-modified and Sr-modified A356 alloys. Their experimental results showed that for A356 alloy castings cast in a permanent mold, the average Si particle area was refined from 3.81 μm^2 in the non-modified alloy casting to 0.24 μm^2 in the 200 ppm Sr-modified alloy casting, and the average aspect ratio improved from 2.17 to 1.74, correspondingly.

With respect to the average and standard deviation values listed in Table 4.2, it must be noted that, due to the wide range of Si particle sizes observed – as can be seen from all the microstructures presented in this chapter, it is expected that the standard deviation will be of the order of or higher than the average value. The particle size distribution plotted by the image analyzer system in the execution of "Feature" measurements (of individual Si particles) provides a range of particle sizes, and the corresponding particle counts. It is found that the maximum particle count generally corresponds to the particle size range which includes or lies close to the average value calculated by the system. In other words, the average values *do* reflect the overall modification effect obtained from casting type to casting type.

Table 4.2 Eutectic Si particle characteristics of different casting samples obtained in the as-cast condition.

Casting Type	Area (μm²)						Length (μm)					
	Level 1 (DAS 37 μm)		Level 2 (DAS 62 μm)		Level 3 (DAS 78 μm)		Level 1 (DAS 37 μm)		Level 2 (DAS 62 μm)		Level 3 (DAS 78 μm)	
	Ave.	S.D.	Ave.	S.D.	Ave.	S.D.	Ave.	S.D.	Ave.	S.D.	Ave.	S.D.
NM	25.33	28.46	26.32	29.11	27.32	30.09	11.96	11.39	13.57	12.85	14.62	13.93
SrM	1.16	1.94	2.82	4.09	3.08	4.26	1.57	1.36	2.36	1.91	2.48	2.03
SH	1.62	3.37	2.8	4.45	4.4	6.2	1.94	2.04	2.62	2.54	3.29	2.96
MTT	2.94	4.56	5.04	8.48	8.98	12.95	3.2	3.21	4.42	5.11	6.11	6.22
SrMTT	0.94	1.85	1.38	2.44	1.53	2.7	1.4	1.28	1.74	1.6	1.87	1.72
Casting Type	Roundness (%)						Aspect Ratio					
	Level 1 (DAS 37 μm)		Level 2 (DAS 62 μm)		Level 3 (DAS 78 μm)		Level 1 (DAS 37 μm)		Level 2 (DAS 62 μm)		Level 3 (DAS 78 μm)	
	Ave.	S.D.	Ave.	S.D.	Ave.	S.D.	Ave.	S.D.	Ave.	S.D.	Ave.	S.D.
NM	45.24	28.42	42.82	28.48	40.8	27.24	2.64	1.37	3.13	1.74	3.3	1.83
SrM	75.24	20.64	77.23	21.45	77.23	21.23	1.81	0.66	1.53	0.37	1.65	0.55
SH	74.76	22.84	74.78	23.2	73.43	23.77	1.85	0.78	1.79	0.75	1.79	0.72
MTT	56.96	27.34	55.26	29.51	51.16	29.97	2.51	1.33	2.91	1.62	2.76	1.52
SrMTT	78.87	20.35	77.32	20.87	75.81	21.48	1.81	0.67	1.83	0.69	1.87	0.72

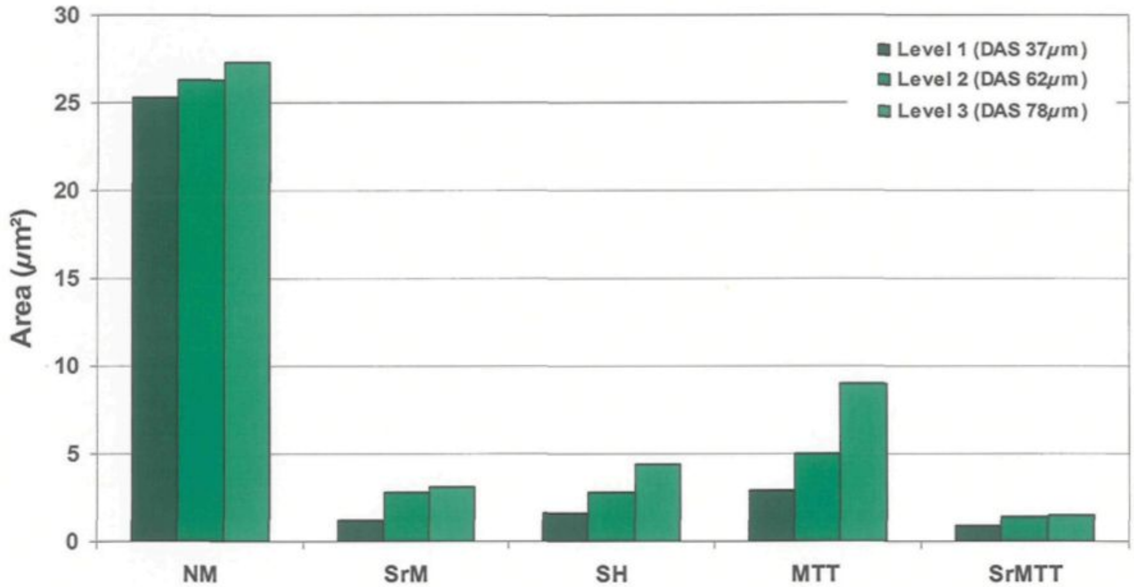
Note: Levels 1, 2 and 3 correspond to heights of 10 mm, 50 mm and 100 mm above the chill end of the casting.

The results of Table 4.2 have been presented in Figures 4.8 through 4.11 in the form of histograms, which facilitates in distinguishing the effect of cooling rate (or dendrite arm spacing), and that of the modification process on the Si particle characteristics.

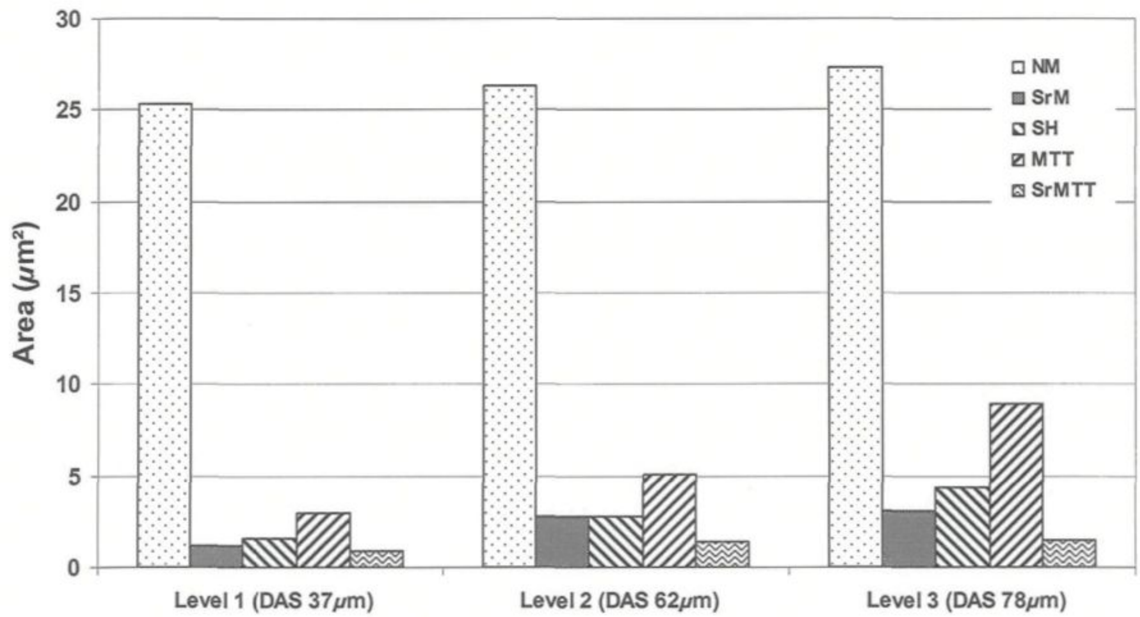
In general, the Si particle area and length of the MTT casting appear to be the most sensitive to the cooling rate, followed by the NM (non-modified) and SH (melt superheat-treated) castings (Figures 4.8 and 4.9). In the SrM casting, an improvement due to cooling rate is evidenced mainly at the cooling rate corresponding to the lowest DAS (37 μm). The particle size remains constant at DAS levels of 62 μm and above.

Compared to all these casting types, the SrMTT casting shows the best results in that not only the Si particle sizes are the smallest among all castings, but these values remain approximately constant over the range of cooling rates studied. This has a great significance from the application point of view. Often, cast parts contain sections of varying thickness, and in such cases, the use of an SrMTT processed Al-Si alloy melt in casting would ensure a relatively uniform eutectic Si particle size throughout the casting and, hence, guarantee its overall properties.

Again, with respect to the roundness parameter, the best results are obtained with the SrMTT casting which displays consistently high roundness values, with a very small influence due to cooling rate. The aspect ratios, however, are similar to those obtained for the SH (superheated) and SrM (Sr-modified) castings. The moderate amount of refinement in the Si particle morphology in the MTT casting compared to the non-modified (NM) casting can also be observed from Figures 4.10 and 4.11.

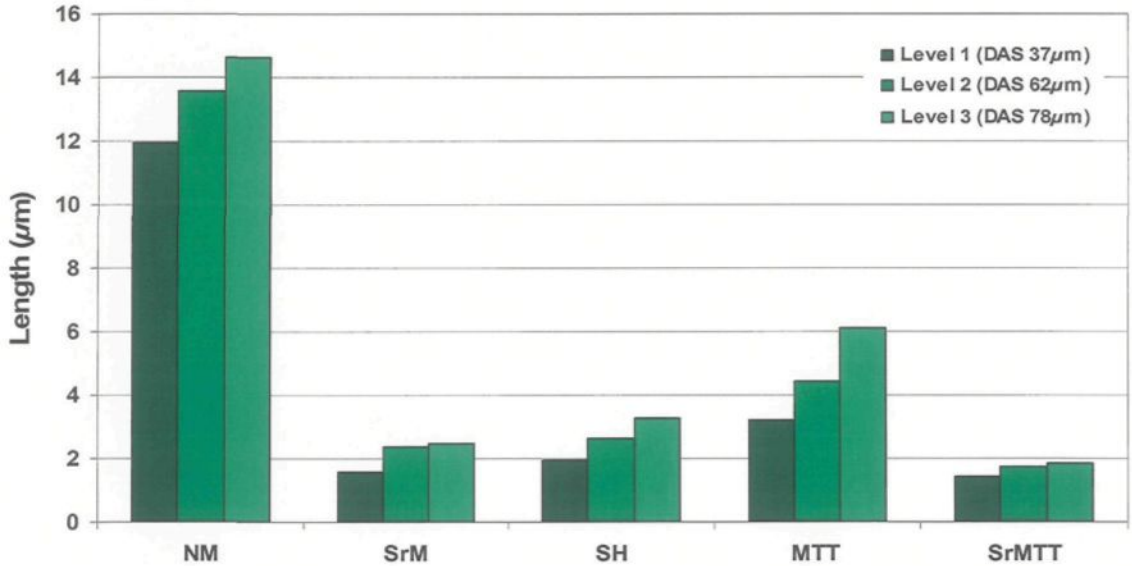


(a)

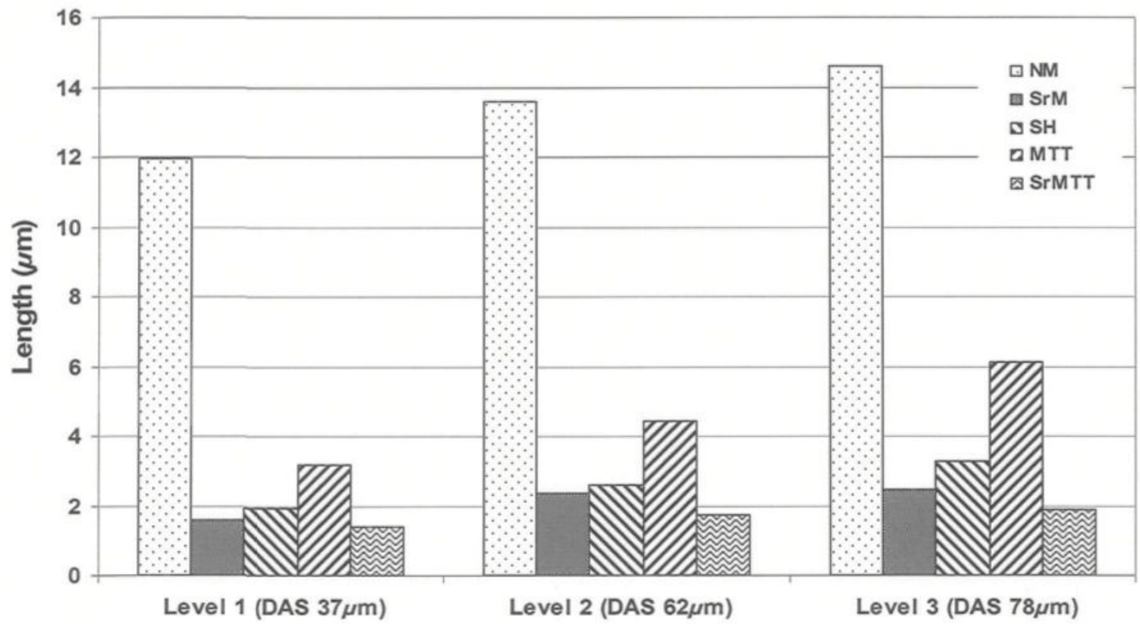


(b)

Figure 4.8 Average Si particle area obtained for as-cast samples taken from different A356.2 alloy castings/levels, showing the effect of (a) cooling rate (casting level/DAS), and (b) modification process (casting type).

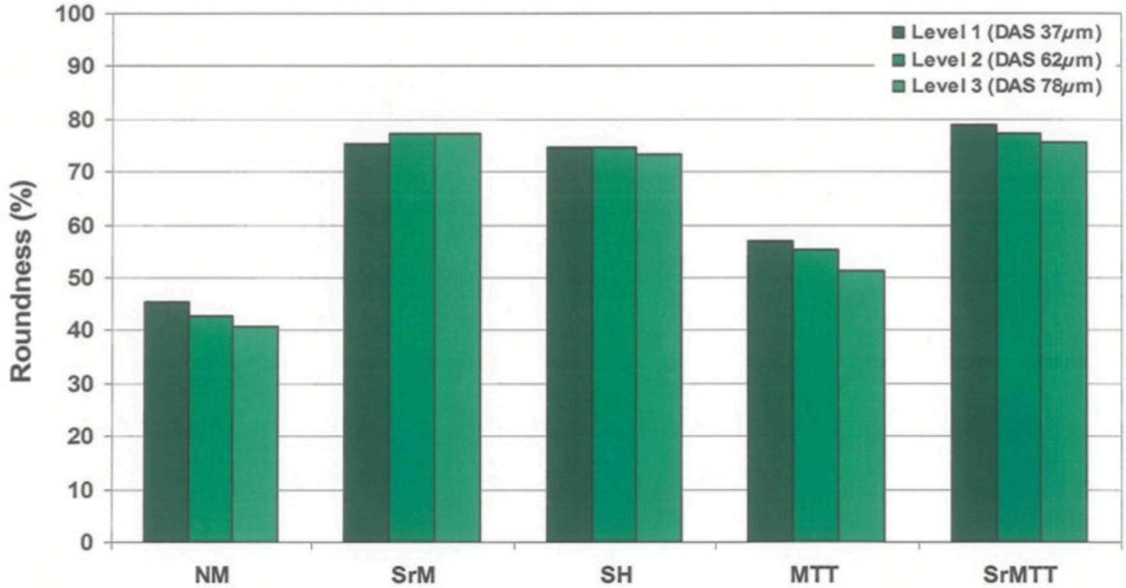


(a)

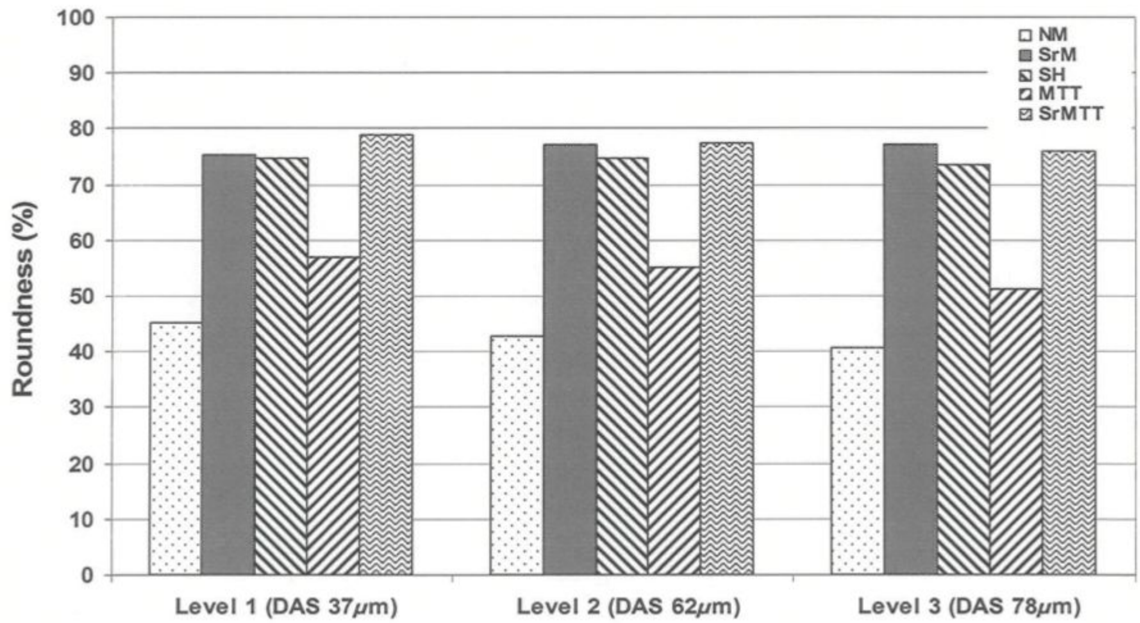


(b)

Figure 4.9 Average Si particle length obtained for as-cast samples taken from different A356.2 alloy castings/levels, showing the effect of (a) cooling rate (casting level/DAS), and (b) modification process (casting type).

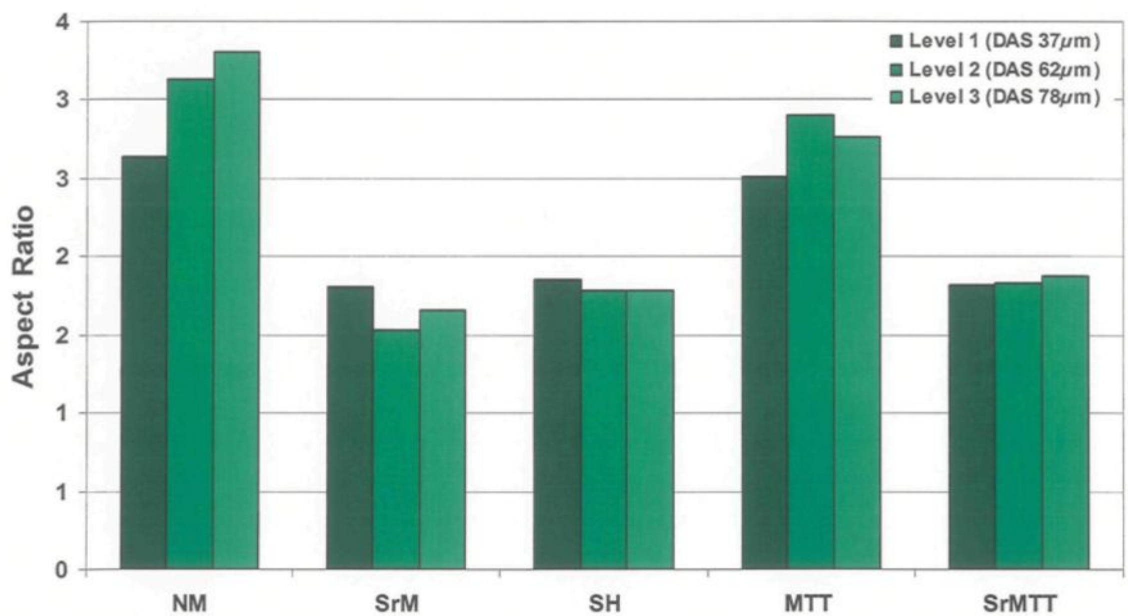


(a)

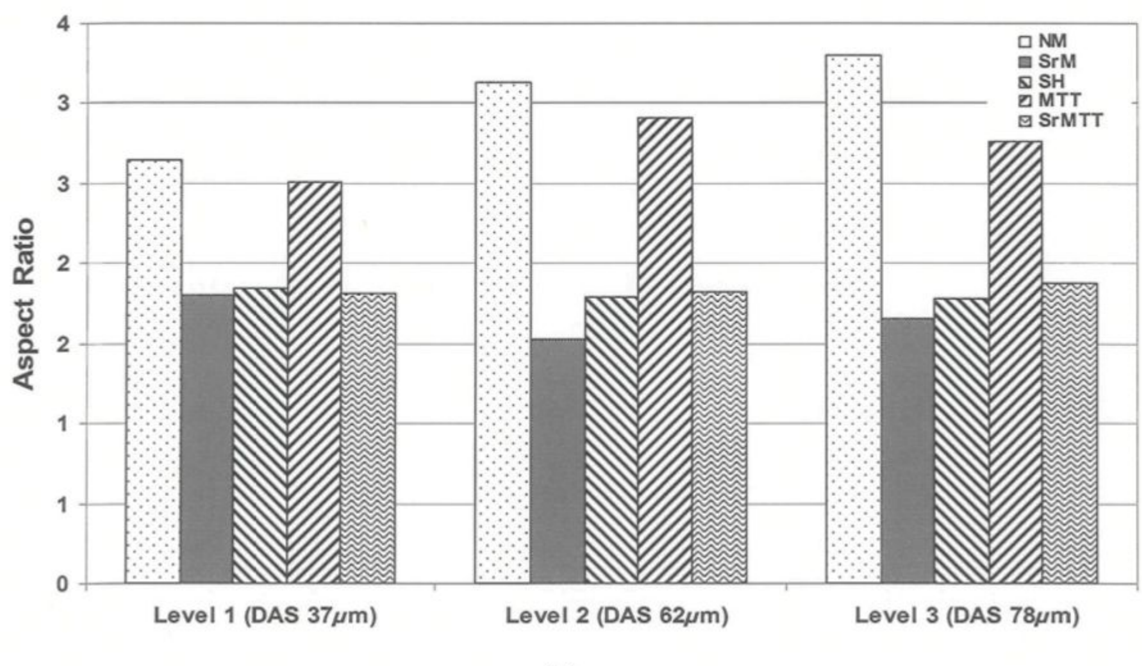


(b)

Figure 4.10 Average Si particle roundness obtained for as-cast samples taken from different A356.2 alloy castings/levels, showing the effect of (a) cooling rate (casting level/DAS), and (b) modification process (casting type).



(a)



(b)

Figure 4.11 Average Si particle aspect ratio obtained for as-cast samples taken from different A356.2 alloy castings/levels, showing the effect of (a) cooling rate (casting level/DAS), and (b) modification process (casting type).

4.3.2 Comparison of Modification Methods

The various modification methods applied to A356.2 alloy in the present work were used to determine which would produce a well-modified, fibrous eutectic structure, *viz.* those that reduced the Si particle size and aspect ratio to a minimum and increased the roundness to a maximum. Theoretically, spherical particles would have a roundness value of ~100% and an aspect ratio of 1.

To compare the efficiencies of the different modification methods, the Si particle characteristics obtained for the SrM, SH, MTT and SrMTT casting samples were compared with those obtained for the non-modified NM casting in terms of the percentage *decrease* in the area and length parameters, the percentage *increase* in the roundness, and the percentage *decrease* in the aspect ratio, as shown in Tables 4.3 and 4.4. The values in the parentheses in the row for the NM casting in both tables represent the actual values obtained for each parameter at the corresponding level. Those listed in the other rows provide the percentage changes in the four parameters (area, length, roundness and aspect ratio) observed in the other casting samples calculated in terms of the NM values in parentheses. The actual values are given in Table 4.2.

In their study of the effect of Sr modification in A356.2 alloy, Paray and Gruzleski[5] found that strontium affects not only the size and morphology of the eutectic Si particles, but also the particle size and morphology distribution. Their conclusions, which correspond to the NM and SrM castings in the present work, can also be extended to the SH, MTT and SrMTT castings, as well, where the standard deviation obtained for each parameter measured can be used to estimate the structural uniformity of the eutectic Si particles in

A356.2 alloy. More precisely, the narrower the standard deviation, the more homogeneous the Si particle size and morphology distribution, in other words, the higher the degree of modification achieved.

Table 4.3 Change in Si particle size achieved for different casting types in comparison to the non-modified casting

Casting Type	Percentage Change in Si Particle Size					
	% Decrease in Area (µm²)			% Decrease in Length (µm)		
	Level 1 (10mm)	Level 2 (50mm)	Level 3 (100mm)	Level 1 (10mm)	Level 2 (50mm)	Level 3 (100mm)
NM	(25.33)	(26.32)	(27.32)	(11.96)	(13.57)	(14.62)
SrM	95.4%	89.3%	88.7%	86.9%	82.6%	83.1%
SH	93.6%	89.4%	83.9%	83.4%	80.7%	77.5%
MTT	88.4%	80.9%	67.1%	73.3%	67.5%	58.2%
SrMTT	96.3%	94.7%	94.4%	88.1%	87.2%	87.2%

Note: levels 1, 2 and 3 correspond to DASs of 37, 62 and 78 μm, respectively

Table 4.4 Change in Si particle shape achieved for different casting types in comparison to the non-modified casting

Cast Type	Percentage Change in Si Particle Shape					
	% Increase in Roundness			% Decrease in Aspect Ratio		
	Level 1 (10mm)	Level 2 (50mm)	Level 3 (100mm)	Level 1 (10mm)	Level 2 (50mm)	Level 3 (100mm)
NM	(45.24)	(42.82)	(40.80)	(2.64)	(3.13)	(3.30)
SrM	66.31%	80.36%	89.29%	31.44%	51.12%	50.00%
SH	65.25%	74.64%	79.98%	29.92%	42.81%	45.76%
MTT	25.91%	29.05%	25.39%	4.92%	7.03%	16.36%
SrMTT	74.34%	80.57%	85.81%	31.44%	41.53%	43.33%

Note: levels 1, 2 and 3 correspond to DASs of 37, 62 and 78 μm, respectively

CHAPTER 5

EFFECT OF SOLUTION HEAT TREATMENT ON EUTECTIC Si PARTICLE CHARACTERISTICS

CHAPTER 5

EFFECT OF SOLUTION HEAT TREATMENT ON EUTECTIC Si PARTICLE CHARACTERISTICS

5.1 INTRODUCTION

According to the results of investigations conducted by many researchers,[7,80,81,82,83] the solution heat treatment of Al-Si-Mg alloys is carried out primarily for two reasons: the first is to dissolve Mg and Si to the maximum extent in the aluminum matrix, and the second is to alter the morphology of the eutectic Si particles from their acicular form in the as-cast condition to a finer and more spheroidized form. Both effects can contribute significantly in improving the mechanical properties of the alloy.

The change in the eutectic Si particle morphology takes place in three stages: fragmentation, spheroidization, and coarsening. The solution treatment temperature and time, and the original eutectic Si particle morphology in the as-cast condition are the main factors that will control the effect of the solution heat treatment. Increasing the solution temperature can expedite the process of fragmentation, spheroidization and coarsening, keeping in mind that the temperature cannot be high enough to cause any microstructural local melting of the alloy. For a given solution temperature, a sufficient solution time must be applied to the alloy to reach a degree of spheroidization that is satisfactory. The original as-cast eutectic Si morphology also plays a critical role. For instance, at a given solution temperature, finer and rounder as-cast Si particles in a Sr-modified alloy can become highly spheroidized compared to those in an unmodified alloy.

In the as-cast condition, Mg_2Si is heterogeneously distributed within the α-Al phase. With solution heat treatment, the Mg_2Si can be dissolved into the aluminum matrix, the solubility being dependent on the solution temperature. Quenching thereafter can lock the Si particles within the aluminum matrix to form a supersaturated solid solution. The solution temperature is the key factor in this regard, and must be high enough so that the Mg_2Si can fully dissolve in solution.

In the present work, all the samples were solution heat treated at 540°C, for solution times of 2 h to 80 h in increasing intervals of 2 h, for the NM and SrM casting samples, and increasing intervals of 8 h for the SH, MTT and SrMTT casting samples, respectively. The solution treated samples were then quenched in warm water (60°C). At 540°C, the solubility of Mg is 0.6%; since the Mg content in A356.2 alloy is around 0.4%, Mg_2Si can be fully dissolved if treated at this temperature for a sufficient time. On the other hand, a solution time span of 2-80 h can provide a wide range of conditions of the spheroidization of the eutectic Si as well as various degrees of Mg_2Si dissolution in the matrix.

The effect of solution heat treatment on the eutectic Si particle characteristics was investigated by measuring the average particle area, length, roundness, and aspect ratio of the corresponding solution heat-treated samples. In general, as the solution treatment time increases, the average area, length, and roundness parameters should increase while the average aspect ratio is expected to decrease, an aspect ratio of 1 corresponding to a perfectly spherical particle. In addition, the effect of solution treatment on the eutectic Si particle characteristics in the A356.2 alloy castings already modified prior to the solution treatment (*i.e.*, SrM, SH, MTT and SrMTT castings) was also investigated.

This chapter presents the results for the solution heat-treated samples corresponding to the various A356.2 alloy casting types/levels and solution treatment times. As was done in Chapter 4, both qualitative aspects (in the form of optical micrographs) and a quantitative evaluation of the image analysis data obtained are presented and discussed in the following sections.

5.2 QUALITATIVE ASPECTS OF THE EFFECT OF SOLUTION HEAT TREATMENT ON THE EUTECTIC Si PARTICLE CHARACTERISTICS

The three stages of eutectic Si development during solution heat treatment, *viz.*, fragmentation, spheroidization and coarsening, resulting in the samples obtained from the various A356.2 alloy casting types are presented in Figures 5.1 through 5.5 for the NM, SrM, SH, MTT and SrMTT castings, respectively. The four optical micrographs presented in each figure were taken from the level 1 samples of the corresponding casting, as the microstructures at this level (corresponding to the highest cooling rate, 37 μm DAS) presented the best results in the as-cast condition (see Table 4.2 in Chapter 4). The as-cast condition in each case is presented in the first micrograph (a) of each figure. The other three micrographs ((b), (c) and (d)) correspond to solution treatment times of 8, 40 and

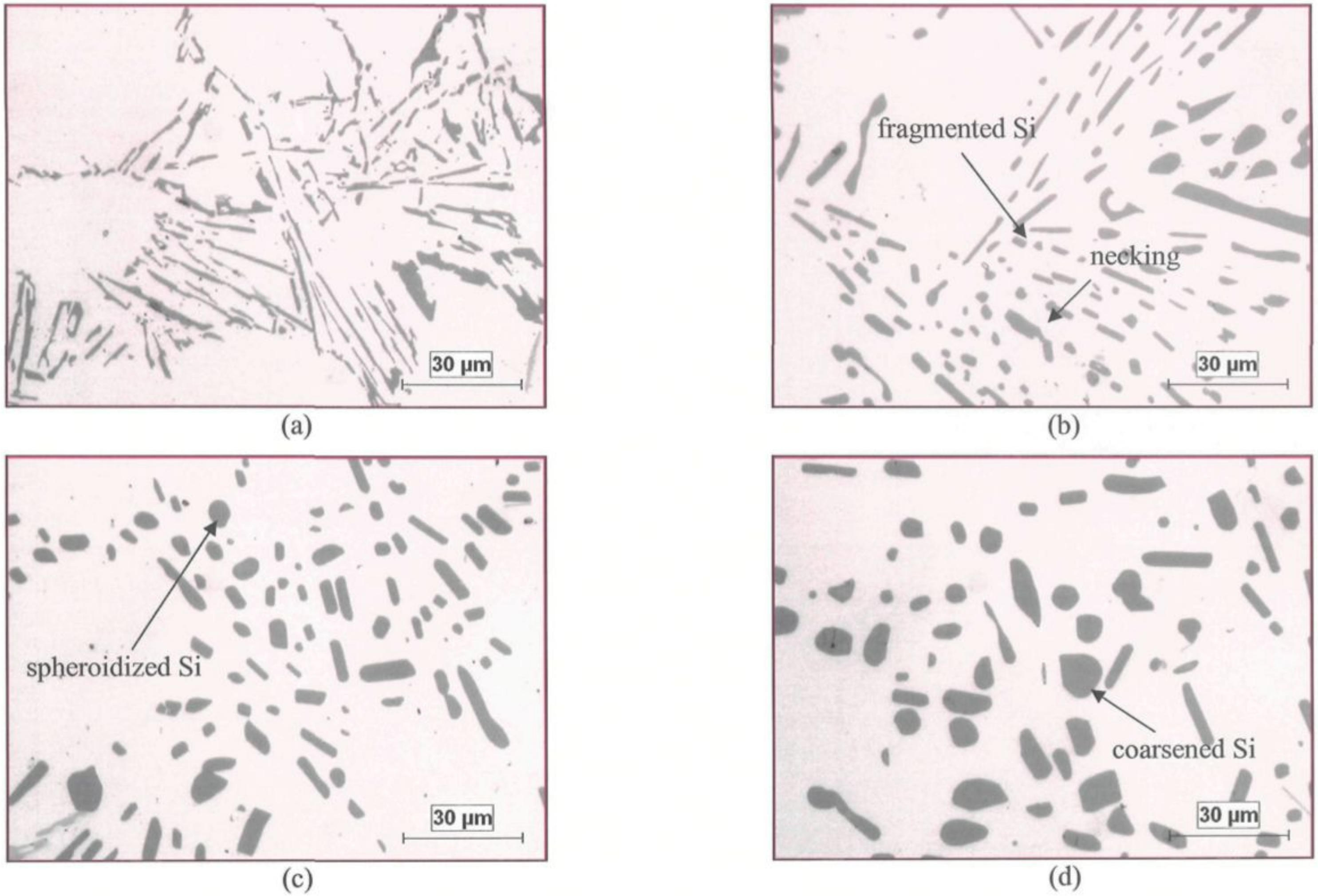


Figure 5.1 **Effect of solution heat treatment on the eutectic Si particle characteristics observed in the non-modified A356.2 alloy NM casting-level 1 samples in (a) the as-cast condition; (b), (c), (d) after solution heat treatment at 540°C for (b) 8 h, (c) 40 h, and (d) 80 h.**

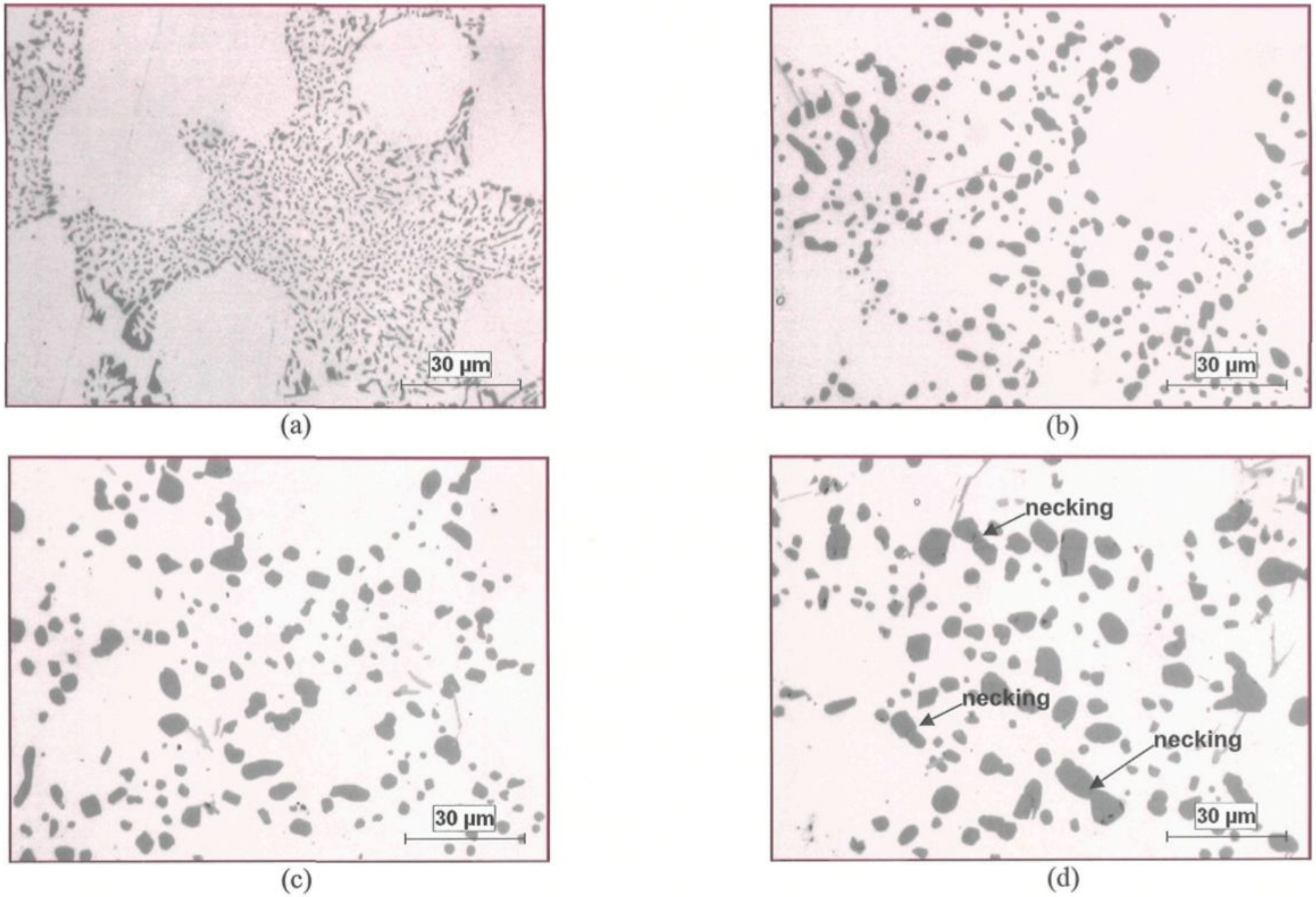


Figure 5.2 **Effect of solution heat treatment on the eutectic Si particle characteristics observed in the Sr-modified A356.2 alloy SrM casting-level 1 samples in (a) the as-cast condition; (b), (c), (d) after solution heat treatment at 540°C for (b) 8 h, (c) 40 h, and (d) 80 h.**

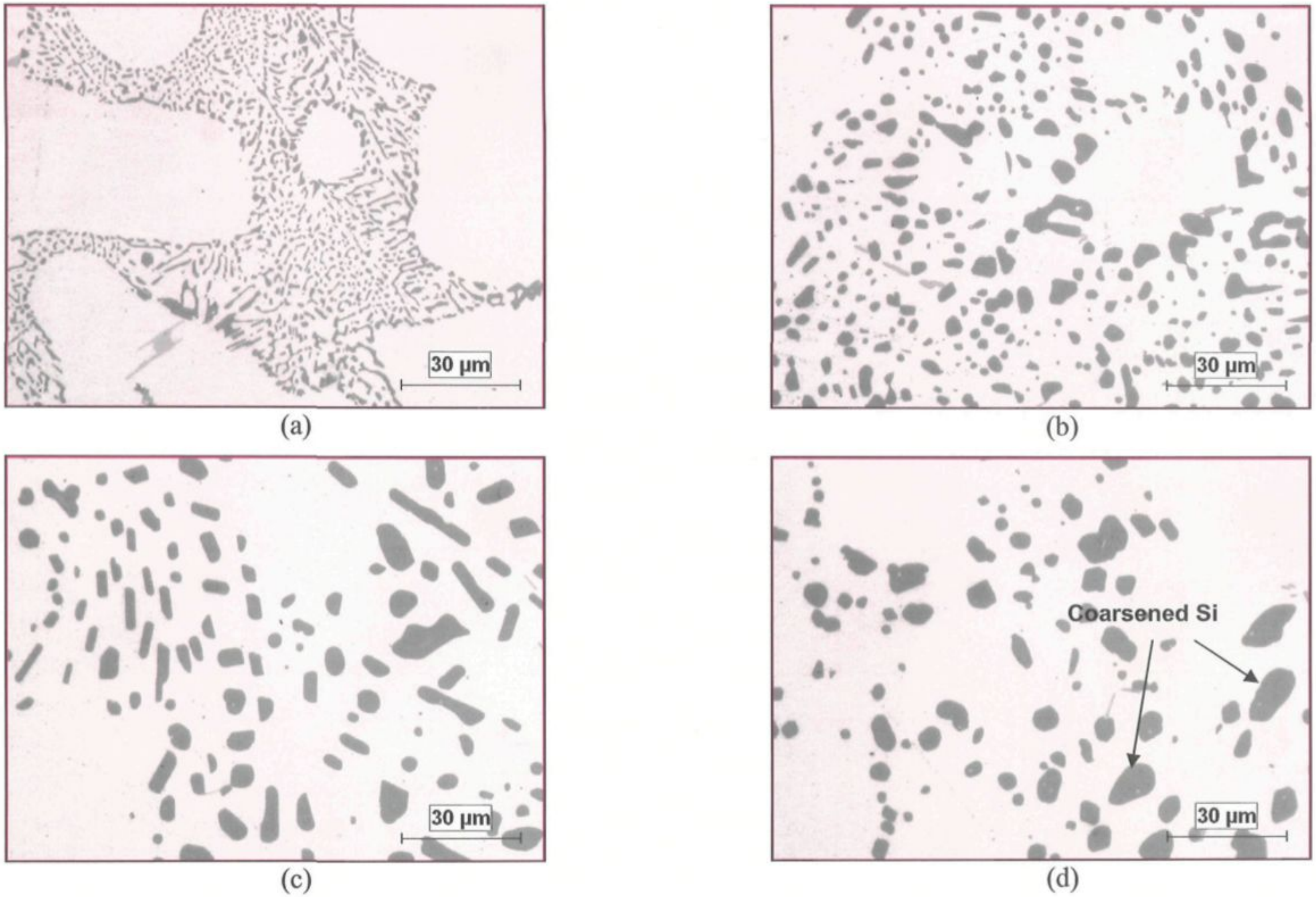


Figure 5.3 **Effect of solution heat treatment on the eutectic Si particle characteristics observed in the melt superheat-treated A356.2 alloy SH casting-level 1 samples in (a) the as-cast condition; (b), (c), (d) after solution heat treatment at 540°C for (b) 8 h, (c) 40 h, and (d) 80 h.**

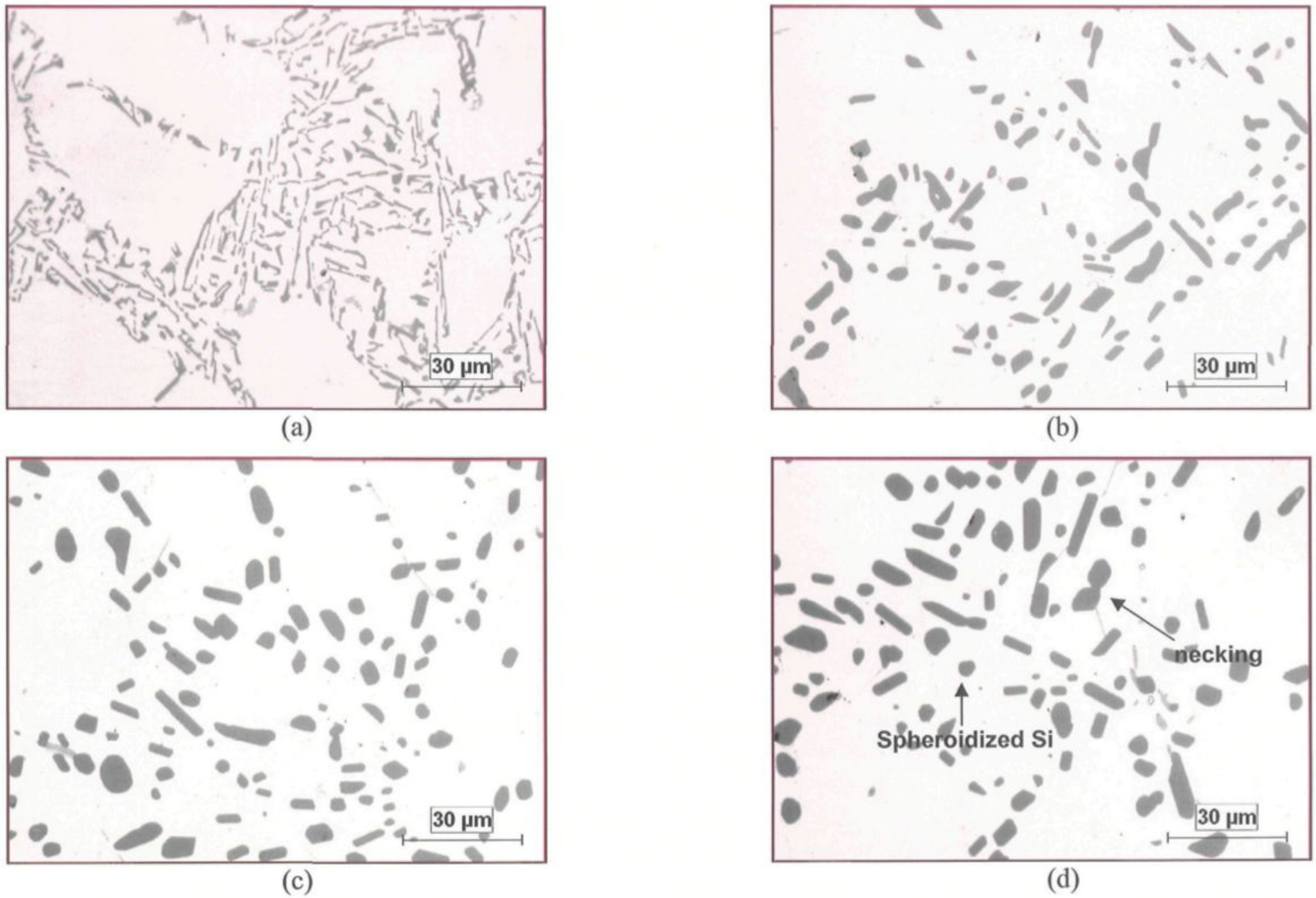


Figure 5.4 **Effect of solution heat treatment on the eutectic Si particle characteristics observed in the MTT processed A356.2 alloy MTT casting-level 1 samples in (a) the as-cast condition; (b), (c), (d) after solution heat treatment at 540°C for (b) 8 h, (c) 40 h, and (d) 80 h.**

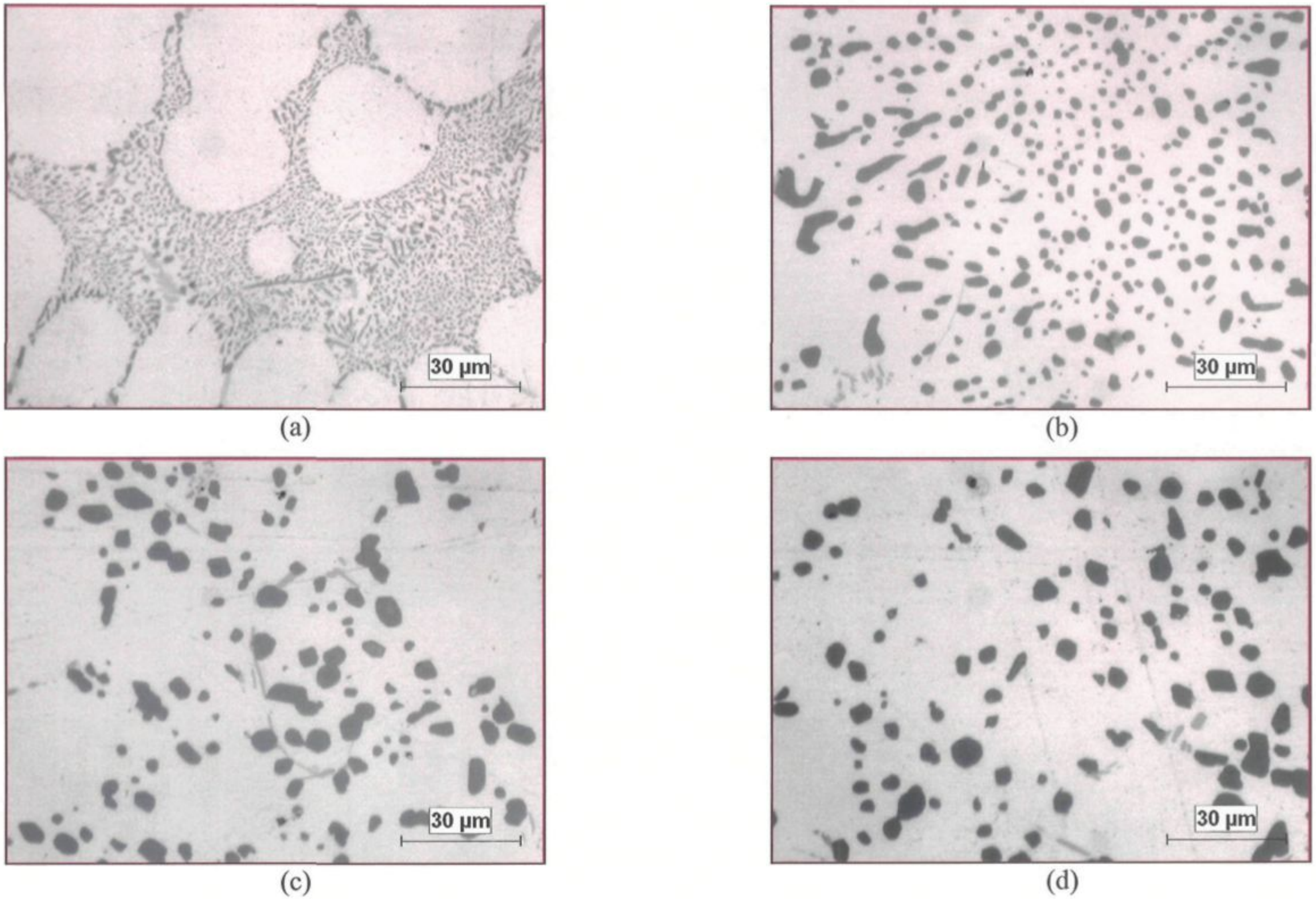


Figure 5.5 **Effect of solution heat treatment on the eutectic Si particle characteristics observed in the Sr-modified MTT processed A356.2 alloy SrMTT casting-level 1 samples in (a) the as-cast condition; (b), (c), (d) after solution heat treatment at 540˚C for (b) 8 h, (c) 40 h, and (d) 80 h.**

80 h, that were selected as best representing the progress of the various stages of solution treatment with time. These solution times were also used for solution heat treatment of the tensile bars used for tensile testing.

The effect of solution treatment on the eutectic Si particles is most evident in the case of the non-modified A356.2 alloy casting. As solution treatment at 540°C is commenced on the as-cast sample, Figure 5.1(a), with increasing solution time, the acicular Si particles are seen to undergo "necking". Following this, such Si particles undergo fragmentation, as can be seen in Figure 5.1(b) for a sample which has been solution heat treated for 8 h. As the solution time is increased further, the Si particles begin to spheroidize and then to coarsen, as shown in Figure 5.1(c) and Figure 5.1(d), for solution times of 40 h and 80 h, respectively.

Considering the various stages of the solution treatment as a whole, it can be seen that the three stages of fragmentation, spheroidization and coarsening can occur together, as well, in the same microstructure, depending upon the variety of Si particle sizes present in the as-cast structure. Thus, while some longer particles may undergo fragmentation, other smaller Si particles may become spheroidized, and those already spheroidized could start coarsening, at any particular time during the solution treatment process.

When the alloys are modified before being solution heat treated, the spheroidization process is accelerated, as shown in Figure 5.2 for the Sr-modified A356.2 alloy SrM casting. Compare to the non-modified alloy, a high level of spheroidization is easily achieved after only 8 h of solution treatment at 540°C, as shown in Figure 5.2(b). Further solution treatment leads to the coarsening of the Si particles, as Figures 5.2(c) and 5.2(d) demonstrate. Nevertheless, the overall size of the 'coarsened' Si particles is still much smaller than that of the coarse particles in the non-modified alloy, Figure 5.1(d).

With the melt superheat-treated SH alloy casting, the results are similar to those obtained for the Sr-modified casting. The slightly less degree to which the SH as-cast sample is modified (Figure 5.3(a)), is reflected in the subsequent micrographs of Figures 5.3(b), (c) and (d), when compared to those of Figure 5.2 for the same solution times. In general, the Si particle sizes are somewhat larger in the SH casting samples.

In the case of the MTT processed casting, the particularities of the as-cast structure (Figure 5.4(a)), which shows a moderate amount of refinement in comparison to the non-modified alloy casting, lead to a corresponding improvement in the extent of spheroidization achieved after 8 h solution treatment, Figure 5.4(b). Although Figures 5.4(c) and 5.4(d) appear similar to those of Figures 5.1(c) and 5.1(d), due to the initial refinement obtained in the as-cast structure of the MTT sample, the particle sizes in Figures 5.4(c) and 5.4(d) are relatively smaller, overall.

Finally, the extremely well-modified eutectic structure in the as-cast SrMTT casting sample (Figure 5.5(a)) leads to the attainment of a high degree of spheroidization after 8 h solution treatment, comparable to that observed in the SrM casting sample. However, the density of fine Si particles (i.e. number of Si particles per unit area) is greater and much more homogeneously distributed than in the latter (*cf.* Figure 5.5(b) and Figure 5.2(b)). Perhaps for this reason, the coarsening effects after 40 h solution time are more pronounced in the SrMTT casting sample (Figure 5.5(c)) than in the SrM casting sample (Figure 5.2(c)). Figure 5.5(d) shows that, after 80 h of solution treatment, the remaining larger-sized and non-spheroidized particles in the SrMTT casting (after 40 h solution treatment) undergo fragmentation and spheroidization. In comparison, the larger-sized Si particles in the Sr-modified casting still appear to be in the process of necking (and fragmentation) after the same amount of solution treatment time (80 h).

In summary, therefore, these observations emphasize the fact that the original eutectic Si structure contributes significantly to the efficiency of the solution heat treatment applied, in terms of the solution time required to achieve optimum spheroidization of the Si particles. Reduced solution treatment times would obviously add to the cost-effectiveness of the production process.

5.3 QUANTITATIVE ASPECTS OF THE EFFECT OF SOLUTION HEAT TREATMENT ON THE EUTECTIC Si PARTICLE CHARACTERISTICS

Quantification of the Si particle characteristics was carried out using image analysis. The particle size and morphology were characterized in terms of the average particle area, length, roundness and aspect ratio for the various A356.2 solution heat-treated casting samples (at 540°C for different solution times). The results are presented in this section in the form of x-y plots. The image analysis data is provided in Appendix 1.

5.3.1 Effect on Eutectic Si Particle Size

Depending upon the as-cast condition of the casting, and whether the A356.2 alloy melt used to prepare the casting was Sr-modified or not, the development of the changes in the eutectic Si particles brought about by the solution heat treatment applied would vary from casting type to casting type.

Figure 5.6 shows a schematic representation of the three stages of eutectic Si particle development, *viz.*, fragmentation, spheroidization and coarsening with the progress of solution treatment, in non-modified and Sr-modified Al-Si alloys.[84] As can be seen, in the non-modified alloy, fragmentation must first occur before spheroidization and then coarsening can take place, whereas in the modified alloy, the as-cast Si particles are already relatively smaller in size and hence spheroidization commences shortly after the solution treatment is underway. Obviously, with the progress of solution treatment time, the Si particles will start to coarsen, exhibiting coarser particles compared to the unmodified alloy after similar solution treatment times.

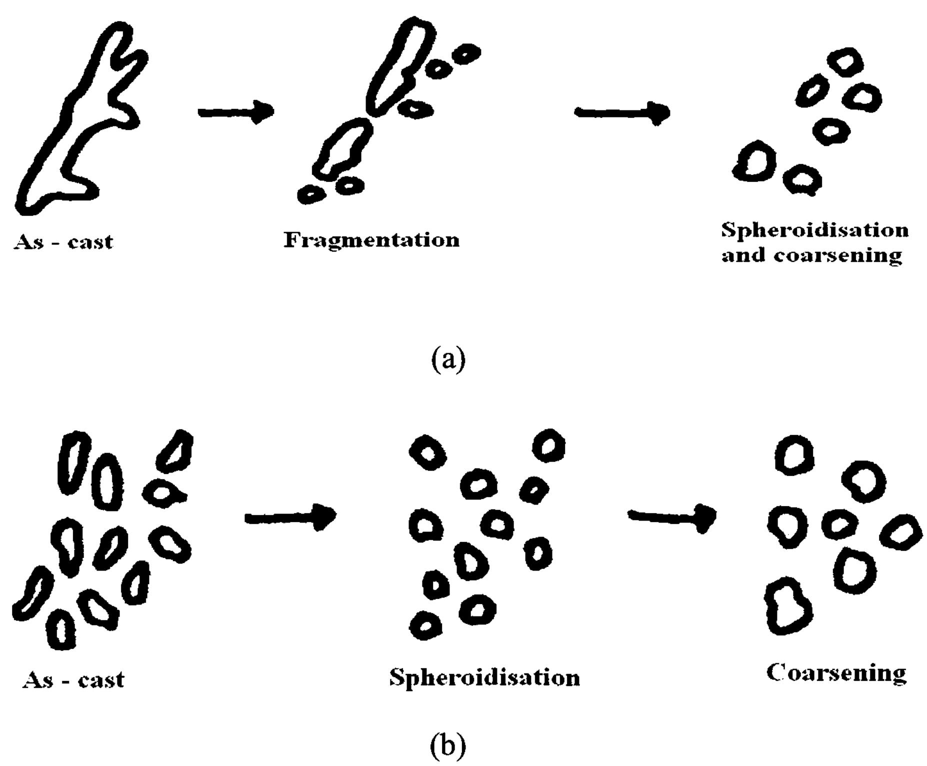


Figure 5.6 Schematic representation of the three stages of eutectic Si particle development during solution heat treatment in: (a) non-modified, and (b) Sr-modified A356.2 alloys.[84]

Figure 5.7 shows the plots of average Si particle area values obtained for the different casting types and levels over the range of solution treatment times studied from 0 h (as-cast condition) through 80 h. The three curves corresponding to the samples taken from the three levels of each casting are distinct from one another in the NM and MTT castings, whereas those for the SrM, SH and SrMTT castings lie together. The potential advantage of this observation in the latter cases is that the effect of Sr modification or superheat overrides that of cooling rate, which has significance in the context of maintaining a uniform eutectic structure in the thick and thin sections of a cast component.

In the non-modified casting, Figure 5.7(a), the as-cast particle size is in the order of 25 – 28 μm^2. During the first four hours of solution treatment (at 540°C), the particle sizes reduce, indicating the progress of fragmentation of the Si particles. The greatest amount of fragmentation is observed at level 1 (DAS 37 μm). As the solution time progresses, the particle sizes begin to increase somewhat, however, in a gradual manner, showing increasing and decreasing values from one solution period to the next (in intervals of 2 h). This range of solution times, from 8 to ~ 40 h, comprises both the spheroidization and the coarsening stages that occur together. After 40 h, the particles coarsen, until at 80 h, they attain particle sizes greater than their as-cast values, except for the level 1 sample which attains its original size, negating the effect of fragmentation brought about by the solution heat treatment.

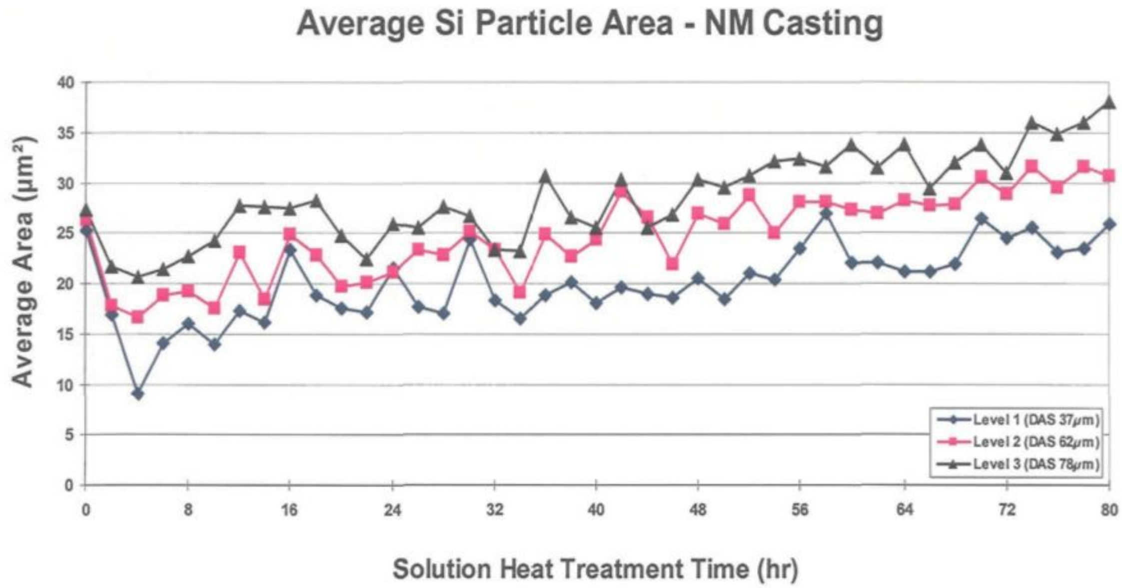
In the SrM casting, Figure 5.7(b), all three levels exhibit almost similar particle sizes over the entire range of solution treatment. In this case, the as-cast values are the lowest, about 3 μm^2 or less, and increase very gradually with increasing solution treatment time.

The spheroidization stage is expected to occur in the 24-60 h range, where the particle area remains more or less constant at ~ 10 μm^2. The Si particles begin to coarsen thereafter. However, even after coarsening, the particle sizes are still below 15 μm^2. Virtually the same results are obtained for the SH casting, Figure 5.7(c).

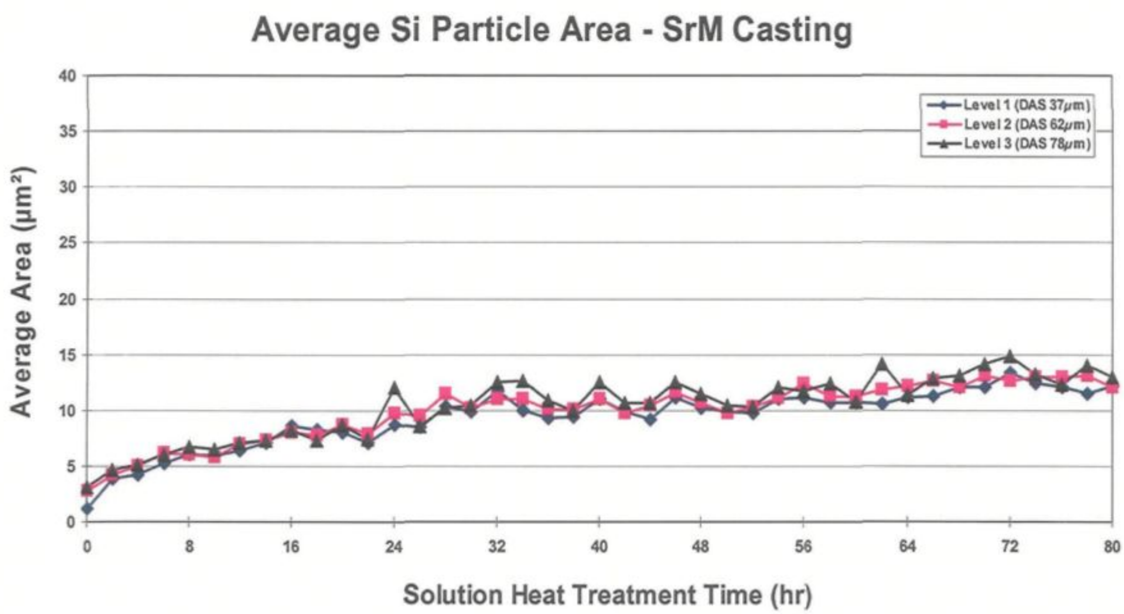
The increase in the particle size in the early stages of solution treatment (unlike the decrease observed for the NM casting) is explained by the fact that there are no large particles to undergo fragmentation, and so the spheroidization stage occurs directly. The same is true for the other modified castings, *i.e.*, the SH and SrMTT castings. In the case of the MTT casting, Figure 5.7(d), however, distinct particle sizes are observed for the three levels, and after about 56 h of solution treatment, the particles attain maximum coarsening and display the same particle size of ~ 20-22 μm at DASs of 62 μm or more.

In terms of refinement achieved with the MTT process, only at level 1 is the cooling rate high enough (DAS 37 μm) to achieve a particle size of ~15 μm after 56 h solution treatment, comparable to that achieved with the SH and SrMTT castings (Figures 5.7(c) and 5.7(e), respectively). As Figure 5.7 shows, with respect to solution heat treatment, the best result are obtained for the SrMTT casting, followed by the SrM and SH castings.

In their review of the fundamental aspect of heat treatment of cast Al-Si-Mg alloys, Apelian *et al.*[7] have analyzed the data from various studies reported in the literature. They report that modification has a great influence on spheroidization. In modified A356 alloy, a high degree of spheroidization is observed after only 12 h of solution treatment, whereas in the unmodified alloy, coarse acicular Si plates are still visible after the same amount of solution treatment. According to Zhu *et al.*,[53] during solution heat treatment, the Si particles

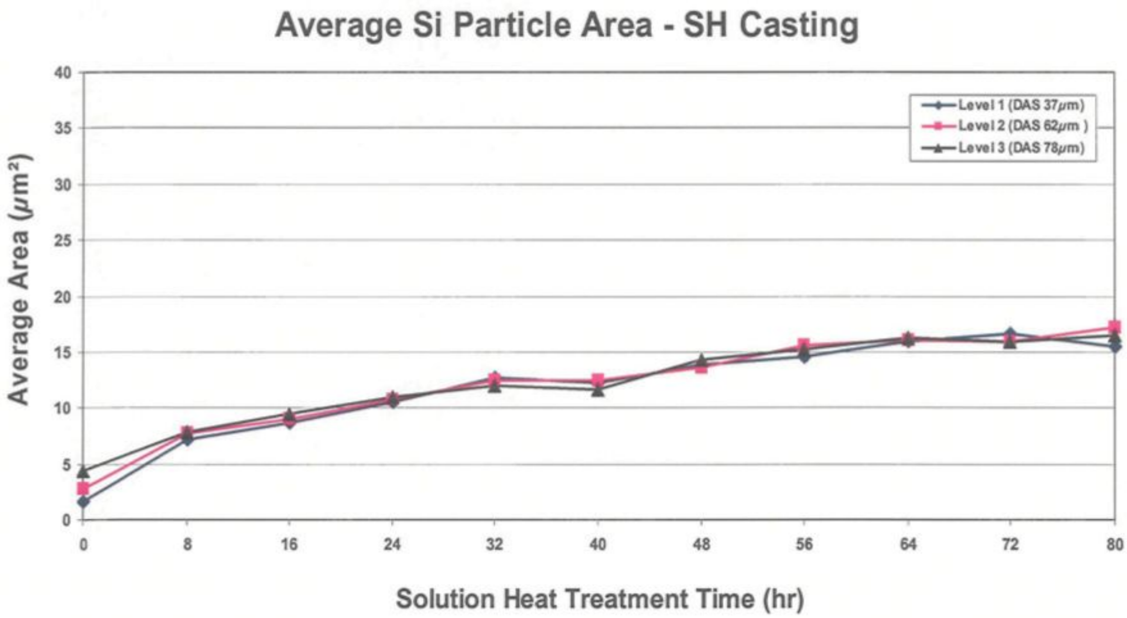


(a)

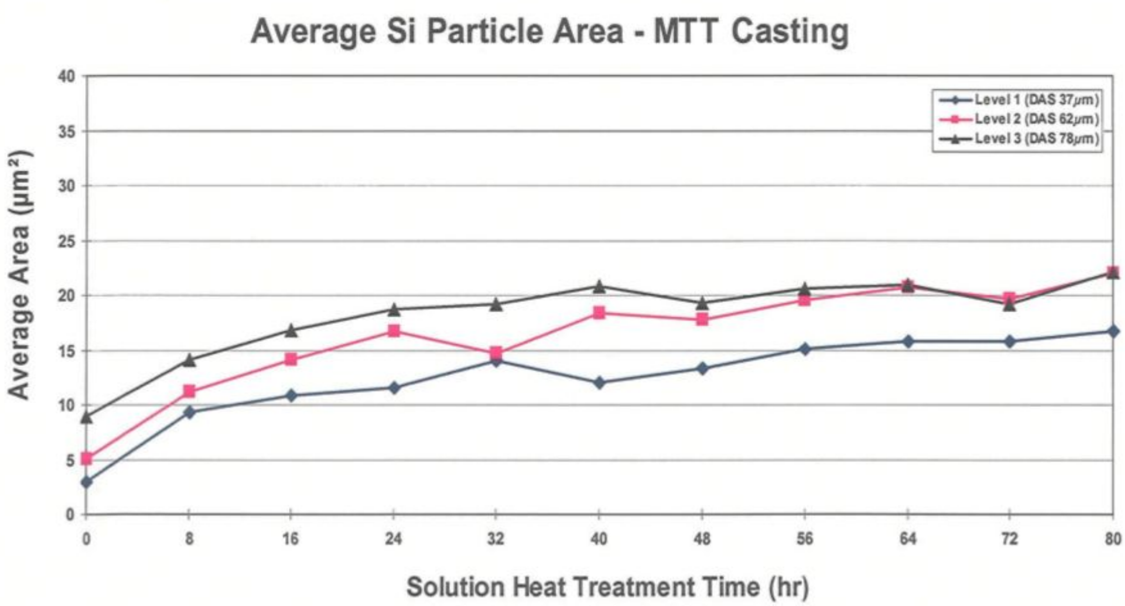


(b)

Figure 5.7 Effect of solution heat treatment on the average Si particle area obtained in the different A356.2 alloy casting samples: (a) NM, (b) SrM, (c) SH, (d) MTT, and (e) SrMTT castings.

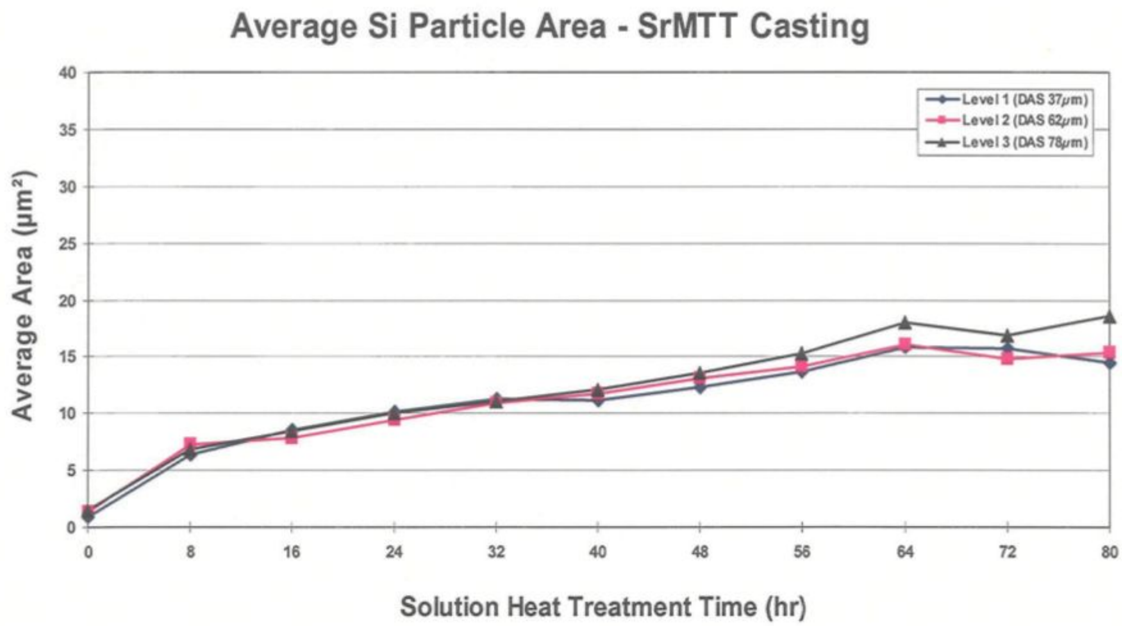


(c)



(d)

Figure 5.7 Effect of solution heat treatment on the average Si particle area obtained in the different A356.2 alloy casting samples: (a) NM, (b) SrM, (c) SH, (d) MTT, and (e) SrMTT castings.



(e)

Figure 5.7 Effect of solution heat treatment on the average Si particle area obtained in the different A356.2 alloy casting samples: (a) NM, (b) SrM, (c) SH, (d) MTT, and (e) SrMTT castings.

are first separated into segments at corners or at thin growth steps, but they still possess their flake morphology. After that, these segments begin to spheroidize. Theoretical studies have suggested that interfacial instabilities in the eutectic structure caused by the increase in shape perturbations and consequent breaking of the eutectic Si particles during the heat treatment do not take place that easily in the unmodified eutectic, and so the acicular eutectic particles are resistant to spheroidization. In fibrous eutectic, however, the shape perturbations are readily accepted and the particles are easily broken. As a result, spheroidization occurs at a much faster rate in modified alloys than in non-modified alloys.

With respect to the various casting types studied in the present work, the data presented in Appendix 1 may be analyzed as follows.

In the modified alloys, *i.e.*, those with modified Si particles, spheroidization starts with solution heat treatment followed by coarsening. The particle size increases in two stages, where the growth occurs relatively fast in the first stage, then slows down in the second stage. The duration of each stage of growth varies from casting type to casting type, depending upon the modification method employed (*i.e.*, SrM, SH, MTT or SrMTT).

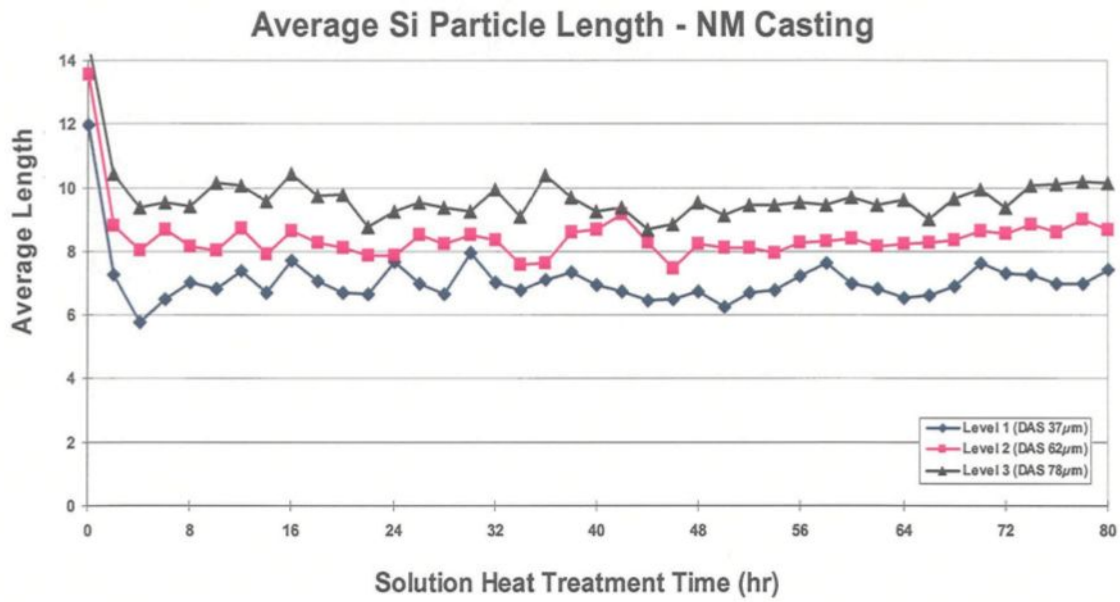
As can be seen from the data provided in Appendix 1, the accelerated growth stages vary from 28 h for SrM, to 32 h for SH, 8 h for MTT and 32 h for the SrMTT castings.

In the case of the unmodified NM casting also, once the fragmentation and spheroidization stages have taken place, there are two stages of coarsening, the accelerated coarsening, extending up to 12 h, as seen from the data in Appendix 1. It should be noted that in this case, however, spheroidization could also be taking place at the same time as coarsening, as the former takes place over the entire duration of the solution treatment, as the optical micrographs of Figure 5.1 show. Also observed is the fact that the accelerated growth periods for the NM and MTT castings are much shorter (10 h ± 2 h) than those noted for the modified castings (30 h ± 2 h).

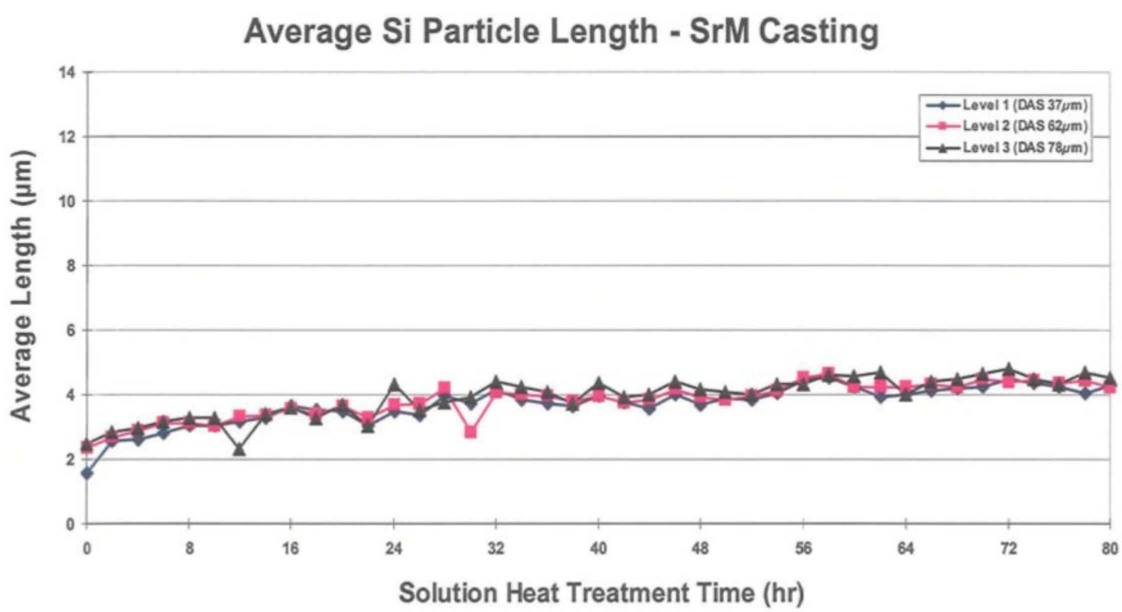
Apelian *et al.*[7] have suggested that the large diversity of particle size and shape in the unmodified alloy is expected to provide a greater driving force for coarsening in this case than in the modified alloys. In addition, the small tips of the acicular needle (or plate) shaped Si particles would favour growth at the corners, and increase their widths, *viz.*, coarsen the particles. Rhines and Aballe[85] have estimated the growth rate to be of the order of 0.0225 $\mu m^3/hr$ in unmodified alloys compared to 0.014 $\mu m^3/hr$ in modified alloys.

Figure 5.8 compares the plots of the average Si particle lengths obtained for the different A356.2 alloy casting types and levels at the various solution treatment times. The plots are very similar to those of Figure 5.7 for the average Si particle area. As before, the non-modified (NM) casting shows distinct particle sizes at the three levels (*i.e.*, cooling rates) where the particle lengths decrease in each case from their as-cast values up to 4 h solution treatment, then begin to increase gradually, attaining more or less constant values (within ± 1 μm) of 7, 8 and 9 μm for the levels 1, 2 and 3, respectively, over the 8 h-80 h range of solution treatment time. The as-cast Si particle lengths range from ~12 μm to ~15 μm.

The other variously modified castings display much smaller particle lengths in the as-cast condition (~3 μm or less), with the MTT casting exhibiting slightly higher values (~3 to 6 μm). After 56 h of solution treatment, the MTT casting samples corresponding to levels 2 and 3 (*i.e.* at DASs ≥62 μm) show similar maximum particle lengths (~7μm), while the level 1 (37 μm DAS) sample produces the best results in terms of refinement. Before 56 h, the three levels exhibit distinct particle lengths as in the case of the non-modified casting. The best results are obtained for the SrMTT casting which displays the minimum values in area (~7.5 μm^2) and length (2 μm) in the as-cast condition, followed by the SrM and SH castings.

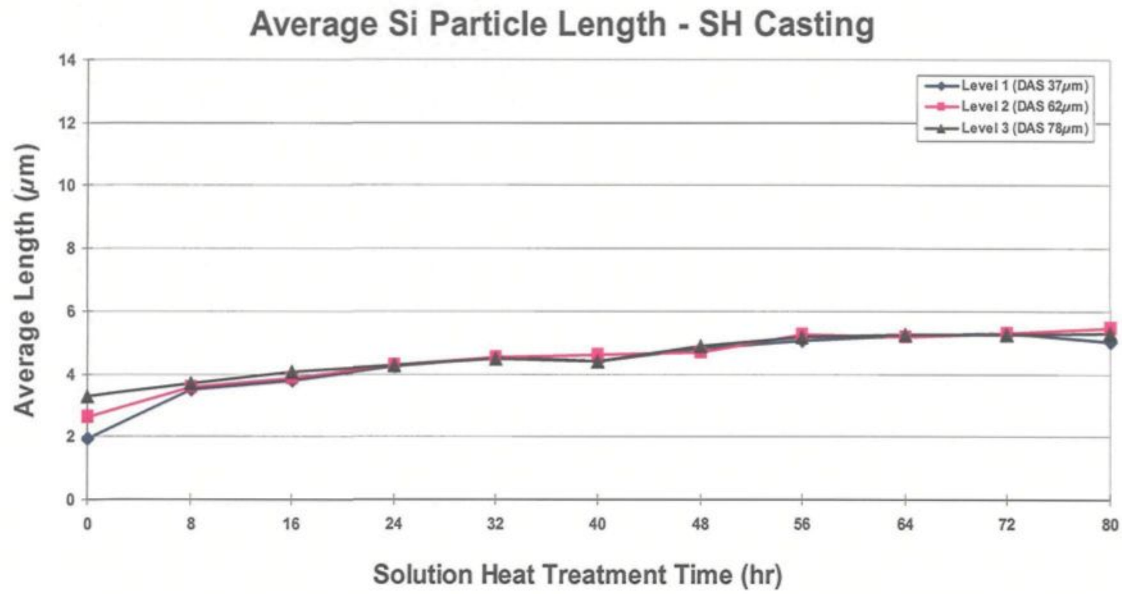


(a)



(b)

Figure 5.8 Effect of solution heat treatment on the average Si particle length obtained in the different A356.2 alloy casting samples: (a) NM, (b) SrM, (c) SH, (d) MTT, and (e) SrMTT castings.



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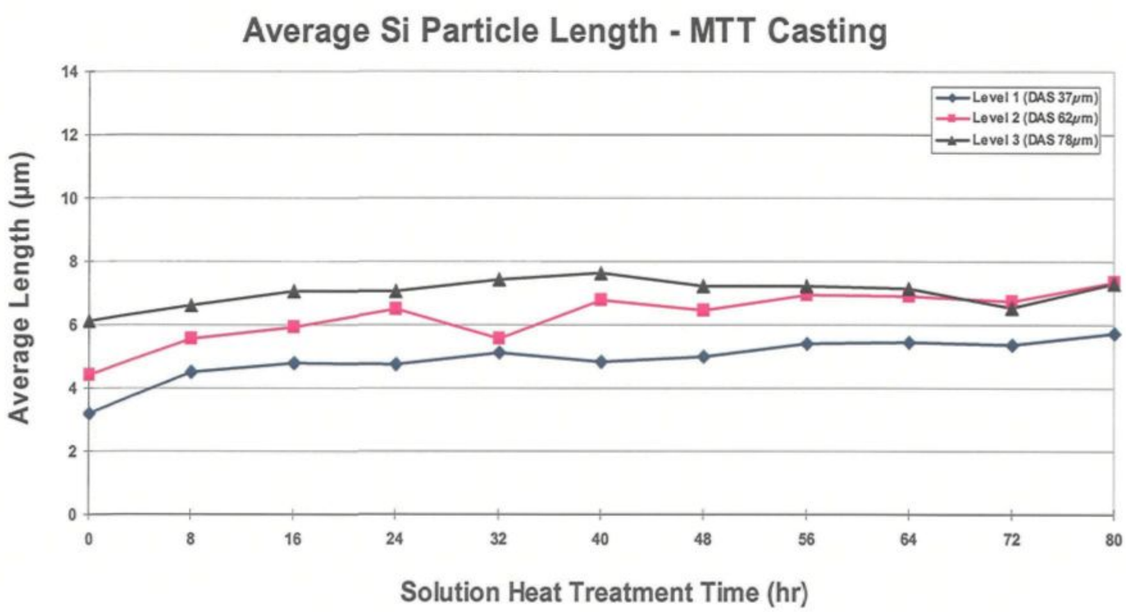
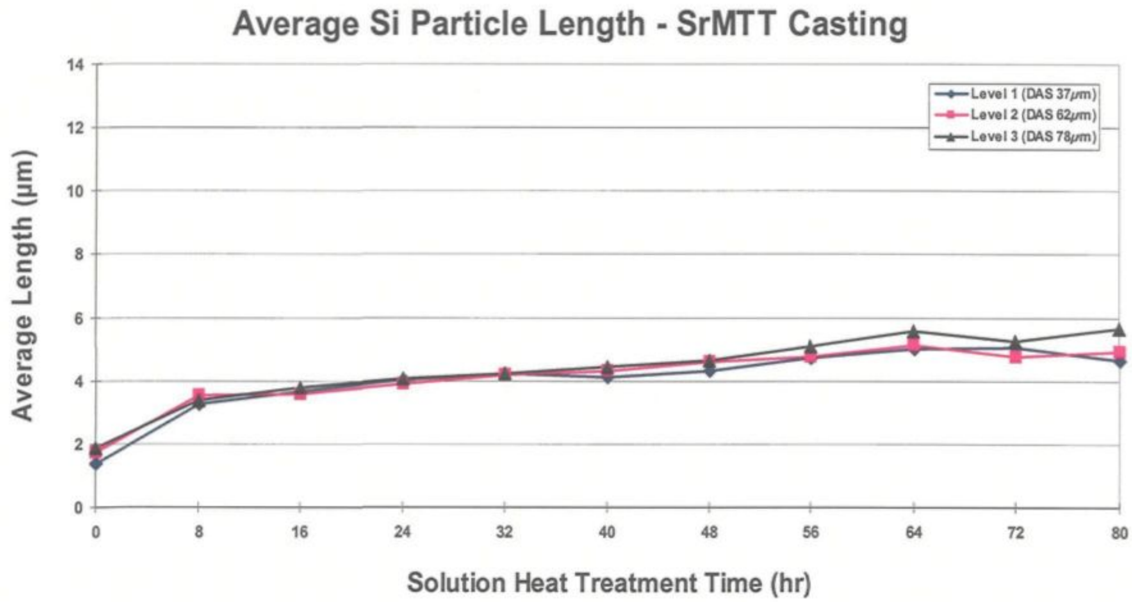


(d)

Figure 5.8 Effect of solution heat treatment on the average Si particle length obtained in the different A356.2 alloy casting samples: (a) NM, (b) SrM, (c) SH, (d) MTT, and (e) SrMTT castings.



(e)

Figure 5.8 Effect of solution heat treatment on the average Si particle length obtained in the different A356.2 alloy casting samples: (a) NM, (b) SrM, (c) SH, (d) MTT, and (e) SrMTT castings.

After 80 hr solution heat treatment, the NM-level 1 and MTT casting samples exhibit similar Si particle sizes (22-26 μm^2), while in the SrM, SH, and SrMTT castings, the particle sizes are much smaller (12-15 μm^2). Nonetheless, irrespective of the modification method used, the Si particle sizes are significantly diminished compared to the particle sizes obtained in the as-cast condition in the non-modified alloy (*i.e.*, without solution heat treatment). Also, as Figures 5.7 and 5.8 show, the effect of cooling rate on particle size is not affected by the solution heat treatment time at 540°C solution temperature.

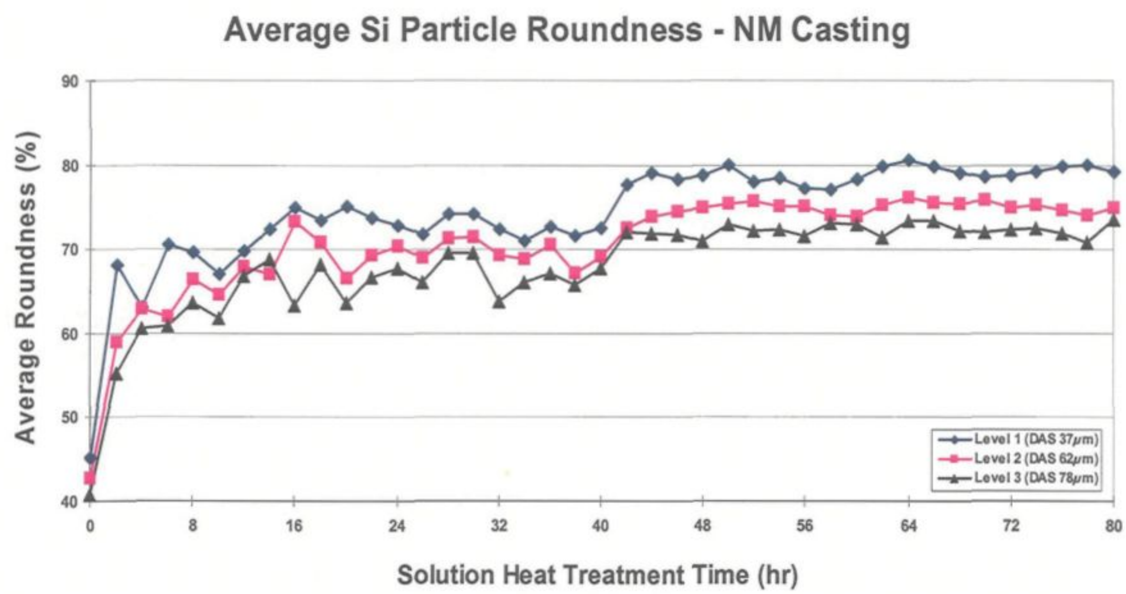
5.3.2 Effect on Eutectic Si Particle Shape

Solution heat treatment can improve the shape of the eutectic Si particles during the speroidization stage, when the particles become rounded, *i.e.*, their roundness increases and correspondingly, the aspect ratio decreases (and approaches the limit of 1 for spherical particles). However, the spheroidization process takes place quite differently in the unmodified and modified alloys.

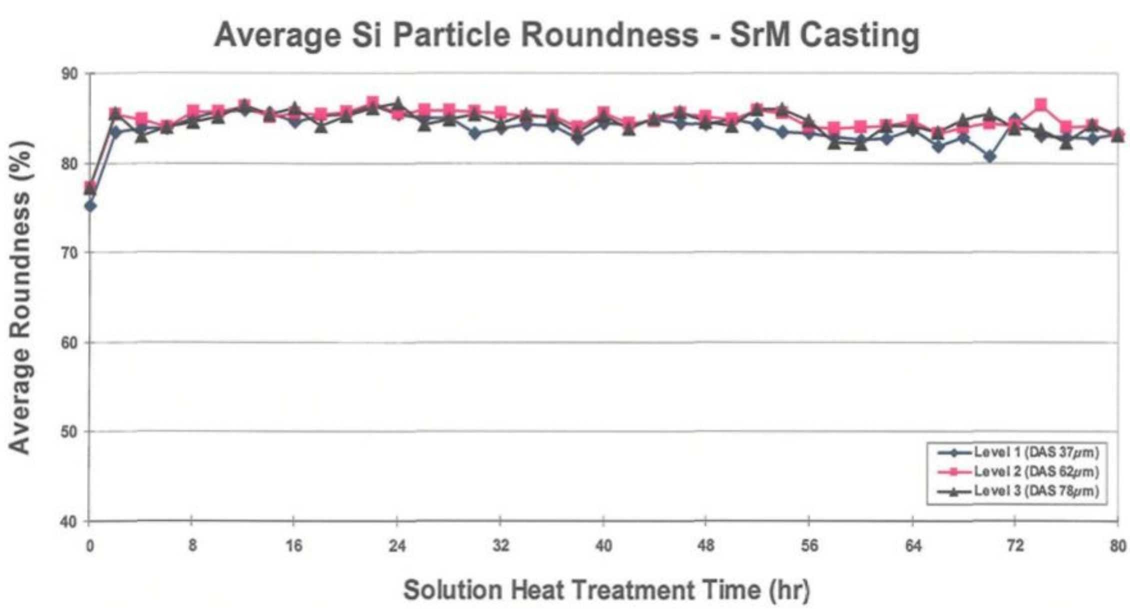
Figure 5.9 displays the variations in the average Si particle roundness as a function of solution treatment time at 540°C for the different A356.2 alloy casting types and levels.

As Figure 5.9(a) shows, the roundness of the Si particles in the non-modified alloy casting shows a large improvement from ~ 40-45 % in the as-cast condition to ~ 60-68 % after only 2 h of solution treatment. The roundness increases gradually as the solution time is prolonged, reaching a maximum at ~ 50 h and then remaining more or less the same up to 80 h, at ~ 75-80 %. Of course, the level 1 samples show maximum improvements, in each case.

Maximum roundness values (~85%) are obtained for the SrM casting samples, Figure 5.9(b), as also for the SH (Figure 5.9(c)) and SrMTT (Figure 5.9(e)) casting samples. In the case of the SrM casting, all cooling rates exhibit the same roundness over the range of solution treatment times, starting from an as-cast roundness of ~ 75-78 %. The SH and SrMTT castings show some influence of cooling rate. As in the case of the NM casting, the MTT casting also shows distinct roundness values for the three levels studied, although the as-cast roundness values are higher (~ 51-56 %) compared to those obtained in the NM

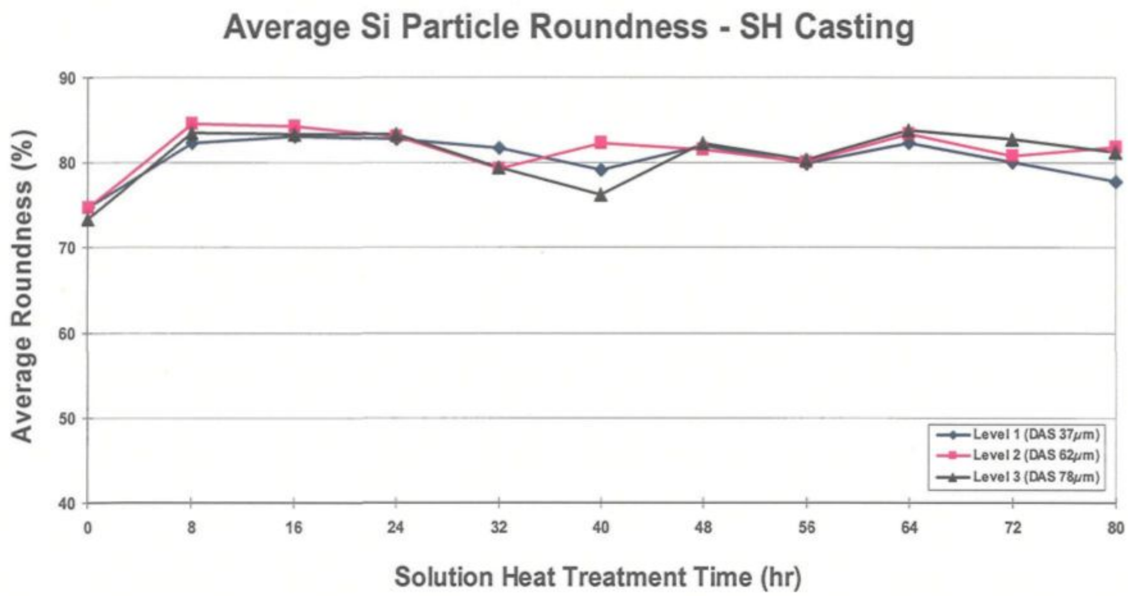


(a)



(b)

Figure 5.9 Effect of solution heat treatment on the average Si particle roundness obtained in the different A356.2 alloy casting samples: (a) NM, (b) SrM, (c) SH, (d) MTT, and (e) SrMTT castings.



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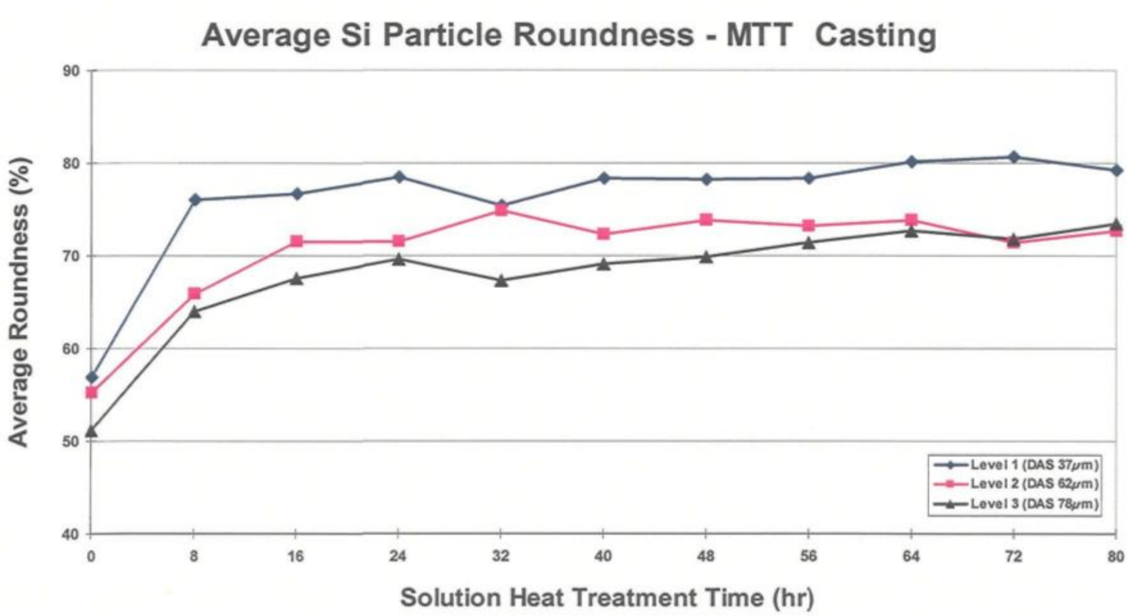
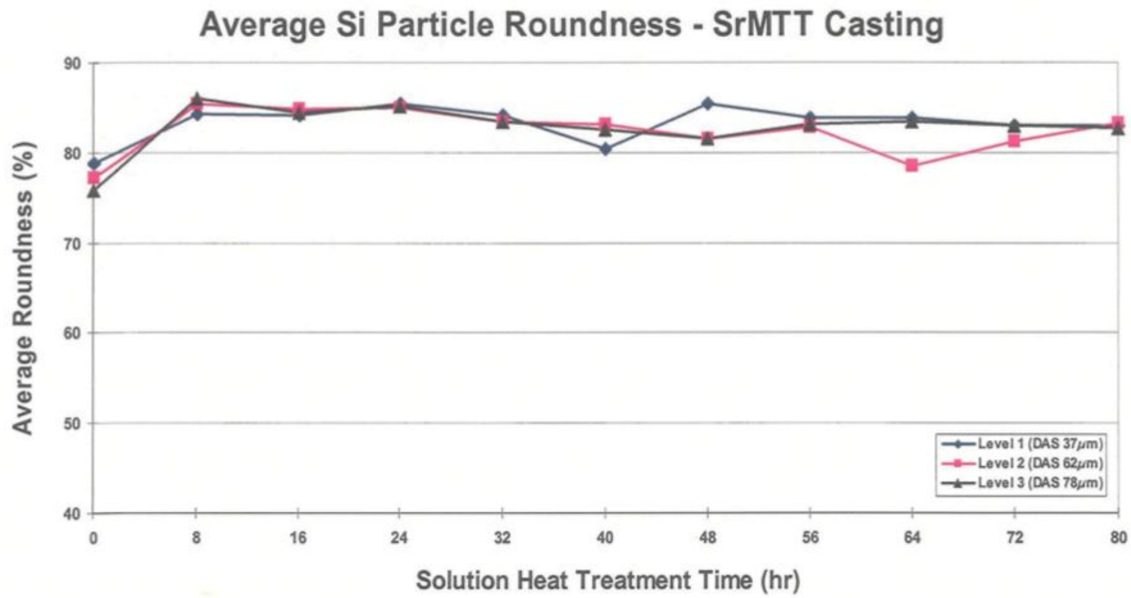


(d)

Figure 5.9 Effect of solution heat treatment on the average Si particle roundness obtained in the different A356.2 alloy casting samples: (a) NM, (b) SrM, (c) SH, (d) MTT, and (e) SrMTT castings.

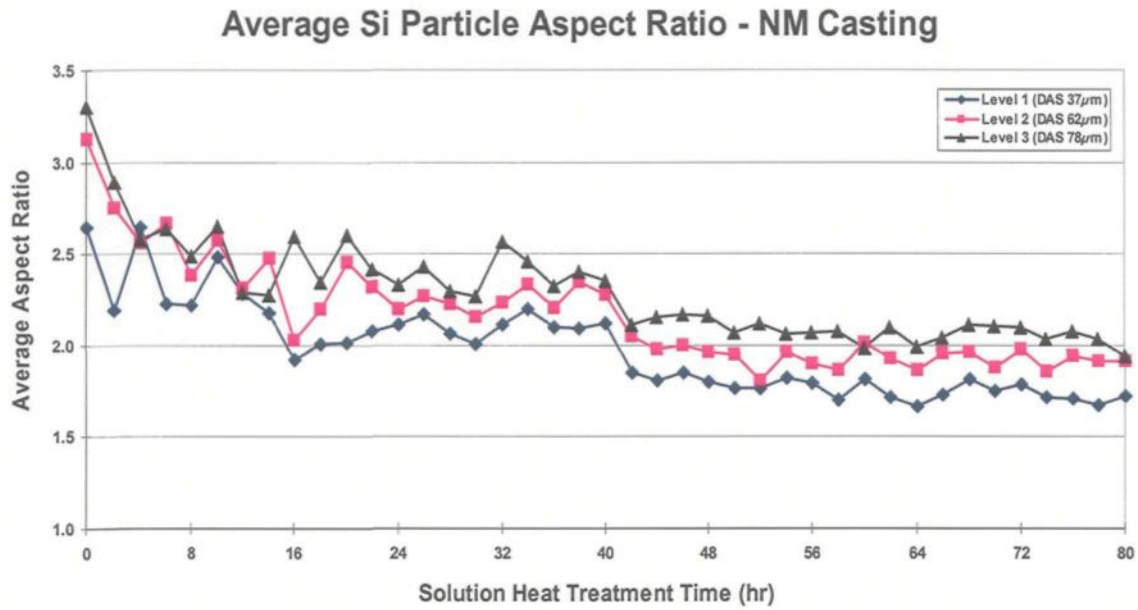


(e)

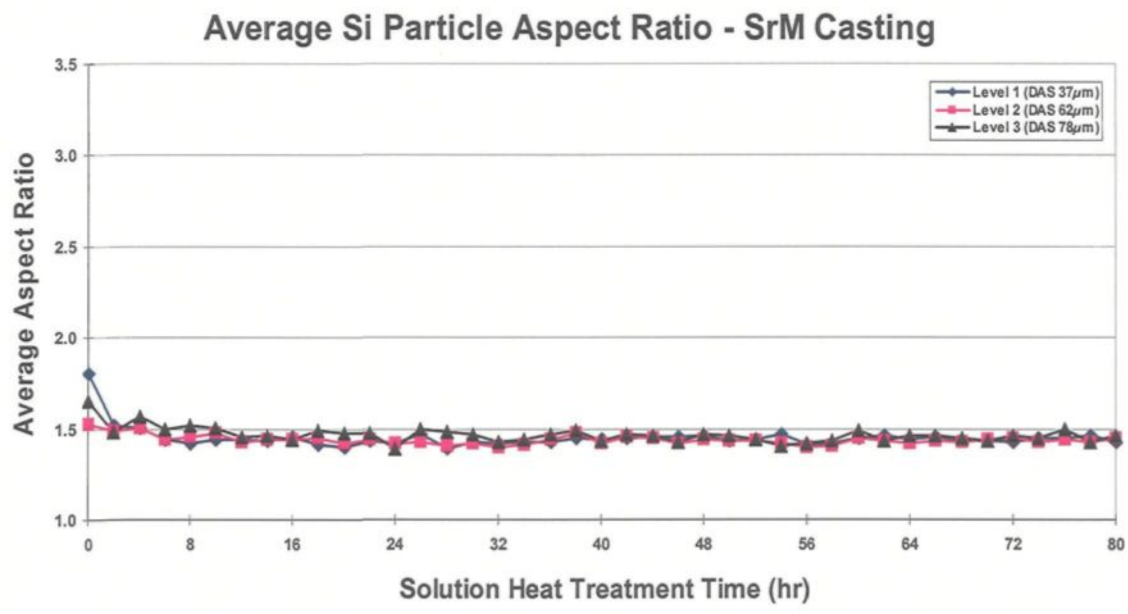
Figure 5.9 Effect of solution heat treatment on the average Si particle roundness obtained in the different A356.2 alloy casting samples: (a) NM, (b) SrM, (c) SH, (d) MTT, and (e) SrMTT castings.

casting (~ 40-45 %). Again, the MTT casting-level 1 (37 μm DAS) sample provides the best roundness values.

Similar tendencies are reflected in the aspect ratio parameters exhibited by these samples, as shown in Figure 5.10, only in this case, the aspect ratios start with a higher value in the as-cast condition to decrease to an aspect ratio of 1 (corresponding to the ~100 % roundness) exhibited by perfectly spherical particles. Again, the lowest aspect ratios are obtained for the SrM casting samples (< 1.5), Figure 5.10(b), where, after an initial improvement after 2 h of solution treatment, the aspect ratio remains constant over the range of solution times studied, and independent of the cooling rate or level. The SH

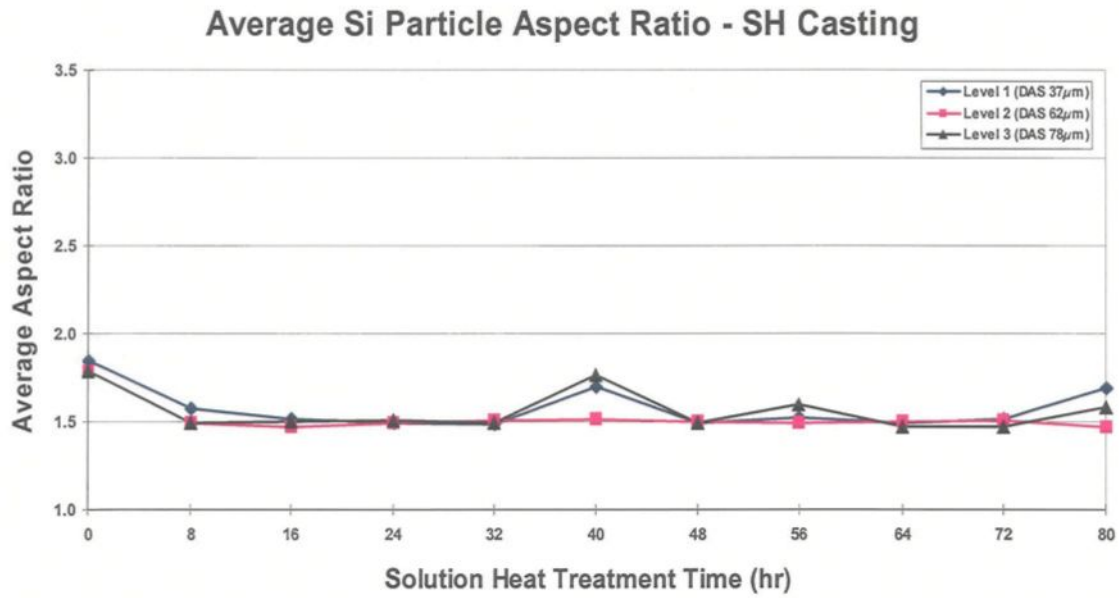


(a)



(b)

Figure 5.10 Effect of solution heat treatment on the average Si particle aspect ratio obtained in the different A356.2 alloy casting samples: (a) NM, (b) SrM, (c) SH, (d) MTT, and (e) SrMTT castings.



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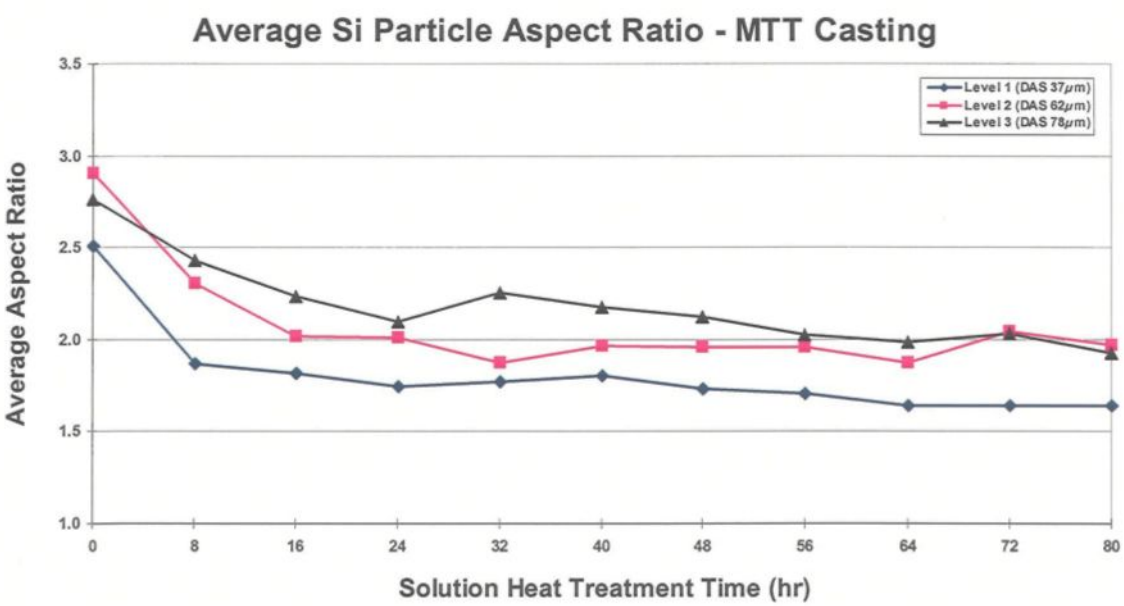
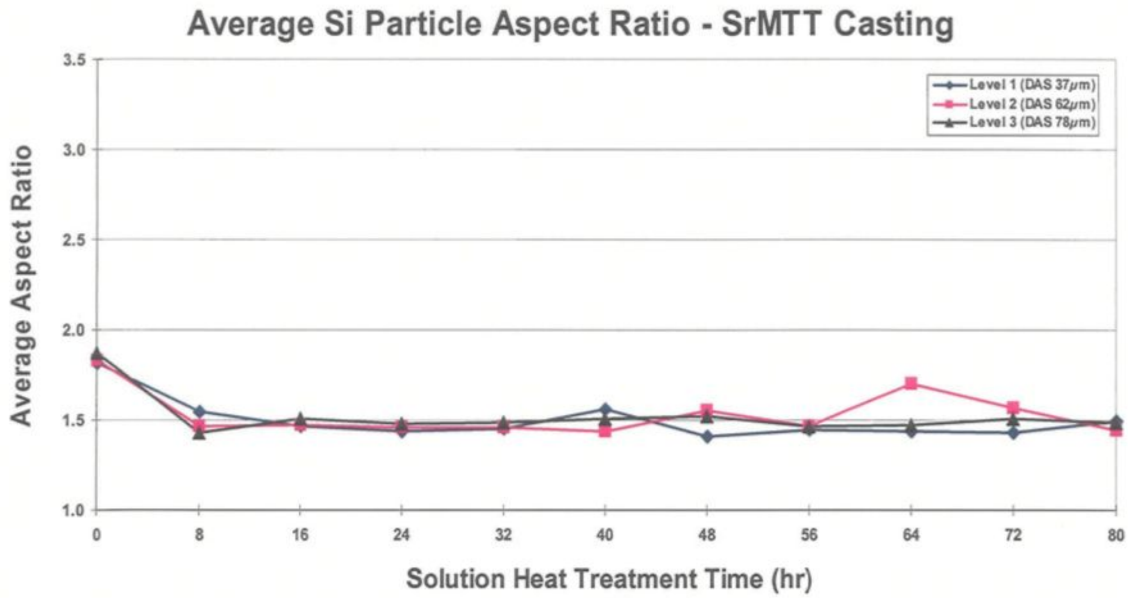


(d)

Figure 5.10 Effect of solution heat treatment on the average Si particle aspect ratio obtained in the different A356.2 alloy casting samples: (a) NM, (b) SrM, (c) SH, (d) MTT, and (e) SrMTT castings.



(e)

Figure 5.10 Effect of solution heat treatment on the average Si particle aspect ratio obtained in the different A356.2 alloy casting samples: (a) NM, (b) SrM, (c) SH, (d) MTT, and (e) SrMTT castings.

and SrMTT castings follow next, where, with the exception of a few changes at ~ 40 h and 80 h solution times, the aspect ratio remains at ~ 1.5 for the SH casting and shows a bit more discrepancy in the case of the SrMTT casting.

It can be concluded from these results that the original Si particle morphology is the key factor which determines the time that the Si particles need for spheroidization. The finer the Si particles, the less time it will take for them to be fully spheroidized.

CHAPTER 6

TENSILE PROPERTIES

CHAPTER 6

TENSILE PROPERTIES

6.1 INTRODUCTION

As one of the main groups of aluminum alloys used in automotive application, the mechanical properties of Al-Si-Mg alloys have been investigated extensively.[61,86,87] Among these, those relating to the tensile properties of A356 alloys have been determined in terms of the secondary dendrite arm spacing (SDAS) or cooling rate, eutectic Si particle characteristics, alloying element addition (Mg, Fe, and others), and casting defects such as porosity and inclusions.[9,61,62] In addition, the effects of modification and solution heat treatment which, through their influence on the eutectic Si particle characteristics, can also control the tensile properties of A356 alloy, have also been studied by several workers. [22,47,82,83]

In the present work, we have focused on the effect of cooling rate, various modification methods, and solution heat treatment on the characteristics of the eutectic Si particles, observed in A356.2 alloys, with the aim of investigating how the changes brought about by these various means will affect the tensile properties of the corresponding castings.

This chapter presents the results of the tensile tests that were carried out for the NM, SrM, SH, MTT and SrMTT end-chilled castings, on samples obtained at the three levels (of 10, 50 and 100 mm above the chill end) to incorporate the effect of cooling rate. The tensile properties (UTS, YS and %El) were measured using an Instron Universal Mechanical Testing machine, the details of the samples preparation and testing procedures have been provided in Chapter 3, section 3.5.

In regard to the different parameters studied and their influence on the tensile properties, a high cooling rate (or fine SDAS) is well known to enhance the tensile properties, due to the overall refinement of the microstructure and its constituents, including the Si particles, as well.

In regard to the various modification methods used, those of Sr modification are well known, according to Hafiz and Kobayashi,[64] Sr modification has little effect on the yield strength of A356 alloy, but can moderately improve the tensile strength. The main impact of Sr modification is on the ductility, where the addition of 240 ppm Sr to A356 alloy melt scan improve the elongation from 8.03% to 22.2%.[64]

In comparison, there are few studies covering the effect of melt superheat and even less on that of melt thermal treatment (MTT) on the tensile properties of A356 alloys. The results of Jie *et al.*,[42] show that superheating an A356 alloy melt to 810°C can improve the tensile properties, especially the ductility (from 5.0% to 8.5%). The investigations of Wang *et al.*[41] show that the MTT process greatly improves the elongation, by almost 112%.

To the best of our knowledge, there is no report on the combined effect of Sr modification and melt thermal treatment on the tensile properties of Al-Si alloys, and A356 alloy, in particular. As has been shown in chapter 4, the SrMTT casting showed the best results in that the eutectic Si particle characteristics were the finest produced among all the casting types studied. It is to be expected, therefore, that the SrMTT casting samples will exhibit the best tensile properties, as well.

The effect of solution heat treatment on the Si particle characteristics (and hence on the tensile properties) of A356 alloy has also been investigated.[82] In the present work, the tensile test bars obtained from the various castings were solution treated at 540°C for times ranging from 0 h (as-cast condition) to 80 h at intervals of 2 h for the non-modified (NM) and Sr-modified (SrM) alloy castings. Based on the results obtained, for the other castings, the test bars were solution treated at 540°C, again for times ranging from 0 h (as-cast condition) to 80 h, but at intervals of 8 h. Following solution treatment, all test bars were quenched in warm water and aged for 5 h at 155°C (standard T6 treatment) before the tensile testing was carried out.

6.2 AS-CAST TENSILE PROPERTIES

The as-cast tensile properties of the various A356 alloy casting types were determined. The results are plotted in Figures 6.1 to 6.3.

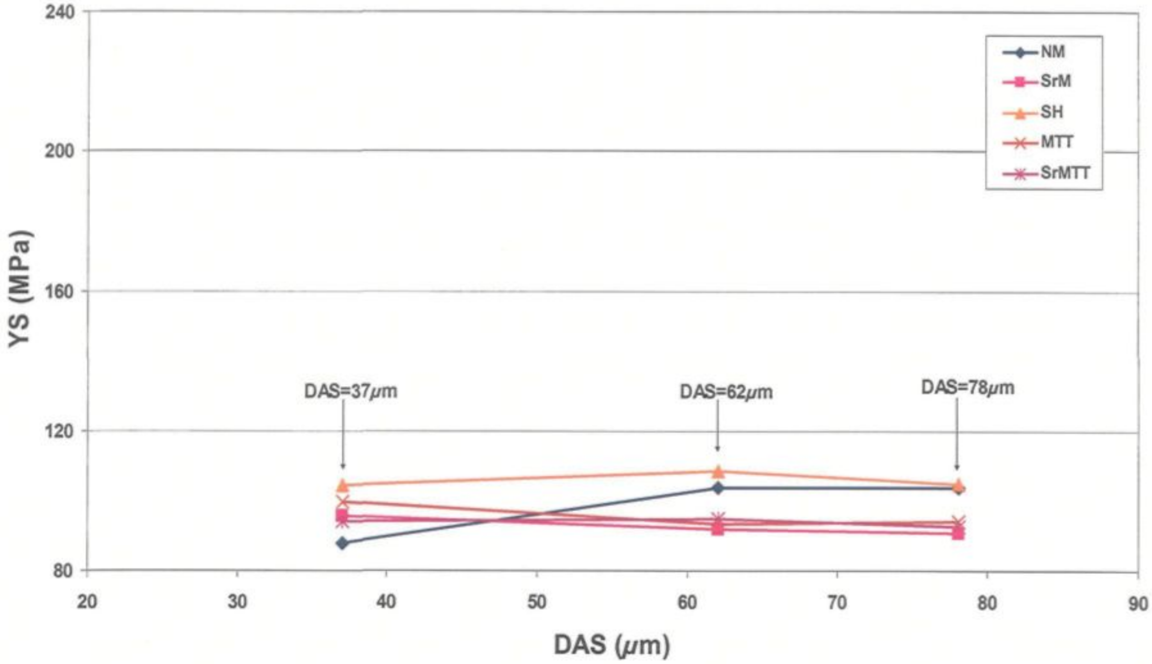


Figure 6.1 Yield strength of samples obtained from different A356.2 alloy castings – as-cast condition.

According to Shivkumar et al.,[47] yield strength is essentially determined by the Mg content and the aging condition rather than the eutectic Si particle characteristics or cooling rate (in term of DAS). This is also evidenced by the experimental results of the present work. As shown in Figure 6.1, under the same cooling rate, although various modification methods produce a wide range of Si particles characteristics (as discussed in Chapter 4 and 5), the yield strength of each casting type remains more or less the same level to level. For instance, at the level 10mm from chilled end (DAS=37μm), the yield strength of the NM, SrM, SH, MTT and SrMTT casting samples are 88, 96, 104, 99 and 94 MPa, respectively. In addition, for each casting type, the cooling rate does not appear to affect the yield strength. For example, in the SrMTT casting samples, the yield strengths obtained at the three levels (DAS=37, 62, 78μm) are 95, 96, 92MPa, respectively, while the other A356 alloy casting types also show the same tendency.

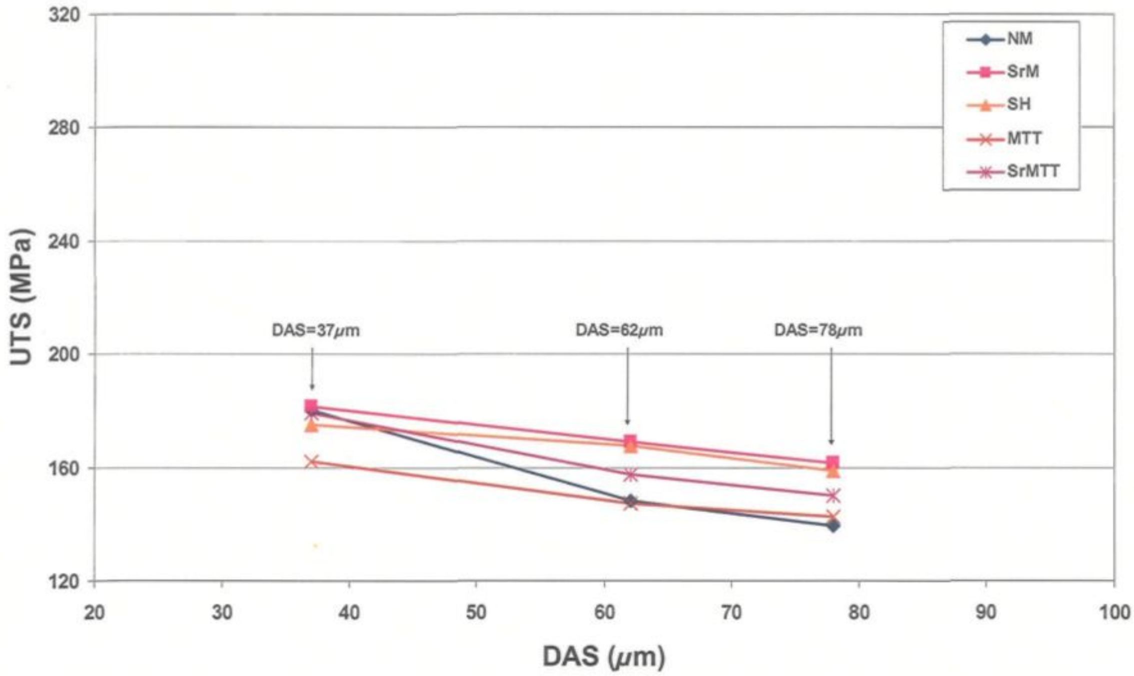


Figure 6.2 Ultimate tensile strength of samples obtained from different A356.2 alloy castings – as-cast condition.

The UTS values obtained for the various casting types reveal that the SrM, SH and SrMTT processes improve the UTS to a certain extent compared to the non-modified (NM) condition, while the MTT processed casting appears to have no effect, as shown in Figure 6.2. For instance, at DAS=62μm, the UTS for NM, SrM, SH, MTT and SrMTT samples are 148, 169, 168, 147 and 158 Mpa, respectively. This effect on UTS is related to the improvement in the Si particle characteristics, especially with regard to the aspect ratio. In SrM, SH and SrMTT-treated castings, the Si particles are modified from acicular form to fibrous morphology while in NM or MTT-treated castings they still appear as acicular flakes. However, it should be noted that the improvement is also affected by the cooling rate. As Figure 6.2 shows, at the high cooling rate (DAS=37μm), none of the modification methods show an obvious improvement in the UTS (182, 175, 162, 179MPa for the SrM, SH, MTT, and SrMTT treated castings respectively, compared to 180MPa for the NM casting). At high cooling rates, the effect of cooling rate (or DAS) dominates that produced by the different modification processes, as at fine dendrite arm spacings, all microconstituents in the microstructure are refined and not only the eutectic silicon, which is the case for the modified castings. However, the effect of modification takes over as the cooling rate decreases, *i.e.*, as the DAS attains larger values. For example, in the SrM casting, the UTS decreases from 182 to 169 to 162 MPa as the DAS increases from 37 to 78 μm. Similarly, in the case of the SH casting, the UTS is lowered from 175, through 168 to 159 MPa, respectively. This decrease in UTS is related to the increase in the Si particle size and aspect ratio resulting from the decrease in cooling rate.

The lower UTS value displayed by the MTT casting at 37 μm DAS could probably be the result of the presence of porosity defect and/or inclusions present in the gage length portion of the corresponding test bars.

Figure 6.3 shows the results for percentage elongation for the various casting types. Both SrM and SrMTT processes improve the ductility considerably from ~ 6% in the non-modified condition to ~ 12%, at 37 μm DAS. Comparing the plots for the NM and SrM casting samples, the same level of improvement is obtained with Sr modification (relative ot the non-modified case) at all cooling rates or DASs.

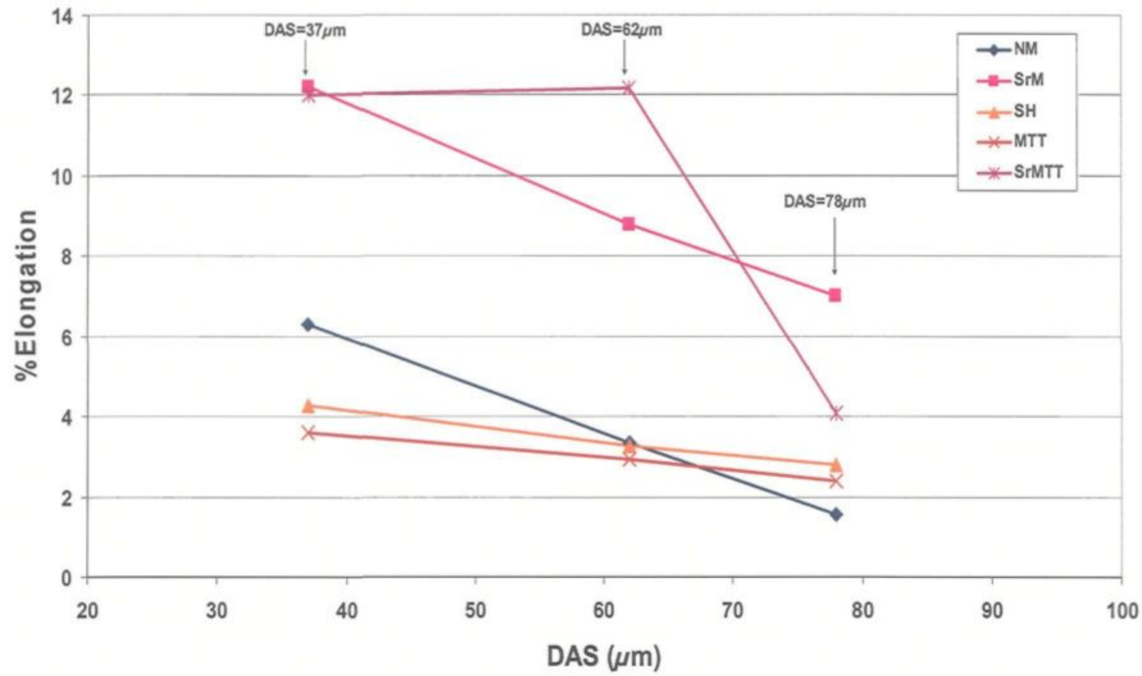


Figure 6.3 Percentage elongation of samples obtained from different A356.2 alloy castings – as-cast condition.

Although the SH and MTT processes do refine the Si particles, no significant improvement in ductility is observed. In fact, the ductility is even lower than that of the NM casting sample, at the high cooling rate, *i.e.*, at DAS=37μm by about 2 to 2.7%. The ductility decreases very gradually with increase in dendrite arm spacing, from ~ 4% at 37 μm DAS to ~ 3% at 78 μm DAS. These observations could be explained by the degree of Si particle clustering observed in the respective microstructures. As was shown in Chapter 4, the Si particle distribution was not homogeneous in these casting samples, particularly at the high cooling rate, where the solidification time was not sufficient to allow for a more even distribution of the Si particles. This general characteristic of the MTT and SH samples would explain the low ductilities observed.

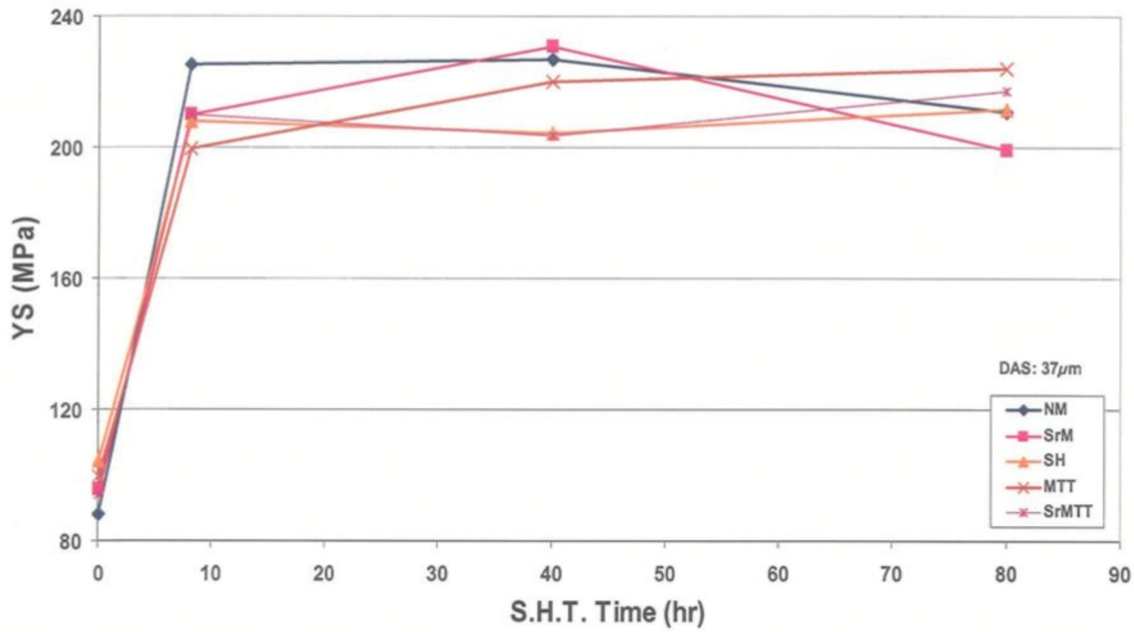
Compared to the NM casting sample, the longer solidification time at 78 μm DAS would provide more time for distributing the Si particles more evenly in the casting, and result in improving the ductility compared to the NM casting sample (~ 3% of ~ 1.5% for NM).

To summarize, the ductility of A356 alloys subjected to various modification processes is determined by the dendrite arm spacing, the eutectic Si particle size and aspect ratio, as well as by the presence of casting defects. The observations for the MTT processed casting are in keeping with those of Wang[61].

6.3 TENSILE PROPERTIES AFTER HEAT TREATMENT

For studying the effect of heat treatment, the tensile test bars were solution heat treated at 540°C for selected times of 8, 40 and 80 h, to cover the range of solution times studied. The samples were artificially aged at 155°C for 5 h (standard T6 temper) before carrying out the test. The results are presented in Figures 6.4 through 6.6, where the variations in YS, UTS and %El obtained at each cooling rate (or DAS level) have been grouped together for the five casting types.

In general, both YS and UTS are significantly improved after solution heat treatment. In regard to the elongation, while the ductilities of the NM, SH and MTT castings are also improved, the case for the SrM and SrMTT castings is more complicated in nature. As Figure 6.4 shows, for each A356.2 alloy casting type, the yield strength is greatly improved after 8 h of solution heat treatment, compared to the as-cast (0 h) condition. Maximum improvement is observed in the case of the NM casting,



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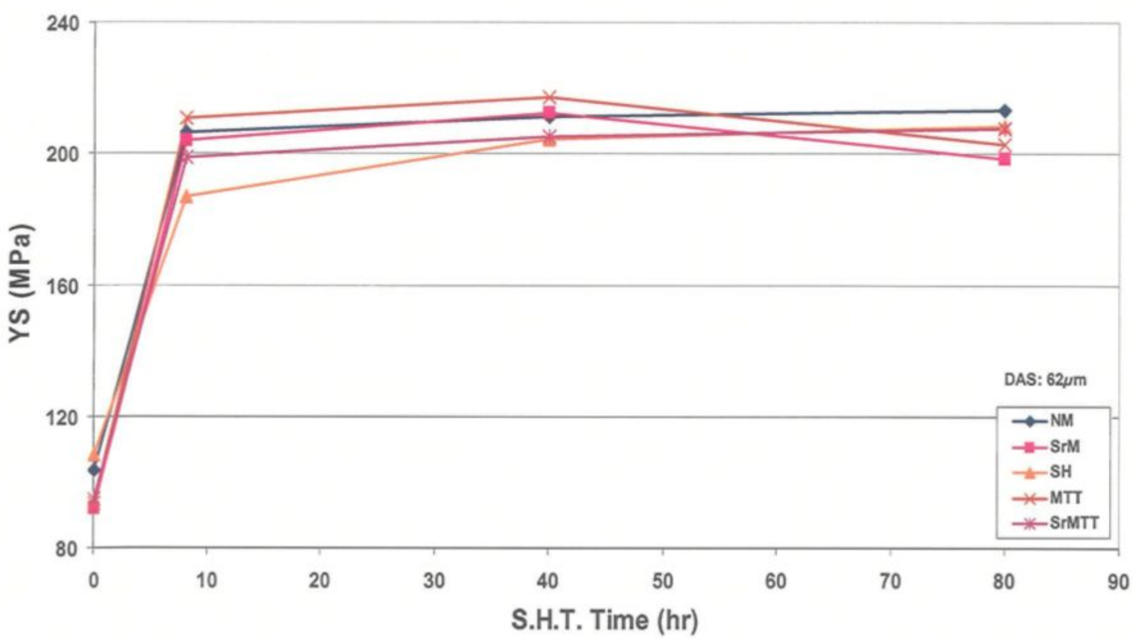
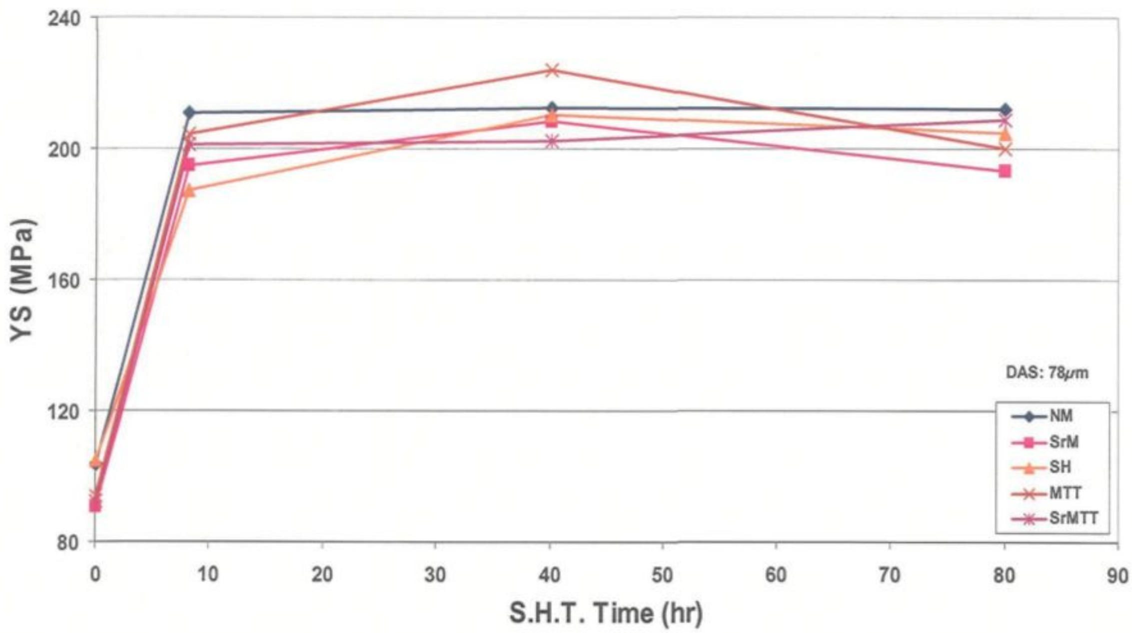


(b)

Figure 6.4 Effect of solution heat treatment on the yield strength of heat-treated samples obtained from various A356.2 alloy castings at: (a) 37 μm, (b) 62 μm, and (c) 78 μm DAS levels.



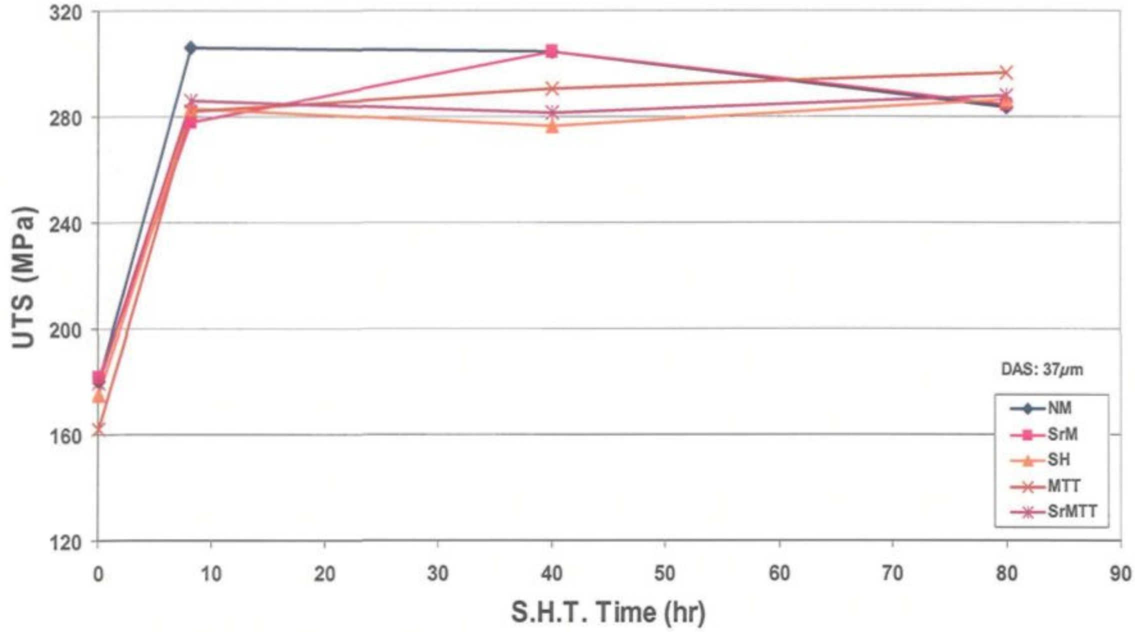
(c)

Figure 6.4 Effect of solution heat treatment on the yield strength of heat-treated samples obtained from various A356.2 alloy castings at: (a) 37 μm, (b) 62 μm, and (c) 78 μm DAS levels.

at the highest cooling rate, where the YS value jumps from ~ 85 MPa to ~ 235 MPa after 8 h of solution treatment. the improvement in yield strength is attributed to the precipitation of Mg_2Si within the Al-matrix after aging. In most cases, the Mg_2Si precipitation is essentially completed within the first 8 h of solution treatment, and the yield strength does not vary much thereafter, with further increase in solution treatment time. Actually, according to Shivkumar *et al.*,[47] the precipitation of Mg_2Si finishes in the first hour of solution treatment. once the samples have been solution heat treated, cooling rate has very little effect on the yield strength.

The plots in Figure 6.4 show that for the SrM casting samples, the maximum yield strength is achieved after 40 h of solution treatment. this may be explained by the fact that the SrM casting from which the corresponding 40 h-solution treatment test bars were obtained contained a higher level of Mg (0.309%) than did those for the 8 h and 80 h solution treatments (0.234% Mg and 0.239% Mg, respectively). In comparing Figures 6.4(a), (b) and (c), it can be observed that, overall, the yield strength does not change from one cooling rate to another for a specific modification process (*i.e.*, casting type), and under the same solution treatment conditions.

Figure 6.5 shows the UTS values obtained for the various A356.2 casting samples after heat treatment. As can be seen, the UTS shows a tendency very similar to that obtained for the yield strength in that a significant improvement is obtained after 8 h solution heat treatment, then remains at the same level with further solution treatment. As in the case of the yield strength, the maximum improvement in UTS is obtained for the NM casting, from ~ 180 MPa in the as-cast condition to ~ 305 MPa after 8 h solution treatment. Up to 40 h solution time, the UTS remains stable but drops to ~ 290 MPa after 80 h of solution treatment. Cooling rate has a certain influence in that different levels of improvement in UTS are obtained. In the case of the SrMTT casting, the UTS improves gradually for the 78 μm DAS samples from 162 MPa to 262 MPa until, after 80 h solution treatment, the UTS attains a value of 261 MPa, comparable to that obtained at 62 μm DAS.



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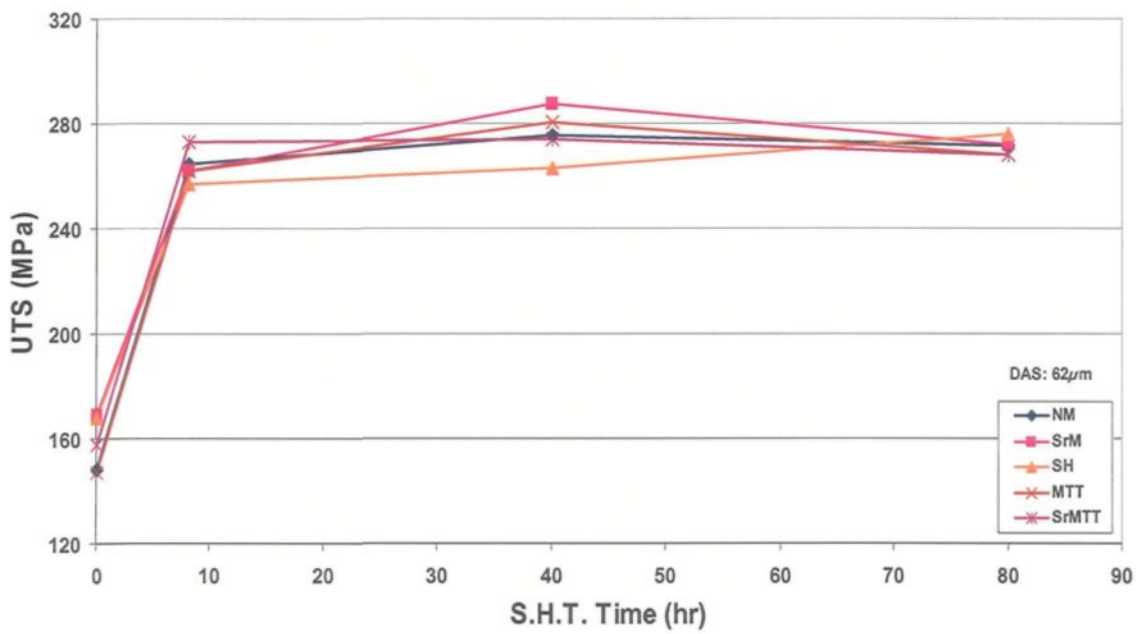
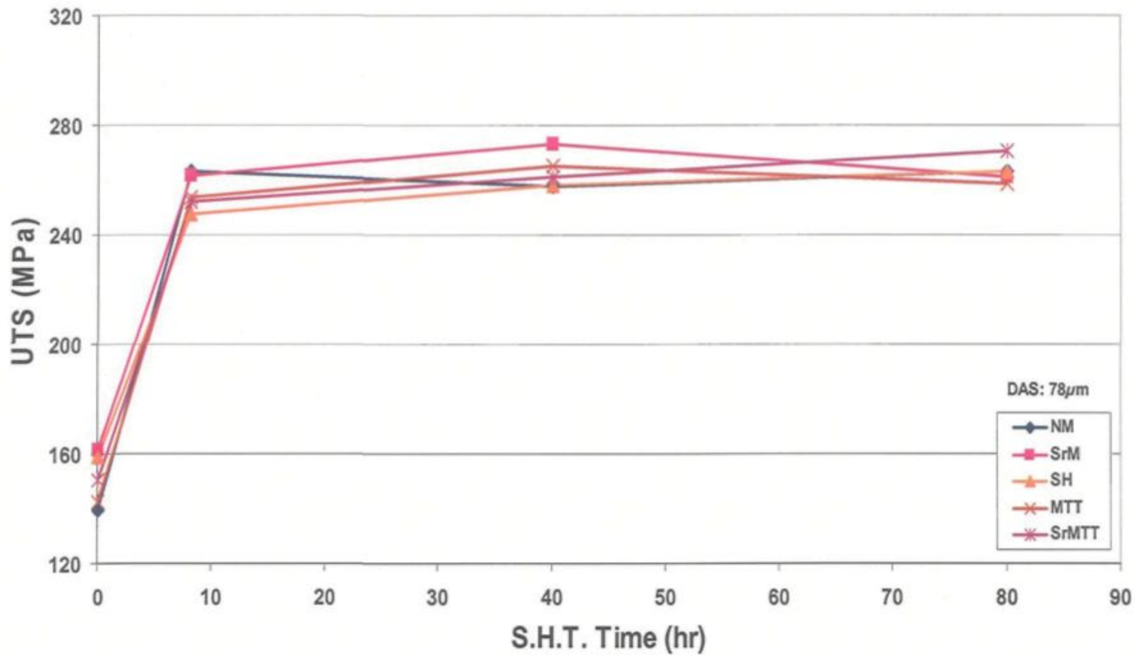


(b)

Figure 6.5 Effect of solution heat treatment on the ultimate tensile strength of heat-treated samples obtained from various A356.2 alloy castings at: (a) 37 μm, (b) 62 μm, and (c) 78 μm DAS levels.



(c)

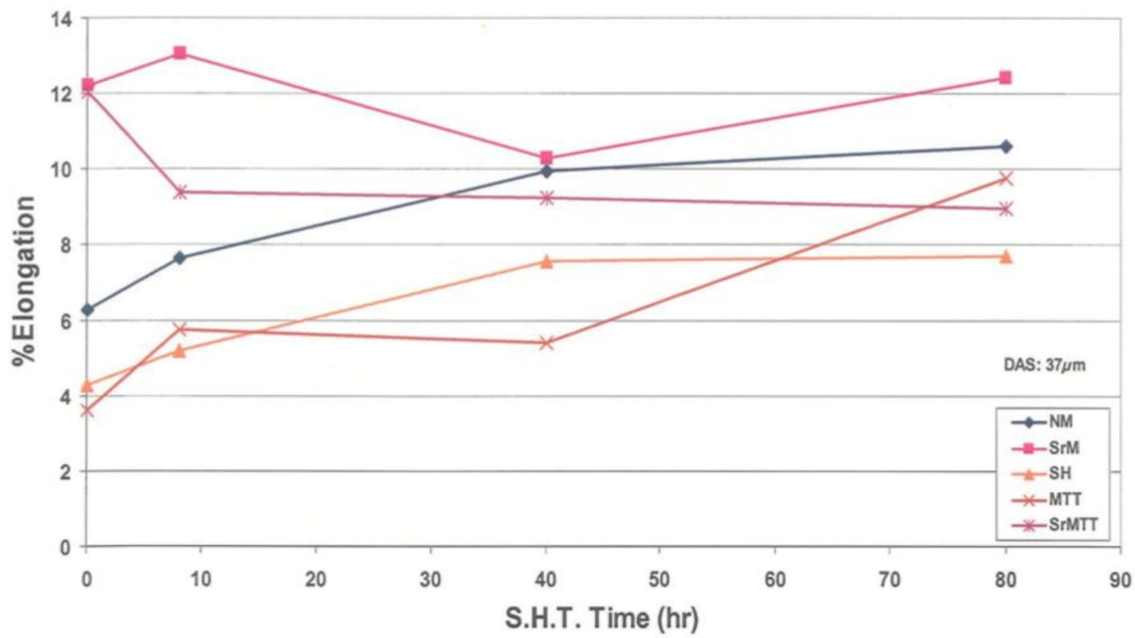
Figure 6.5 Effect of solution heat treatment on the ultimate tensile strength of heat-treated samples obtained from various A356.2 alloy castings at: (a) 37 μm, (b) 62 μm, and (c) 78 μm DAS levels.

According to Pan *et al.*,[82] the improvement in UTS can be attributed three factors: Mg_2Si precipitation, dissolution of Si within the Al-matrix, and change in the Si particle morphology. Among these, Mg_2Si precipitation and change in Si particle morphology favor an increase in the UTS, while dissolution of Si has a negative influence. The rapid increase in UTS obtained for heat-treated samples solution treated for 8h is due to maximum dissolution of Mg and Si (and, hence, precipitation of Mg_2Si), and the spheroidization of the Si particles. With further increase in solution treatment time (up to 80h), there is no further dissolution of Mg and Si (and hence no further Mg_2Si precipitation), while the positive effect of spheroidization is offset by the dissolution of

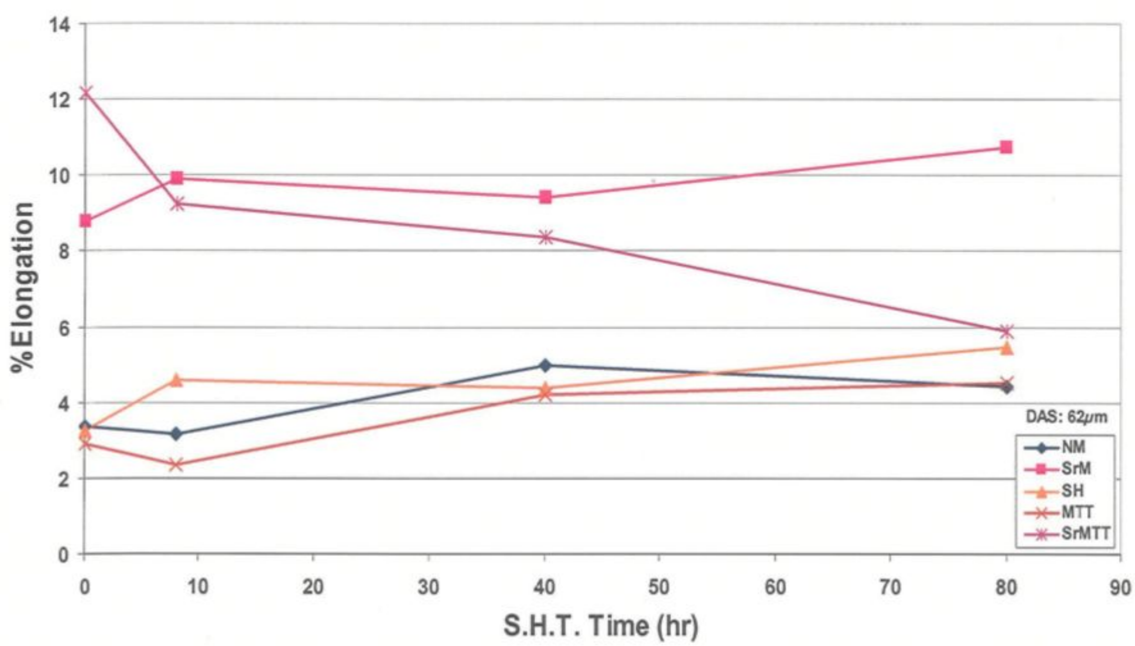
Si within the Al-matrix, thus maintaining the UTS around the same level, Figure 6.5. Also, from a comparison of Figures 6.5(a), (b) and (c), it can be seen that the effect of cooling rate on UTS is not affected by the solution treatment time, and that the tensile strength of the various castings lie in the same range, within 10-20 MPa of each other, for the three cooling rates studied. While the Si particle characteristics may vary from one casting type to another, this difference does not affect the UTS after solution heat treatment/aging, so long as the castings contain the same Mg level.

Figure 6.6 shows the effect of heat treatment on the ductility of the various A356.2 alloy casting samples at each of the three DAS levels. In general, the ductility is seen to improve with solution heat treatment, as well as increase in solution time. The ductility is controlled to a great extent by the changes in the Si particle morphology and size brought about by the modification methods used, as well as the spheroidization due to solution heat treatment. As discussed in Chapter 5, the development of the Si particle characteristics during solution treatment varied from casting type to casting type depending upon the modification process used and the particle characteristics in the as-cast condition. Thus, the ductility for the NM casting samples is expected to contribute to improve with increasing solution time, as the Si particle pass through the stages of fragmentation and spheroidization, then remain constant or decrease somewhat depending upon the amount of coarsening that has taken place after 80 h of solution treatment.

Both the SrM and SrMTT samples display the highest percentage elongations in the as-cast condition at the highest cooling rate (37 μm). The drop in ductility in the SrM

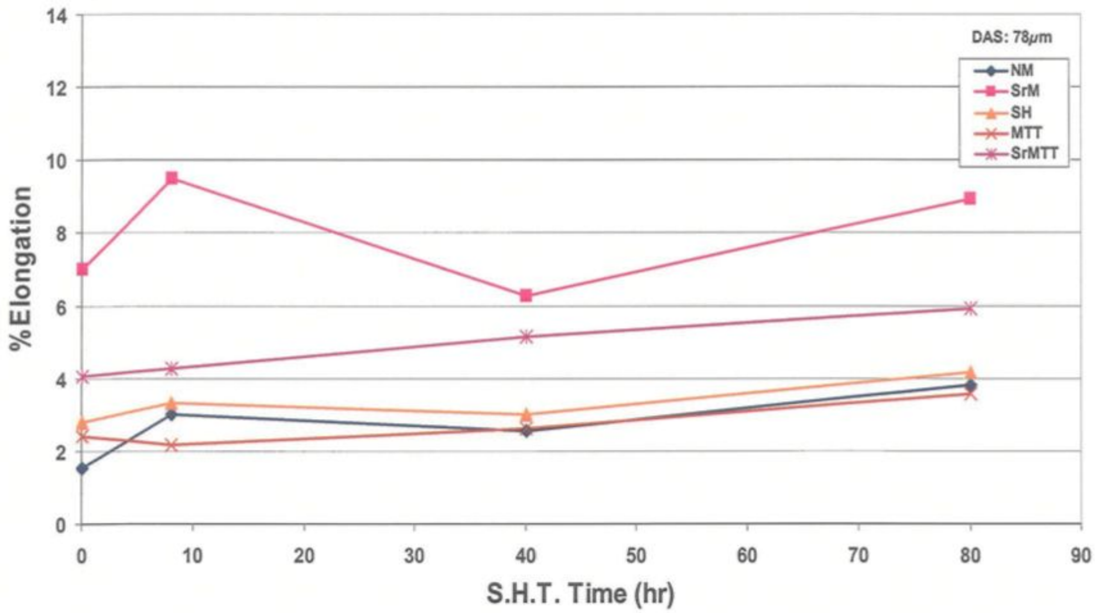


(a)



(b)

Figure 6.6 Effect of solution heat treatment on percentage elongation of heat-treated samples obtained from various A356.2 alloy castings at: (a) 37 μm, (b) 62 μm, and (c) 78 μm DAS levels.



(c)

Figure 6.6 Effect of solution heat treatment on percentage elongation of heat-treated samples obtained from various A356.2 alloy castings at: (a) 37 μm, (b) 62 μm, and (c) 78 μm DAS levels.

casting samples after 40 h of solution treatment is attributed to the increase in the Mg content of the SrM casting from which these samples were prepared. As was observed in the case of Figure 6.5(b), corresponding to the lowering of the ductility, the UTS exhibited higher values of the same samples. The very fine eutectic Si structure achieved in the SrMTT casting is responsible for the high ductility of ~ 12%, which is maintained even at DAS of 62 μm. The drop in ductility with solution treatment is probably the result of coarsening.

In general, in samples exhibiting low ductilities which is mostly the case at the lowest cooling rate (78 μm DAS), as for example in the MTT and SH castings, the ductility improves progressively with prolonged solution treatment. This is also observed to be the case of the SrMTT casting sample corresponding to the 78 μm DAS level.

To summarize, therefore, among the various modification methods used, the SrM and SrMTT modification processes provide the highest ductilities for A356.2 alloy in the as-cast condition and at the 37 μm DAS level. Solution treatment is useful in increasing the ductility of samples exhibiting low ductilities in the as-cast condition, irrespective of the casting-type. The improvement is observed to increase as the solution time is increased.

6.3.1 Quality Index

As described in Chapter 2, in section 2.8.5, the quality index, Q, defined as Q = UTS + k logEl was introduced by Drouzy *et al.*[71] as a means to better interpret tensile test data. Rather than using ductility directly, they defined, instead, the quality index Q, in terms of the ultimate tensile strength and percent elongation (El > 1%) and a coefficient k, having a value of 150 MPa for the Al-7Si G06 alloy studied by them. This alloy is equivalent in composition to A357 alloy without beryllium.

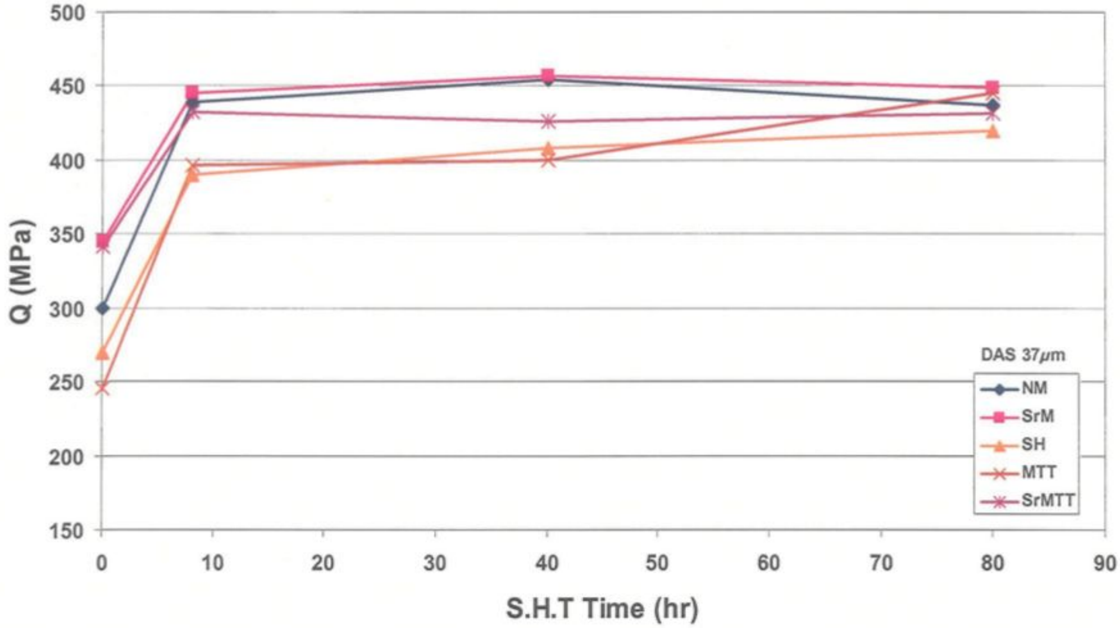
In view of the tensile properties of the different A356.2 alloy casting studied in the present work, it would be interesting to see how the different factors, *viz.*, cooling rate, modification process, superheat and solution heat treatment would affect the 'quality' of the alloy or casting, in terms of the quality index.

Accordingly, the Q values for the various samples were calculated based on the equation:

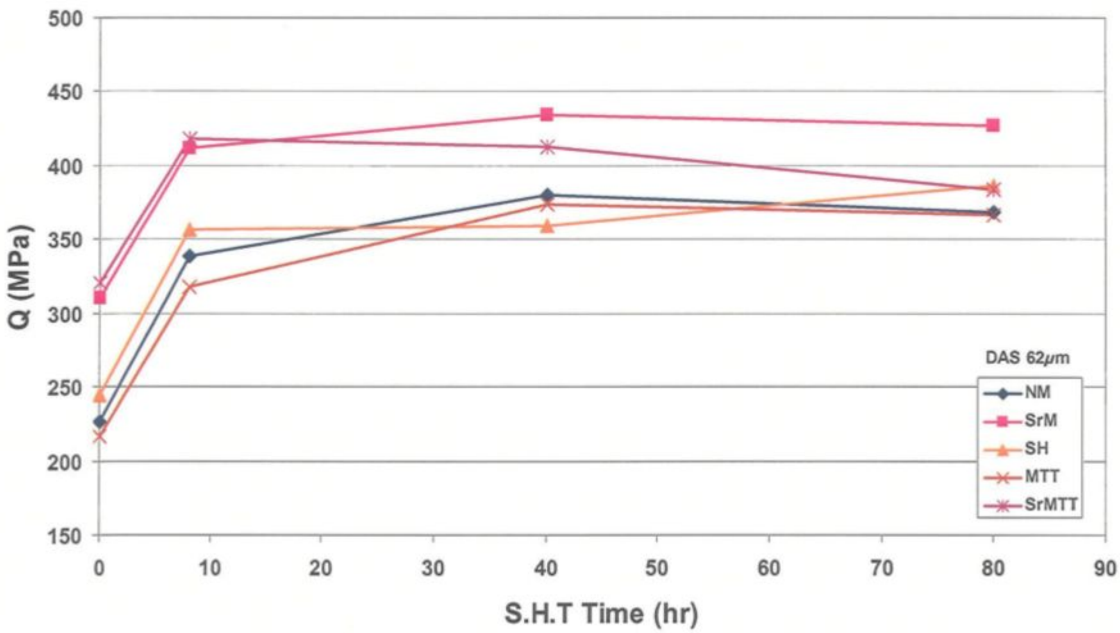
$$\text{Quality index} = \text{UTS (MPa)} + 150 \log (\text{EL}\%)$$

with Q expressed in MPa units. The results are plotted in Figure 6.7 for the various A356.2 alloy casting types, at each of the three DAS levels. As can be seen, a much more consistent behavior is observed when the quality index is used as an indication of the tensile properties than the individual properties themselves. Whatever the casting type, the response to solution treatment follows the same bend. The 'quality' of the alloy is significantly increased by about 100 to 125 MPa after 8 h solution treatment, at teach DAS level. Obviously, the finer microstructures at the 37 μm DAS level display a somewhat superior quality. After 8 h, the Q values remain more or less steady with further increase solution time up to 80 h.

From the application point of view, a compromise is often sought between the strength and ductility requirements of a casting prepared for a specific application. The Q plots of Figure 6.7, are a very convenient means to determine this. As can be seen, the Sr and SrMTT castings display the best 'quality' overall, among all the casting types. The lower 'quality' of the SH and MTT castings would probably be attributed to particle clustering effects and inhomogeneous distribution of the Si particles in their microstructures.

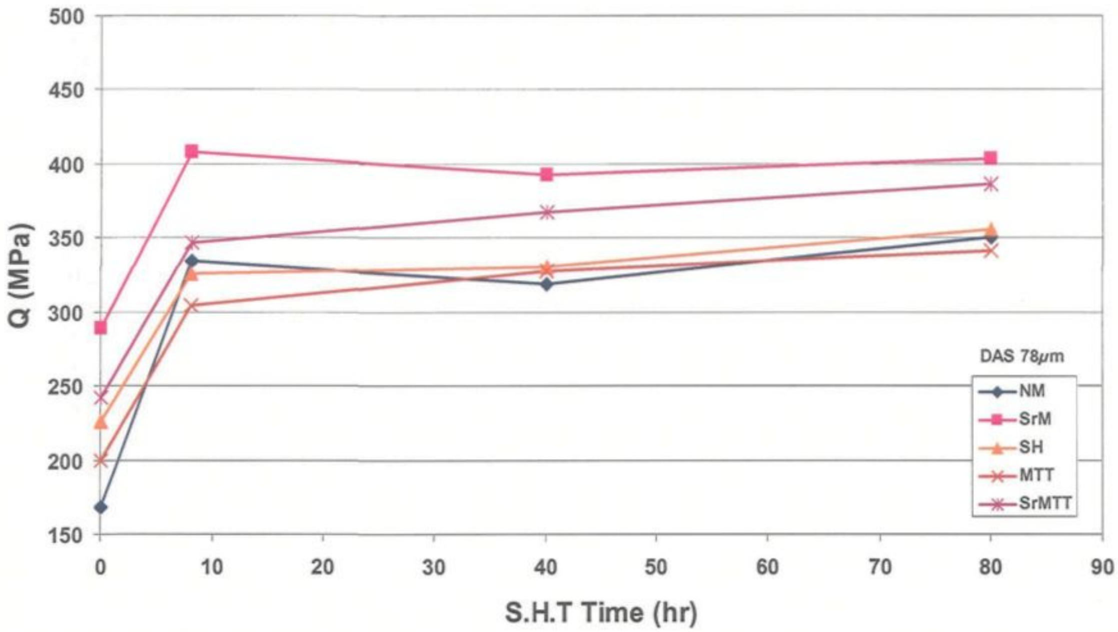


(a)



(b)

Figure 6.7 Effect of solution heat treatment on quality index of heat-treated samples obtained from various A356.2 alloy castings at: (a) 37μm, (b) 62μm, and (c) 78μm DAS levels.



(c)

Figure 6.7 Effect of solution heat treatment on quality index of heat-treated samples obtained from various A356.2 alloy castings at: (a) 37 μm, (b) 62 μm, and (c) 78 μm DAS levels.

CHAPTER 7

CONCLUSIONS

CHAPTER 7

CONCLUSIONS

A study of the effect of cooling rate, strontium modification, superheat treatment, melt thermal treatment, and solution heat treatment on the characteristics of eutectic Si particles in A356.2 alloy was carried out. The effect on the mechanical properties was also investigated through a study of the tensile properties. Based on the results obtained from the microstructural analysis and tensile testing, the following may be concluded:

1. The acicular eutectic silicon observed in non-modified A356.2 alloy can be modified using various means such as Sr-modification, superheat, melt thermal treatment (MTT) and a combination of Sr-modification and MTT. Strontium modification, superheat and Sr-modified-MTT processed castings provide fine eutectic Si particles, the SrMTT process giving the best modification results. The MTT process alone provides a moderate amount of modification.

2. Compared to all casting types, the SrMTT casting shows the best results in that not only the Si particle sizes are the smallest among all the castings, but these values remain approximately constant over the ranges of cooling rates studied. This has great significance from an application point of view, as cast parts often contain sections of ranging thickness, and the use of an SrMTT processed Al-Si alloy melt

would ensure a relatively uniform eutectic Si particle size throughout the casting and, hence, guarantee its overall properties.

3. Both size and morphology of the eutectic silicon particles are affected by the modification process used. The SrM, SH and SrMTT castings show well modified fibrous Si particles, whereas the MTT casting exhibits Si particles that, although refined to a certain extent, still retain their acicular morphology.

4. Cooling rate affects the eutectic Si particle size in that a higher cooling rate produces finer Si particles. However, within the range of cooling rates provided by the end-chill mold used in this work, the cooling rate does not affect the morphology of the Si particles.

5. During solution heat treatment at 540°C, the eutectic Si particles undergo fragmentation, spheroidization, and coarsening, affecting the Si particle morphology. The spheroidization process is determined by the size and morphology of the Si particles in the as-cast condition. The Sr-modified, superheat and SrMTT processed castings with their refined Si partcles require much less solution treatment time for the spheroidization process to take place that do the non-modified (NM) and MTT castings.

6. An analysis of the tensile test data for the various A356.2 alloy castings (NM, SRM, SH MTT and SrMTT) in the as-cast condition shows that both cooling rate

and modification process have no influence on the yield strength. The tensile strength can be improved by SrM, SH, and SrMTT treatment. The MTT process has no apparent influence on the UTS. Both SrM and SrMTT treatment can greatly improve the percentage elongation of A356 alloy castings. SH and MTT processes do not show any significant improvement in the percentage elongation. Higher percentage elongation can be produced at higher cooling rate.

7. The effect of solution heat treatment on the tensile properties of the various A356.2 alloy castings can be summed up as follows.

    i) The yield strength of the various A356.2 alloy castings is significantly improved after 8 h solution heat treatment due to the precipitation of Mg_2Si. The yield strength remains more or less the same with further increase in solution treatment time to 80 h.

    ii) The UTS is also greatly improved within the first 8 h of solution heat treatment and then remains at the same level as solution time increases up to 80h. The improvement is attributed to Mg_2Si precipitation, dissolution of Si within the Al-matrix, and change in the Si particle morphology (spheroidization).

    iii) The ductility of the NM, SH, and MTT processed A356.2 alloy castings can be improved considerably with solution heat treatment (*e.g.* from ~6% in the non-modified casting in the as-cast condition to

~10% after 80 h solution treatment). However, that of the SrM and SrMTT processed castings shows no remarkable improvement.

8. The quality index shows that considering about the combination effect on UTS and EL%, SrM and SrMTT processes can greatly improve the tensile properties of A356 alloy compared to the NM process. On the other hand, although SH and MTT processes can refine the eutectic Si particle, these two modification methods do not show any remarkable improvement effect on the tensile properties of A356 alloy.

Recommendations for Future Work

- Based on the results obtained in this study, it would be interesting to apply the MTT process to alloys using very low quantities of strontium (in the range of 30-50 ppm), to investigate the fundamental phenomena underlying the MTT modification process.
- It would be useful to expand the study of the mechanical properties to include impact and fatigue properties as well.

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APPENDIX 1

Effect of Solution Heat Treatment on the Eutectic Si Particle Characteristics Observed in Various A356.2 Alloy Casting Types

Image Analysis Data

Silicon Particles Analysis (Non-modified)

Magnification:	500 X	Field Area (µm2) :	22608	Updated:
No. of Fields:	40	Total Area (µm2) :	9,04328E+05	2005-09-30

Level	Sample ID	Area (µm2)			Length (µm)			Roundness (%)			Aspect Ratio			Total # Features	Si Particle Density
		Ave.	SD		Ave.	SD		Ave.	SD		Ave.	SD			
Level 1 (10mm)	#1- 0h	25,33	28,460		11,960	11,390		45,24	28,42		2,642	1,365		4066	4496
		Range	Qty.	Percent	Range	Qty.	Percent	Range	Qty.	Percent	Range	Qty.	Percent		
	Distri-bution	0-6	1131	27,82%	0-4	1021	25,11%	12.8-16.8	273	6,71%	1.46-1.92	815	20,04%		
		6-12	599	14,73%	4-8	911	22,41%	16.8-20.8	264	6,49%	1.00-1.46	671	16,50%		
		12-18	471	11,58%	8-12	690	16,97%	8.92-12.8	262	6,44%	1.92-2.38	663	16,31%		
Level 2 (50mm)	#43- 0h	26,32	29,110		13,570	12,850		42,82	28,48		3,127	1,743		5042	5575
	Distri-bution	0-6	1426	28,28%	0-4	1246	24,71%	12.8-16.8	401	7,95%	1.46-1.92	788	15,63%		
		6-12	684	13,57%	4-8	900	17,85%	16.8-20.8	388	7,70%	1.92-2.38	702	13,92%		
		12-18	532	10,55%	8-12	797	15,81%	20.8-24.7	355	7,04%	1.00-1.46	627	12,44%		
level 3 (100mm)	#85- 0h	27,320	30,090		14,620	13,930		40,80	27,24		3,303	1,831		4289	4743
	Distri-bution	0-6	1102	25,69%	0-4	926	21,59%	12.8-16.8	371	8,65%	1.46-1.92	611	14,25%		
		6-12	641	14,95%	4-8	805	18,77%	8.92-12.8	346	8,07%	1.92-2.38	586	13,66%		
		12-18	447	10,42%	8-12	681	15,88%	16.8-20.8	327	7,62%	2.38-2.84	466	10,87%		
Level 1 (10mm)	#2- 2h	16,850	18,520		7,254	6,215		68,11	24,03		2,187	1,085		6391	7067
	Distri-bution	0-6	1903	29,78%	0-4	2293	35,88%	96-100	672	10,51%	1.00-1.46	1768	27,66%		
		6-12	1551	24,27%	4-8	2075	32,47%	88.1-92.0	578	9,04%	1.46-1.92	1587	24,83%		
		12-18	938	14,68%	8-12	1012	15,83%	84.1-88.1	518	8,11%	1.92-2.38	985	15,41%		
Level 2 (50mm)	#44- 2h	17,790	20,390		8,792	7,645		58,95	25,97		2,752	1,513		5354	5920
	Distri-bution	0-6	1643	30,69%	0-4	1637	30,58%	88.1-92.0	347	6,48%	1.46-1.92	986	18,42%		
		6-12	1157	21,61%	4-8	1540	28,76%	96.0-100	334	6,24%	1.00-1.46	944	17,63%		
		12-18	805	15,04%	8-12	939	17,54%	84.1-88.1	299	5,58%	1.92-2.38	797	14,89%		
level 3 (100mm)	#86- 2h	21,700	24,940		10,430	9,640		55,22	27,14		2,890	1,654		4439	4909
	Distri-bution	0-6	1277	28,77%	0-4	1248	28,11%	88.1-92.0	272	6,13%	1.00-1.46	760	17,12%		
		6-12	826	18,61%	4-8	1112	25,05%	96.0-100	248	5,59%	1.46-1.92	760	17,12%		
		12-18	552	12,44%	8-12	731	16,47%	16.8-20.8	247	5,56%	1.92-2.38	604	13,61%		
Level 1 (10mm)	#3- 4h	9,067	11,270		5,765	4,796		62,98	24,04		2,646	1,425		5676	6276
	Distri-bution	0-6	3121	54,99%	0-4	2676	47,15%	96.0-100	441	7,77%	1.46-1.92	1090	19,20%		
		6-12	1270	22,37%	4-8	1720	30,30%	84.1-88.1	358	6,31%	1.00-1.46	1001	17,64%		
		12-18	540	9,51%	8-12	755	13,30%	80.2-84.1	357	6,29%	1.92-2.38	975	17,18%		
Level 2 (50mm)	#45- 4h	16,680	19,190		8,045	7,133		62,82	25,24		2,560	1,418		4905	5424
	Distri-bution	0-6	1617	32,97%	0-4	1674	34,13%	84.1-88.1	376	7,67%	1.46-1.92	1036	21,12%		
		6-12	1125	22,94%	4-8	1445	29,46%	88.1-92.0	349	7,12%	1.00-1.46	983	20,04%		
		12-18	664	13,54%	8-12	814	16,60%	96.0-100	338	6,89%	1.92-2.38	796	16,23%		
level 3 (100mm)	#87- 4h	20,640	23,610		9,370	8,781		60,58	26,33		2,580	1,444		4514	4992
	Distri-bution	0-6	1390	30,79%	0-4	1487	32,94%	96.0-100	344	7,62%	1.00-1.46	948	21,00%		
		6-12	774	17,15%	4-8	1116	24,72%	88.1-92.0	296	6,56%	1.46-1.92	901	19,96%		
		12-18	571	12,65%	8-12	717	15,88%	84.1-88.1	295	6,54%	1.92-2.38	698	15,46%		

Level 1 (10mm)	#4- 6h	14,120	15,250		6,497	5,204		70,45	21,86		2,222	1,116		5143	5687
	Distri-bution	0-6	1712	33,29%	0-4	1946	37,84%	88.1-92.0	449	8,73%	1.00-1.46	1360	26,44%		
		6-12	1380	26,83%	4-8	1860	36,17%	84.1-88.1	464	9,02%	1.46-1.92	1259	24,48%		
		12-18	787	15,30%	8-12	750	14,58%	92.0-96.0	452	8,79%	1.92-2.38	843	16,39%		
Level 2 (50mm)	#46- 6h	18,830	20,210		8,693	7,284		61,97	24,85		2,663	1,453		4431	4900
	Distri-bution	0-6	1134	25,59%	4-8	1388	31,32%	88.1-92.0	352	7,94%	1.46-1.92	870	19,63%		
		6-12	1040	23,47%	0-4	1266	28,57%	84.1-88.1	299	6,75%	1.00-1.46	831	18,75%		
		12-18	688	15,53%	8-12	788	17,78%	92.0-96.0	265	5,98%	1.92-2.38	671	15,14%		
level 3 (100mm)	#88- 6h	21,420	23,310		9,546	8,625		60,83	26,18		2,634	1,520		4471	4944
	Distri-bution	0-6	1197	26,77%	0-4	1305	29,19%	88.1-92.0	312	6,98%	1.00-1.46	970	21,70%		
		6-12	860	19,24%	4-8	1259	28,16%	96.0-100	308	6,89%	1.46-1.92	875	19,57%		
		12-18	612	13,69%	8-12	706	15,79%	84.1-88.1	297	6,64%	1.92-2.38	647	14,47%		
Level 1 (10mm)	#5- 8h	16,010	17,040		7,021	5,803		69,60	22,56		2,219	1,122		5091	5630
	Distri-bution	0-6	1499	29,44%	4-8	1785	35,06%	88.1-92.0	506	9,94%	1.00-1.46	1412	27,74%		
		6-12	1255	24,65%	0-4	1783	35,02%	96.0-100	458	9,00%	1.46-1.92	1184	23,26%		
		12-18	814	15,99%	8-12	834	16,38%	84.1-88.1	436	8,56%	1.92-2.38	821	16,13%		
Level 2 (50mm)	#47- 8h	19,290	20,650		8,145	6,922		66,42	23,84		2,380	1,281		4774	5279
	Distri-bution	0-6	1266	26,52%	4-8	1506	31,55%	88.1-92.0	399	8,36%	1.00-1.46	1115	23,36%		
		6-12	1008	21,11%	0-4	1477	30,94%	84.1-88.1	384	8,04%	1.46-1.92	1088	22,79%		
		12-18	695	14,56%	8-12	844	17,68%	96.0-100	365	7,65%	1.92-2.38	752	15,75%		
level 3 (100mm)	#89- 8h	22,730	24,790		9,409	8,708		63,58	25,49		2,486	1,435		4113	4548
	Distri-bution	0-6	1079	26,23%	0-4	1238	30,10%	88.1-92.0	331	8,05%	1.00-1.46	962	23,39%		
		6-12	725	17,63%	4-8	1111	27,01%	96.0-100	323	7,85%	1.46-1.92	906	22,03%		
		12-18	529	12,86%	8-12	675	16,41%	88.1-92.0	297	7,22%	1.92-2.38	623	15,15%		
Level 1 (10mm)	#6- 10h	13,890	15,220		6,798	5,328		66,91	22,90		2,478	1,320		4653	5145
	Distri-bution	0-6	1584	34,04%	4-8	1652	35,50%	88.1-92.0	397	8,53%	1,46-1,92	998	21,45%		
		6-12	1264	27,17%	0-4	1631	35,05%	92,0-96,0	351	7,54%	1,00-1,46	974	20,93%		
		12-18	691	14,85%	8-12	772	16,59%	80,2-84,1	335	7,20%	1,92-2,38	801	17,21%		
Level 2 (50mm)	#48- 10h	17,530	19,000		8,016	6,648		64,58	23,90		2,573	1,390		4640	5131
	Distri-bution	0-6	1294	27,89%	4-8	1546	33,32%	88.1-92.0	390	8,41%	1,46-1,92	976	21,03%		
		6-12	1133	24,42%	0-4	1425	30,71%	84.1-88.1	340	7,33%	1,00-1,46	913	19,68%		
		12-18	687	14,81%	8-12	792	17,07%	80,2-84,1	314	6,77%	1.92-2.38	734	15,82%		
level 3 (100mm)	#90- 10h	24,270	24,880		10,140	8,984		61,73	25,58		2,649	1,487		3830	4235
	Distri-bution	0-6	810	21,15%	4-8	1134	29,61%	88.1-92.0	293	7,65%	1,46-1,92	782	20,42%		
		6-12	731	19,09%	0-4	936	24,44%	96.0-100	257	6,71%	1,00-1,46	761	19,87%		
		12-18	529	13,81%	8-12	683	17,83%	84,1-88,1	242	6,32%	1,92-2,38	576	15,04%		
Level 1 (10mm)	#7- 12h	17,340	17,360		7,380	5,742		69,74	22,26		2,284	1,193		4565	5048
	Distri-bution	6-12	1160	25,41%	4-8	1717	37,61%	88.1-92.0	433	9,49%	1,00-1,46	1148	25,15%		
		0-6	1138	24,93%	0-4	1386	30,36%	84,1-88,1	395	8,65%	1,46-1,92	1133	24,82%		
		12-18	736	16,12%	8-12	782	17,13%	80,2-84,1	377	8,26%	1,92-2,38	767	16,80%		
Level 2 (50mm)	#49- 12h	23,160	22,970		8,711	6,974		67,91	22,95		2,307	1,194		4579	5063
	Distri-bution	6-12	940	20,53%	4-8	1606	35,07%	84,1-88,1	423	9,24%	1,46-1,92	1127	24,61%		
		0-6	841	18,37%	0-4	1114	24,33%	88,1-92,0	403	8,80%	1,00-1,46	1090	23,80%		
		12-18	750	16,38%	8-12	866	18,91%	92,0-96,0	335	7,32%	1.92-2.38	752	16,42%		
level 3 (100mm)	#91- 12h	27,790	29,290		10,070	9,403		66,76	24,90		2,290	1,258		3910	4324
	Distri-bution	0-6	983	25,14%	0-4	1128	28,85%	96,0-100	395	10,10%	1,00-1,46	1050	26,85%		
		6-12	491	12,56%	4-8	1014	25,93%	88,1-92,0	360	9,21%	1,46-1,92	917	23,45%		
		12-18	420	10,74%	8-12	662	16,93%	84,1-88,1	283	7,24%	1,92-2,38	624	15,96%		

Level 1 (10mm)	#8- 14h	16,130	17,090		6,712	5,108		72,37	20,66		2,176	1,097		3846	4253
	Distri-bution	0-6	1101	28,63%	4-8	1616	42,02%	88.1-92.0	417	10,84%	1,00-1,46	1141	29,67%		
		6-12	1074	27,93%	0-4	1319	34,30%	84,1-88,1	388	10,09%	1,46-1,92	980	25,48%		
		12-18	661	17,19%	8-12	625	16,25%	92,0-96,0	370	9,62%	1,92-2,38	686	17,84%		
Level 2 (50mm)	#50- 14h	18,470	18,390		7,932	6,253		67,03	22,70		2,470	1,318		4310	4766
	Distri-bution	6-12	1244	28,86%	4-8	1833	42,53%	88,1-92,0	470	10,90%	1,46-1,92	1090	25,29%		
		0-6	1168	27,10%	0-4	1374	31,88%	84,1-88,1	428	9,93%	1,00-1,46	1072	24,87%		
		12-18	814	18,89%	8-12	881	20,44%	92,0-96,0	361	8,38%	1.92-2.38	796	18,47%		
level 3 (100mm)	#92- 14h	27,630	26,560		9,571	7,797		68,88	22,76		2,274	1,163		4402	4868
	Distri-bution	0-6	784	17,81%	4-8	1678	38,12%	88,1-92,0	489	11,11%	1,00-1,46	1237	28,10%		
		6-12	775	17,61%	0-4	1028	23,35%	84,1-88,1	444	10,09%	1,46-1,92	1165	26,47%		
		12-18	751	17,06%	8-12	926	21,04%	92,0-96,0	420	9,54%	1,92-2,38	809	18,38%		
Level 1 (10mm)	#9- 16h	23,380	20,890		7,726	5,463		74,90	20,00		1,918	0,829		4996	5525
	Distri-bution	6-12	955	19,12%	4-8	2143	42,89%	88.1-92.0	665	13,31%	1,00-1,46	1722	34,47%		
		0-6	889	17,79%	0-4	1089	21,80%	92,0-96,0	632	12,65%	1,46-1,92	1408	28,18%		
		12-18	747	14,95%	8-12	992	19,86%	84,1-88,1	551	11,03%	1,92-2,38	801	16,03%		
Level 2 (50mm)	#51- 16h	24,860	24,160		8,645	6,644		73,24	20,88		2,028	0,953		4711	5209
	Distri-bution	12-18	772	16,39%	4-8	1881	39,93%	88,1-92,0	593	12,59%	1,00-1,46	1453	30,84%		
		6-12	719	15,26%	0-4	933	19,80%	92,0-96,0	505	10,72%	1,46-1,92	1280	27,17%		
		0-6	691	14,67%	8-12	929	19,72%	84,1-88,1	463	9,83%	1.92-2.38	796	16,90%		
level 3 (100mm)	#93- 16h	27,430	25,990		10,420	8,508		63,32	24,14		2,596	1,432		3620	4003
	Distri-bution	6-12	693	19,14%	4-8	1217	33,62%	88,1-92,0	301	8,31%	1,46-1,92	743	20,52%		
		0-6	512	14,14%	8-12	689	19,03%	84,1-88,1	277	7,65%	1,00-1,46	703	19,42%		
		12-18	506	13,98%	0-4	657	18,15%	92,0-96,0	238	6,57%	1,92-2,38	592	16,35%		
Level 1 (10mm)	#10- 18h	18,900	18,470		7,044	5,168		73,42	20,18		2,009	0,927		4609	5097
	Distri-bution	6-12	1087	23,58%	4-8	1955	42,42%	88.1-92.0	570	12,37%	1,00-1,46	1448	31,42%		
		0-6	1007	21,85%	0-4	1312	28,47%	84,1-88,1	468	10,15%	1,46-1,92	1275	27,66%		
		12-18	760	16,49%	8-12	758	16,45%	92,0-96,0	448	9,72%	1,92-2,38	729	15,82%		
Level 2 (50mm)	#52- 18h	22,830	22,120		8,275	6,450		70,84	21,22		2,195	1,077		4062	4492
	Distri-bution	6-12	804	19,79%	4-8	1611	39,66%	88,1-92,0	441	10,86%	1,00-1,46	1070	26,34%		
		0-6	732	18,02%	0-4	941	23,17%	84,1-88,1	358	8,81%	1,46-1,92	1002	24,67%		
		12-18	697	17,16%	8-12	722	17,77%	92,0-96,0	353	8,69%	1.92-2.38	709	17,45%		
level 3 (100mm)	#94- 18h	28,300	26,020		9,731	7,540		68,27	22,22		2,349	1,242		3128	3459
	Distri-bution	6-12	550	17,58%	4-8	1152	36,83%	92,0-96,0	296	9,46%	1,00-1,46	741	23,69%		
		12-18	447	14,29%	8-12	614	19,63%	84,1-88,1	290	9,27%	1,46-1,92	721	23,05%		
		0-6	409	13,08%	0-4	548	17,52%	88,1-92,0	286	9,14%	1.92-2.38	523	16,72%		
Level 1 (10mm)	#11- 20h	17,540	16,930		6,684	4,740		75,09	18,64		2,015	0,904		3914	4328
	Distri-bution	6-12	1009	25,78%	4-8	1799	45,96%	88,1-92,0	452	11,55%	1,00-1,46	1184	30,25%		
		0-6	855	21,84%	0-4	1090	27,85%	84,1-88,1	426	10,88%	1,46-1,92	1097	28,03%		
		12-18	710	18,14%	8-12	625	15,97%	92,0-96,0	422	10,78%	1.92-2.38	673	17,19%		
Level 2 (50mm)	#53- 20h	19,780	20,480		8,105	6,388		66,50	22,18		2,450	1,271		3826	4231
	Distri-bution	0-6	911	23,81%	4-8	1406	36,75%	88,1-92,0	324	8,47%	1.46-1.92	852	22,27%		
		6-12	856	22,37%	0-4	1005	26,27%	84,1-88,1	304	7,95%	1.00-1.46	773	20,20%		
		12-18	609	15,92%	8-12	687	17,96%	80.2-84.1	284	7,42%	1.92-2.38	656	17,15%		
level 3 (100mm)	#95- 20h	24,810	24,990		9,797	8,149		63,59	23,95		2,602	1,414		3694	4085
	Distri-bution	6-12	729	19,73%	4-8	1246	33,73%	88.1-92.0	322	8,72%	1.46-1.92	738	19,98%		
		0-6	664	17,98%	0-4	788	21,33%	84,1-88,1	277	7,50%	1.00-1.46	706	19,11%		
		12-18	553	14,97%	8-12	684	18,52%	80.2-84.1	232	6,28%	1.92-2.38	618	16,73%		

Level 1 (10mm)	#12- 22h	17,150	17,360		6,671	4,842		73,66	19,42		2,080	0,976		4608	5095
	Distri-bution	0-6	1265	27,45%	4-8	1863	40,43%	88,1-92,0	529	11,48%	1,00-1,46	1300	28,21%		
		6-12	1004	21,79%	0-4	1466	31,81%	84,1-88,1	464	10,07%	1,46-1,92	1216	26,39%		
		12-18	790	17,14%	8-12	729	15,82%	92.0-100	424	9,20%	1.92-2.38	931	20,20%		
Level 2 (50mm)	#54- 22h	20,190	21,230		7,870	6,257		69,31	21,83		2,314	1,200		4378	4841
	Distri-bution	0-6	1045	23,87%	4-8	1598	36,50%	88,1-92,0	393	8,98%	1.46-1.92	1099	25,10%		
		6-12	885	20,21%	0-4	1207	27,57%	84,1-88,1	381	8,70%	1.00-1.46	1026	23,44%		
		12-18	708	16,17%	8-12	818	18,68%	96.0-100	344	7,86%	1.92-2.38	669	15,28%		
level 3 (100mm)	#96- 22h	22,510	22,860		8,758	7,208		66,67	22,92		2,416	1,273		3993	4415
	Distri-bution	0-6	848	21,24%	4-8	1358	34,01%	88.1-92.0	379	9,49%	1.46-1.92	906	22,69%		
		6-12	823	20,61%	0-4	1011	25,32%	84,1-88,1	321	8,04%	1.00-1.46	880	22,04%		
		12-18	569	14,25%	8-12	744	18,63%	80.2-84.1	296	7,41%	1.92-2.38	659	16,50%		
Level 1 (10mm)	#13- 24h	21,580	20,460		7,686	5,580		72,75	19,85		2,112	0,984		4111	4546
	Distri-bution	6-12	863	20,99%	4-8	1713	41,67%	88,1-92,0	517	12,58%	1,00-1,46	1148	27,93%		
		0-6	748	18,20%	0-4	990	24,08%	84,1-88,1	398	9,68%	1,46-1,92	1068	25,98%		
		12-18	704	17,12%	8-12	790	19,22%	92.0-100	367	8,93%	1.92-2.38	717	17,44%		
Level 2 (50mm)	#55- 24h	21,130	21,370		7,890	6,317		70,27	21,82		2,197	1,082		4701	5198
	Distri-bution	0-6	1139	24,23%	4-8	1731	36,82%	88,1-92,0	499	10,61%	1.46-1.92	1221	25,97%		
		6-12	870	18,51%	0-4	1289	27,42%	96.0-100	405	8,62%	1.00-1.46	1188	25,27%		
		12-18	712	15,15%	8-12	831	17,68%	84.1-88.1	398	8,47%	1.92-2.38	794	16,89%		
level 3 (100mm)	#97- 24h	25,980	25,910		9,271	7,647		67,81	22,84		2,333	1,197		4007	4431
	Distri-bution	0-6	819	20,44%	4-8	1319	32,92%	84.1-88.1	372	9,28%	1,00-1,46	964	24,06%		
		6-12	606	15,12%	0-4	934	23,31%	88.1-92.0	364	9,08%	1,46-1,92	904	22,56%		
		12-18	563	14,05%	8-12	761	18,99%	96.0-100	314	7,84%	1.92-2.38	669	16,70%		
Level 1 (10mm)	#14- 26h	17,740	17,630		6,987	5,096		71,72	19,37		2,169	1,007		4866	5381
	Distri-bution	0-6	1234	25,36%	4-8	1937	39,81%	88,1-92,0	496	10,19%	1.46-1.92	1291	26,53%		
		6-12	1131	23,24%	0-4	1451	29,82%	80.2-84.1	433	8,90%	1.00-1.46	1183	24,31%		
		12-18	751	15,43%	8-12	871	17,90%	84.1-88.1	407	8,36%	1.92-2.38	914	18,78%		
Level 2 (50mm)	#56- 26h	23,340	22,090		8,529	6,489		68,94	21,66		2,266	1,122		4207	4652
	Distri-bution	6-12	799	18,99%	4-8	1621	38,53%	88,1-92,0	438	10,41%	1.46-1.92	1034	24,58%		
		0-6	735	17,47%	0-4	895	21,27%	84.1-88.1	393	9,34%	1.00-1.46	1012	24,06%		
		12-18	701	16,66%	8-12	850	20,20%	92.0-96.0	299	7,11%	1.92-2.38	737	17,52%		
level 3 (100mm)	#98- 26h	25,510	25,940		9,548	8,217		66,07	23,53		2,431	1,286		3992	4414
	Distri-bution	0-6	818	20,49%	4-8	1323	33,14%	88.1-84.1	336	8,42%	1.46-1.92	902	22,60%		
		6-12	695	17,41%	0-4	942	23,60%	84.1-88.1	315	7,89%	1.00-1.146	847	21,22%		
		12-18	569	14,25%	8-12	699	17,51%	96.0-100	277	6,94%	1.92-2.38	655	16,41%		
Level 1 (10mm)	#15- 28h	17,070	16,790		6,652	4,709		74,19	18,54		2,063	0,942		4941	5464
	Distri-bution	0-6	1245	25,20%	4-8	2065	41,79%	88,1-92,0	567	11,48%	1.00-1.46	1358	27,48%		
		6-12	1190	24,08%	0-4	1511	30,58%	84.1-88.1	500	10,12%	1.46-1.92	1288	26,07%		
		12-18	842	17,04%	8-12	833	16,86%	92.0-96.0	423	8,56%	1.92-2.38	892	18,05%		
Level 2 (50mm)	#57- 28h	22,870	21,780		8,223	5,970		71,19	20,07		2,226	1,070		4719	5218
	Distri-bution	6-12	1021	21,64%	4-8	1923	40,75%	88,1-92,0	501	10,62%	1.46-1.92	1182	25,05%		
		12-18	761	16,13%	0-4	986	20,89%	84.1-88.1	457	9,68%	1.00-1.46	1151	24,39%		
		0-6	744	15,77%	8-12	950	20,13%	92.0-96.0	398	8,43%	1.92-2.38	858	18,18%		
level 3 (100mm)	#99- 28h	27,660	25,410		9,389	7,165		69,64	21,53		2,299	1,170		4237	4685
	Distri-bution	12-18	700	16,52%	4-8	1602	37,81%	88.1-92.0	470	11,09%	1.00-1.46	1055	24,90%		
		6-12	677	15,98%	8-12	873	20,60%	84.1-88.1	361	8,52%	1.46-1.92	963	22,73%		
		0-6	578	13,64%	0-4	746	17,61%	92.0-96.0	340	8,02%	1.92-2.38	727	17,16%		

Level 1 (10mm)	#16- 30h	24,450	22,680		7,943	5,703		74,18	19,21		2,009	0,891		4189	4632
	Distri-bution	0-6	718	17,14%	4-8	1715	40,94%	88,1-92,0	519	12,39%	1.00-1.46	1293	30,87%		
		6-12	695	16,59%	0-4	916	21,87%	84.1-88.1	427	10,19%	1.46-1.92	1121	26,76%		
		12-18	675	16,11%	8-12	864	20,63%	92.0-96.0	410	9,79%	1.92-2.38	722	17,24%		
Level 2 (50mm)	#58- 30h	25,160	23,730		8,539	6,420		71,43	20,72		2,156	1,028		4742	5244
	Distri-bution	12-18	795	16,77%	4-8	1870	39,43%	88.1-92.0	518	10,92%	1.00-1.46	1270	26,78%		
		0-6	777	16,39%	8-12	1000	21,09%	84.1-88.1	440	9,28%	1.46-1.92	1198	25,26%		
		6-12	773	16,30%	0-4	969	20,43%	92.0-96.0	401	8,46%	1.92-2.38	856	18,05%		
level 3 (100mm)	#100- 30h	26,760	25,500		9,246	7,380		69,64	21,59		2,266	1,105		4528	5007
	Distri-bution	0-6	767	16,94%	4-8	1573	34,74%	88.1-92.0	414	9,14%	1.00-1.46	1133	25,02%		
		6-12	725	16,01%	0-4	975	21,53%	84.1-88.1	394	8,70%	1.46-1.92	1052	23,23%		
		12-18	659	14,55%	8-12	874	19,30%	92.0-96.0	370	8,17%	1.92-2.38	782	17,27%		
Level 1 (10mm)	#17- 32h	18,280	17,450		7,032	4,968		72,26	18,99		2,111	0,944		4516	4994
	Distri-bution	6-12	1057	23,41%	4-8	1927	42,67%	88,1-92,0	467	10,34%	1.00-1.46	1193	26,42%		
		0-6	975	21,59%	0-4	1237	27,39%	84.1-88.1	465	10,30%	1.46-1.92	1189	26,33%		
		12-18	884	19,57%	8-12	818	18,11%	80,2-84,1	416	9,21%	1.92-2.38	820	18,16%		
Level 2 (50mm)	#59- 32h	23,390	22,380		8,365	6,245		69,27	20,86		2,232	1,074		4884	5401
	Distri-bution	6-12	916	18,76%	4-8	1937	39,66%	88,1-92,0	482	9,87%	1,46-1,92	1222	25,02%		
		0-6	860	17,61%	0-4	1044	21,38%	84.1-88.1	450	9,21%	1,00-1,42	1195	24,47%		
		12-18	817	16,73%	8-12	976	19,98%	80,2-84,1	383	7,84%	1.92-2.38	844	17,28%		
level 3 (100mm)	#101- 32h	23,360	25,720		9,929	7,937		63,83	23,16		2,567	1,375		3548	3923
	Distri-bution	6-12	659	18,57%	4-8	1205	33,96%	88.1-92.0	270	7,61%	1.46-1.92	741	20,89%		
		0-6	590	16,63%	0-4	685	19,31%	84.1-88.1	260	7,33%	1.00-1.46	702	19,79%		
		12-18	524	14,77%	8-12	683	19,25%	80,2-84,1	246	6,93%	1.92-2.38	558	15,73%		
Level 1 (10mm)	#18- 34h	16,500	16,900		6,774	4,962		70,87	19,99		2,198	1,052		4618	5107
	Distri-bution	0-6	1321	28,61%	4-8	1828	39,58%	88,1-92,0	471	10,20%	1.46-1.92	1230	26,63%		
		6-12	1095	23,71%	0-4	1468	31,79%	84.1-88.1	457	9,90%	1.00-1.46	1105	23,93%		
		12-18	724	15,68%	8-12	775	16,78%	80,2-84,1	441	9,55%	1.92-2.38	813	17,61%		
Level 2 (50mm)	#60- 34h	19,160	20,980		7,607	6,156		68,79	21,26		2,331	1,174		4369	4831
	Distri-bution	0-6	1240	28,38%	4-8	1543	35,32%	88,1-92,0	397	9,09%	1,46-1,92	993	22,73%		
		6-12	927	21,22%	0-4	1339	30,65%	84.1-88.1	371	8,49%	1,00-1,42	979	22,41%		
		12-18	621	14,21%	8-12	746	17,07%	80,2-84,1	340	7,78%	1.92-2.38	812	18,59%		
level 3 (100mm)	#102- 34h	23,280	23,780		9,073	7,637		66,11	22,61		2,460	1,305		3850	4257
	Distri-bution	0-6	820	21,30%	4-8	1271	33,01%	84,1-88,1	312	8,10%	1.46-1.92	834	21,66%		
		6-12	738	19,17%	0-4	944	24,52%	88,1-92,0	311	8,08%	1.00-1.46	816	21,19%		
		12-18	544	14,13%	8-12	755	19,61%	80,2-84,1	291	7,56%	1.92-2.38	636	16,52%		
Level 1 (10mm)	#19- 36h	18,780	18,480		7,084	5,050		72,62	18,93		2,099	0,925		4778	5283
	Distri-bution	6-12	1118	23,40%	4-8	2087	43,68%	88,1-92,0	477	9,98%	1.46-1.92	1284	26,87%		
		0-6	1058	22,14%	0-4	1257	26,31%	84.1-88.1	453	9,48%	1.00-1.46	1231	25,76%		
		12-18	848	17,75%	8-12	852	17,83%	80,2-84,1	420	8,79%	1.92-2.38	904	18,92%		
Level 2 (50mm)	#61- 36h	24,860	23,140		7,618	6,543		70,50	20,92		2,203	1,081		4728	5228
	Distri-bution	6-12	888	18,78%	4-8	1862	39,38%	88,1-92,0	496	10,49%	1.00-1.46	1197	25,32%		
		12-18	756	15,99%	8-12	964	20,39%	84.1-88.1	441	9,33%	1.46-1.92	1186	25,08%		
		0-6	738	15,61%	0-4	957	20,24%	80,2-84,1	397	8,40%	1.92-2.38	821	17,36%		
level 3 (100mm)	#103- 36h	30,720	28,580		10,380	8,627		67,12	23,00		2,324	1,253		3638	4023
	Distri-bution	0-6	584	16,05%	4-8	1158	31,83%	88.1-92.0	342	9,40%	1.00-1.46	907	24,93%		
		6-12	454	12,48%	8-12	774	21,28%	84.1-88.21	309	8,49%	1.46-1.92	833	22,90%		
		12-18	447	12,29%	0-4	685	18,83%	92.0-96.0	257	7,06%	1.92-2.38	599	16,47%		

Level 1 (10mm)	#20- 38h	20,140	19,820		7,340	5,303		71,63	19,61		2,094	0,937		4819	5329
	Distri-bution	0-6	1066	22,12%	4-8	1966	40,80%	88,1-92,0	465	9,65%	1.00-1.46	1275	26,46%		
		6-12	966	20,05%	0-4	1265	26,25%	84.1-88.1	434	9,01%	1.46-1.92	1229	25,50%		
		12-18	829	17,20%	8-12	913	18,95%	80,2-84,1	404	8,38%	1.92-2.38	982	20,38%		
Level 2 (50mm)	#62- 38h	22,660	22,810		8,598	6,936		67,09	21,86		2,348	1,159		3779	4179
	Distri-bution	6-12	775	20,51%	4-8	1389	36,76%	88,1-92,0	345	9,13%	1.46-1.92	901	23,84%		
		0-6	746	19,74%	0-4	894	23,66%	84.1-88.1	301	7,97%	1.00-1.46	830	21,96%		
		12-18	594	15,72%	4-12	707	18,71%	80,2-84,1	279	7,38%	1.92-2.38	621	16,43%		
level 3 (100mm)	#104- 38h	26,550	26,180		9,679	7,952		65,83	22,69		2,402	1,261		3691	4081
	Distri-bution	6-12	661	17,91%	4-8	1212	32,84%	84.1-88.1	316	8,56%	1.00-1.46	853	23,11%		
		0-6	637	17,26%	0-4	781	21,16%	88.1-92.0	301	8,15%	1.46-1.92	796	21,57%		
		12-18	498	13,49%	8-12	753	20,40%	80.2-84.1	261	7,07%	1.92-2.38	607	16,45%		
Level 1 (10mm)	#21- 40h	18,100	18,660		6,932	5,202		72,53	19,30		2,120	0,987		4775	5280
	Distri-bution	0-6	1296	27,14%	4-8	1857	38,89%	88,1-92,0	519	10,87%	1.00-1.46	1290	27,02%		
		6-12	962	20,15%	0-4	1490	31,20%	84.1-88.1	466	9,76%	1.46-1.92	1218	25,51%		
		12-18	783	16,40%	8-12	839	17,57%	80,2-84,1	386	8,08%	1.92-2.38	880	18,43%		
Level 2 (50mm)	#63- 40h	24,350	24,090		8,685	6,890		69,17	21,09		2,276	1,126		4366	4828
	Distri-bution	0-6	815	18,67%	4-8	1660	38,02%	88,1-92,0	405	9,28%	1.46-1.92	1100	25,19%		
		6-12	739	16,93%	0-4	944	21,62%	84.1-88.1	397	9,09%	1.00-1.46	989	22,65%		
		12-18	706	16,17%	4-12	869	19,90%	80,2-84,1	323	7,40%	1.92-2.38	783	17,93%		
level 3 (100mm)	#105- 40h	25,500	25,610		9,245	7,779		67,69	22,29		2,353	1,241		4358	4819
	Distri-bution	0-6	849	19,48%	4-8	1519	34,86%	88.1-92.0	395	9,06%	1.00-1.46	1067	24,48%		
		6-12	744	17,07%	0-4	1005	23,06%	84.1-88.1	371	8,51%	1.46-1.92	986	22,63%		
		12-18	620	14,23%	8-12	792	18,17%	80.2-84.1	345	7,92%	1.92-2.38	709	16,27%		
Level 1 (10mm)	#22- 42h	19,660	17,790		6,717	4,376		77,69	17,68		1,849	0,773		5734	6341
	Distri-bution	6-12	1211	21,12%	4-8	2674	46,63%	88,1-92,0	897	15,64%	1.00-1.46	2093	36,50%		
		0-6	1114	19,43%	0-4	1505	26,25%	92.0-96.0	704	12,28%	1.46-1.92	1694	29,54%		
		12-18	1025	17,88%	8-12	1008	17,58%	84.1-88.1	652	11,37%	1.92-2.38	950	16,57%		
Level 2 (50mm)	#64- 42h	29,170	26,420		9,154	6,974		72,49	20,25		2,045	0,923		4240	4689
	Distri-bution	6-12	648	15,28%	4-8	1633	38,51%	88,1-92,0	472	11,13%	1.00-1.46	1222	28,82%		
		12-18	599	14,13%	8-12	926	21,84%	84.1-88.1	450	10,61%	1.46-1.92	1156	27,26%		
		18-24	541	12,76%	0-4	746	17,59%	92.0-96.0	438	10,33%	1.92-2.38	753	17,76%		
level 3 (100mm)	#106- 42h	30,330	25,180		9,369	6,613		72,04	20,36		2,110	0,978		3989	4411
	Distri-bution	12-18	591	14,82%	4-8	1547	38,78%	88.1-92.0	447	11,21%	1.46-1.92	1083	27,15%		
		18-24	513	12,86%	8-12	952	23,87%	92.0-96.0	426	10,68%	1.00-1.46	1073	26,90%		
		6-12	471	11,81%	0-4	583	14,62%	84.1-88.1	378	9,48%	1.92-2.38	702	17,60%		
Level 1 (10mm)	#23- 44h	18,950	18,400		6,457	4,551		79,00	16,99		1,806	0,736		5432	6007
	Distri-bution	0-6	1297	23,88%	4-8	2374	43,70%	88.1-92.0	831	15,30%	1.00-1.46	2078	38,25%		
		6-12	1035	19,05%	0-4	1653	30,43%	92.0-96.0	676	12,44%	1.46-1.92	1592	29,31%		
		12-18	925	17,03%	8-12	910	16,75%	84.1-88.1	666	12,26%	1.92-2.38	899	16,55%		
Level 2 (50mm)	#65- 44h	26,540	25,540		8,295	6,407		73,90	19,91		1,979	0,878		4400	4865
	Distri-bution	0-6	928	21,09%	4-8	1521	34,57%	88,1-92,0	539	12,25%	1.00-1.46	1368	31,09%		
		6-12	594	13,50%	0-4	1119	25,43%	84.1-88.1	459	10,43%	1.46-1.92	1279	29,07%		
		12-18	541	12,30%	8-12	890	20,23%	92.0-96.0	420	9,55%	1.92-2.38	709	16,11%		
level 3 (100mm)	#107- 44h	25,580	24,740		8,693	7,156		71,91	20,95		2,154	1,070		4280	4733
	Distri-bution	0-6	867	20,26%	4-8	1476	34,49%	88,1-92,0	461	10,77%	1.00-1.46	1167	27,27%		
		6-12	630	14,72%	0-4	1044	24,39%	84.1-88.1	413	9,65%	1.46-1.92	1100	25,70%		
		12-18	615	14,37%	8-12	874	20,42%	92.0-96.0	412	9,63%	1.92-2.38	699	16,33%		

Level 1 (10mm)	#24- 46h	18,570	17,400		6,478	4,439		78,29	16,89		1,850	0,752		4957	5481
	Distri-bution	0-6	1114	22,47%	4-8	2199	44,36%	88.1-92.0	723	14,59%	1.00-1.46	1767	35,65%		
		6-12	1064	21,46%	0-4	1470	29,66%	84.1-88.1	603	12,16%	1.46-1.92	1489	30,04%		
		12-18	867	17,49%	8-12	848	17,11%	92.0-96.2	576	11,62%	1.92-2.38	816	16,46%		
Level 2 (50mm)	#66- 46h	21,880	20,490		7,473	5,304		74,48	18,61		2,002	0,884		4526	5005
	Distri-bution	0-6	842	18,60%	4-8	1938	42,82%	88,1-92,0	584	12,90%	1.00-1.46	1369	30,25%		
		6-12	832	18,38%	0-0	1077	23,80%	84.1-88.1	502	11,09%	1.46-1.92	1259	27,82%		
		12-18	809	17,87%	8-12	892	19,71%	92.0-96.0	418	9,24%	1.92-2.38	796	17,59%		
level 3 (100mm)	#108- 46h	26,800	25,830		8,854	6,901		71,65	20,76		2,172	1,074		3914	4328
	Distri-bution	0-6	682	17,42%	4-8	1390	35,51%	88.1-92.0	436	11,14%	1.46-1.92	1043	26,65%		
		12-18	613	15,66%	0-4	859	21,95%	84.1-88.1	391	9,99%	1.00-1.46	1027	26,24%		
		6-12	577	14,74%	8-12	809	20,67%	92.0-96.0	326	8,33%	1.92-2.38	631	16,12%		
Level 1 (10mm)	#25- 48h	20,560	19,600		6,744	4,741		78,73	17,51		1,800	0,742		5050	5584
	Distri-bution	0-6	1101	21,80%	4-8	2216	43,88%	88.1-92.0	728	14,42%	1.00-1.46	1954	38,69%		
		6-12	932	18,46%	0-4	1408	27,88%	92.0-96.0	696	13,78%	1.46-1.92	1500	29,70%		
		12-18	850	16,83%	8-12	936	18,53%	84.1-88.1	579	11,47%	1.92-2.38	815	16,14%		
Level 2 (50mm)	#67- 48h	26,960	23,770		8,255	5,686		74,95	18,94		1,961	0,862		4274	4726
	Distri-bution	12-18	637	14,90%	4-8	1760	41,18%	88,1-92,0	556	13,01%	1.00-1.46	1342	31,40%		
		0-6	628	14,69%	8-12	914	21,39%	84.1-88.1	464	10,86%	1.46-1.92	1254	29,34%		
		6-12	611	14,30%	0-4	821	19,21%	92.0-96.0	446	10,44%	1.92-2.38	716	16,75%		
level 3 (100mm)	#109- 48h	30,290	28,140		9,527	7,503		71,01	21,36		2,159	1,060		3518	3890
	Distri-bution	0-6	537	15,26%	4-8	1212	34,45%	88.1-92.0	380	10,80%	1.00-1.46	1001	28,45%		
		6-12	476	13,53%	8-12	735	20,89%	84.1-88.1	338	9,61%	1.46-1.92	845	24,02%		
		12-18	466	13,25%	0-4	682	19,39%	92.0-96.0	309	8,78%	1.92-2.38	588	16,71%		
Level 1 (10mm)	#26- 50h	18,430	18,110		6,241	4,293		80,01	16,60		1,763	0,682		5377	5946
	Distri-bution	0-6	1349	25,09%	4-8	2318	43,11%	88,1-92,0	851	15,83%	1.00-1.46	2164	40,25%		
		6-12	1089	20,25%	0-4	1725	32,08%	92.0-96.0	711	13,22%	1.46-1.92	1605	29,85%		
		12-18	921	17,13%	8-12	905	16,83%	84.1-88.1	653	12,14%	1.92-2.38	808	15,03%		
Level 2 (50mm)	#68- 50h	25,900	22,830		8,115	5,703		75,36	19,03		1,949	0,849		4277	4729
	Distri-bution	12-18	649	15,17%	4-8	1750	40,92%	88.1-92.0	581	13,58%	1.00-1.46	1395	32,62%		
		0-6	648	15,15%	8-12	950	22,21%	92.0-96.0	482	11,27%	1.46-1.92	1214	28,38%		
		6-12	630	14,73%	0-4	850	19,87%	84.1-88.1	467	10,92%	1.92-2.38	727	17,00%		
level 3 (100mm)	#110- 50h	29,560	26,550		9,144	6,880		72,94	20,17		2,069	0,961		3867	4276
	Distri-bution	0-6	542	14,02%	4-8	1439	37,21%	88,1-92,0	500	12,93%	1.00-1.46	1125	29,09%		
		12-18	539	13,94%	8-12	864	22,34%	84,1-88,1	382	9,88%	1.46-1.92	1013	26,20%		
		18-24	491	12,70%	0-4	689	17,82%	92.0-96.0	362	9,36%	1.92-2.38	692	17,90%		
Level 1 (10mm)	#27- 52h	21,060	20,300		6,693	4,540		77,98	18,07		1,763	0,720		5177	5725
	Distri-bution	0-6	1219	23,55%	4-8	2181	42,13%	88,1-92,0	771	14,89%	1.00-1.46	2065	39,89%		
		6-12	874	16,88%	0-4	1500	28,97%	92.0-96.0	626	12,09%	1.46-1.92	1570	30,33%		
		12-18	810	15,65%	8-12	980	18,93%	84.1-88.1	569	10,99%	1.92-2.38	802	15,49%		
Level 2 (50mm)	#69- 52h	28,720	28,400		8,113	6,180		75,60	19,46		1,804	0,709		5059	5594
	Distri-bution	0-6	1194	23,60%	4-8	1648	32,58%	88.1-92.0	632	12,49%	1,00-1,46	1821	36,00%		
		6-12	527	10,42%	0-4	1366	27,00%	96.0-100	566	11,19%	1,46-1,92	1600	31,63%		
		12-18	520	10,28%	8-12	1070	21,15%	84.1-88.1	520	10,28%	1.92-2.38	822	16,25%		
level 3 (100mm)	#111- 52h	30,670	27,470		9,472	7,433		72,23	20,58		2,117	1,015		4067	4497
	Distri-bution	0-6	678	16,67%	4-8	1352	33,24%	88,1-92,0	465	11,43%	1,00-1,46	1127	27,71%		
		18-24	489	12,02%	8-12	953	23,43%	84.1-88.1	379	9,32%	1,46-1,92	1073	26,38%		
		12-18	472	11,61%	0-4	784	19,28%	92,0-96,0	364	8,95%	1.92-2.38	723	17,78%		

Level 1 (10mm)	#28- 54h	20,430	18,710		6,771	4,528		78,42	16,92		1,818	0,723		4834	5345
	Distri-bution	0-6	911	967,00%	4-8	2342	48,45%	88,1-92,0	745	15,41%	1,00-1,46	1745	36,10%		
		6-12	301	896,00%	0-4	1190	24,62%	84,1-88,1	607	12,56%	1,46-1,92	1550	32,06%		
		12-18	219	4,53%	8-12	828	17,13%	92.0-96.0	595	12,31%	1.92-2.38	752	15,56%		
Level 2 (50mm)	#70- 54h	25,050	23,080		7,950	5,727		75,13	19,07		1,963	0,858		4402	4868
	Distri-bution	0-6	769	17,47%	4-8	1765	40,10%	88,1-92,0	564	12,81%	1,00-1,46	1348	30,62%		
		12-18	711	16,15%	0-4	977	22,19%	92.0-96.0	483	10,97%	1,46-1,92	1329	30,19%		
		6-12	640	14,54%	8-12	942	21,40%	84.1-88.1	472	10,72%	1.92-2.38	737	16,74%		
level 3 (100mm)	#112- 54h	32,120	28,800		9,442	7,002		72,38	20,22		2,063	0,943		3979	4400
	Distri-bution	0-6	633	15,91%	4-8	1290	32,42%	88.1-92.0	441	11,08%	1,00-1,46	1149	28,88%		
		12-18	438	11,01%	8-12	960	24,13%	84.1-88.1	399	10,03%	1,46-1,92	1063	26,72%		
		18-24	422	10,61%	0-4	752	18,90%	92.0-96.0	353	8,87%	1.92-2.38	700	17,59%		
Level 1 (10mm)	#29- 56h	23,530	21,390		7,243	4,801		77,19	18,16		1,796	0,749		4902	5421
	Distri-bution	0-6	860	17,54%	4-8	2201	44,90%	88,1-92,0	731	14,91%	1,00-1,46	1867	38,09%		
		6-12	832	16,97%	0-4	1123	22,91%	84,1-88,1	621	12,67%	1,46-1,92	1569	32,01%		
		12-18	817	16,67%	8-12	1010	20,60%	92.0-96.0	578	11,79%	1.92-2.38	734	14,97%		
Level 2 (50mm)	#71- 56h	28,110	24,620		8,285	5,549		75,13	18,36		1,900	0,769		4390	4854
	Distri-bution	12-18	642	14,62%	4-8	1759	40,07%	88,1-92,0	565	12,87%	1,00-1,46	1419	32,32%		
		0-6	633	14,42%	8-12	1063	24,21%	84.1-88.1	480	10,93%	1,46-1,92	1320	30,07%		
		18-24	562	12,80%	0-4	797	18,15%	92.0-96.0	448	10,21%	1.92-2.38	779	17,74%		
level 3 (100mm)	#113- 56h	32,370	27,180		9,551	6,684		71,52	19,92		2,072	0,910		4074	4505
	Distri-bution	12-18	550	13,50%	4-8	1483	36,40%	88,1-92,0	438	10,75%	1.46-1.92	1119	27,47%		
		0-6	494	12,13%	8-12	927	22,75%	84.1-88.1	409	10,04%	1.00-1.46	1113	27,32%		
		6-12	493	12,10%	0-4	637	15,64%	92.0-96.0	373	9,16%	1.92-2.38	700	17,18%		
Level 1 (10mm)	#30- 58h	27,000	25,140		7,627	5,321		77,09	18,45		1,701	0,629		4464	4936
	Distri-bution	0-6	854	19,13%	4-8	1746	39,11%	88,1-92,0	653	14,63%	1,00-1,46	1898	42,52%		
		6-12	585	13,10%	0-4	1074	24,06%	92.0-96.0	522	11,69%	1,46-1,92	1376	30,82%		
		12-18	548	12,28%	8-12	978	21,91%	84.1-88.1	495	11,09%	1.92-2.38	686	15,37%		
Level 2 (50mm)	#72- 58h	28,070	25,350		8,322	5,948		74,03	18,52		1,867	0,733		4378	4841
	Distri-bution	0-6	751	17,15%	4-8	1615	36,89%	84.1-88.1	514	11,74%	1,00-1,46	1470	33,58%		
		12-18	556	12,70%	8-12	1077	24,60%	92.0-96.0	510	11,65%	1,46-1,92	1333	30,45%		
		18-24	544	12,43%	0-4	917	20,95%	80.2-84.1	417	9,52%	1.92-2.38	733	16,74%		
level 3 (100mm)	#114- 58h	31,570	26,670		9,443	6,667		73,02	19,37		2,079	0,957		3568	3945
	Distri-bution	12-18	486	13,62%	4-8	1403	39,32%	88,1-92,0	445	12,47%	1,00-1,46	1010	28,31%		
		18-24	474	13,28%	8-12	874	24,50%	92.0-96.0	368	10,31%	1,46-1,92	951	26,65%		
		6-12	472	13,23%	0-4	493	13,82%	84.1-88.1	340	9,53%	1.92-2.38	696	19,51%		
Level 1 (10mm)	#31- 60h	22,020	19,940		6,984	4,499		78,25	17,19		1,811	0,770		4498	4974
	Distri-bution	0-6	832	18,50%	4-8	2032	45,18%	88,1-92,0	660	14,67%	1,00-1,46	1689	37,55%		
		6-12	780	17,34%	0-4	1095	24,34%	92.0-96.0	571	12,69%	1,46-1,92	1413	31,41%		
		12-18	767	17,05%	8-12	910	20,23%	84.1-88.1	533	11,85%	1.92-2.38	696	15,47%		
Level 2 (50mm)	#73- 60h	27,320	24,580		8,404	5,665		73,88	18,51		2,011	0,872		4280	4733
	Distri-bution	12-18	658	15,37%	4-8	1741	40,68%	84.1-88.1	461	10,77%	1,00-1,46	1214	28,36%		
		6-12	614	14,35%	8-12	1005	23,48%	88.1-92.0	457	10,68%	1,46-1,92	1210	28,27%		
		0-6	596	13,93%	0-4	762	17,80%	80.2-84.1	407	9,51%	1.92-2.38	798	18,64%		
level 3 (100mm)	#115- 60h	33,770	29,600		9,689	7,375		72,97	20,13		1,984	0,867		3839	4245
	Distri-bution	0-6	585	15,24%	4-8	1254	32,66%	88,1-92,0	442	11,51%	1,00-1,46	1168	30,42%		
		18-24	401	10,45%	8-12	902	23,50%	84.1-88.1	371	9,66%	1,46-1,92	1075	28,00%		
		12-18	394	10,26%	0-4	699	18,21%	92.0-96.0	353	9,20%	1.92-2.38	694	18,08%		

	#32- 62h	22,080	19,870		6,835	4,538		79,83	17,00		1,714	0,673			
Level 1 (10mm)	Distri-bution	0-6	862	18,81%	4-8	2050	44,74%	88,1-92,0	749	16,35%	1,00-1,46	1994	43,52%	4582	5067
		6-12	845	18,44%	0-4	1191	25,99%	92.0-96.0	671	14,64%	1,46-1,92	1373	29,97%		
		12-18	711	15,52%	8-12	912	19,90%	84.1-88.1	558	12,18%	1.92-2.38	677	14,78%		
	#74- 62h	26,990	23,790		8,166	5,481		75,14	17,82		1,930	0,829			
Level 2 (50mm)	Distri-bution	12-18	553	13,34%	4-8	1772	42,76%	88.1-92.0	501	12,09%	1,00-1,46	1290	31,13%	4144	4582
		6-12	577	13,92%	8-12	974	23,50%	84.1-88.1	494	11,92%	1,46-1,92	1277	30,82%		
		0-6	576	13,90%	0-4	725	17,50%	92.0-96.0	406	9,80%	1.92-2.38	731	17,64%		
	#116- 62h	31,490	27,630		9,450	6,714		71,45	19,65		2,097	0,985			
level 3 (100mm)	Distri-bution	12-18	539	13,81%	4-8	1433	36,71%	88,1-92,0	441	11,30%	1.00-1.46	1058	27,10%	3904	4317
		6-12	508	13,01%	8-12	918	23,51%	84.1-88.1	381	9,76%	1,46-1,92	1036	26,54%		
		0-6	469	12,01%	0-4	615	15,75%	92.0-96.0	342	8,76%	1.92-2.38	738	18,90%		
	#33- 64h	21,160	19,490		6,528	4,244		80,51	17,17		1,669	0,638			
Level 1 (10mm)	Distri-bution	0-6	1088	21,19%	4-8	2283	44,47%	92.0-96.0	858	16,71%	1,00-1,46	2345	45,68%	5134	5677
		12-18	887	17,28%	0-4	1449	28,22%	88.1-92.0	810	15,78%	1,46-1,92	1560	30,39%		
		6-12	871	16,97%	8-12	961	18,72%	96.0-100	603	11,75%	1.92-2.38	686	13,36%		
	#75- 64h	28,290	25,300		8,218	5,662		76,08	18,24		1,865	0,776			
Level 2 (50mm)	Distri-bution	0-6	744	16,36%	4-8	1755	38,58%	88.1-92.0	593	13,04%	1,00-1,46	1548	34,03%	4549	5030
		12-18	588	12,93%	8-12	1096	24,09%	84.1-88.1	513	11,28%	1,46-1,92	1402	30,82%		
		18-24	583	12,82%	0-4	910	20,00%	92.0-96.0	495	10,88%	1.92-2.38	744	16,36%		
	#117- 64h	33,800	28,910		9,630	6,976		73,34	19,30		1,993	0,908			
level 3 (100mm)	Distri-bution	0-6	514	14,04%	4-8	1216	33,21%	88,1-92,0	407	11,11%	1.00-1.46	1138	31,08%	3662	4049
		12-18	403	11,00%	8-12	893	24,39%	84.1-88.1	377	10,29%	1,46-1,92	998	27,25%		
		18-24	379	10,35%	0-4	616	16,82%	92.0-96.0	356	9,72%	1.92-2.38	657	17,94%		
	#34- 66h	21,110	19,420		6,625	4,360		79,84	16,77		1,729	0,682			
Level 1 (10mm)	Distri-bution	0-6	1002	20,72%	4-8	2223	45,98%	88.1-92.0	814	16,84%	1,00-1,46	2025	41,88%	4835	5347
		6-12	839	17,35%	0-4	1276	26,39%	92.0-96.0	691	14,29%	1,46-1,92	1462	30,24%		
		12-18	797	16,48%	8-12	917	18,97%	84.1-88.1	563	11,64%	1.92-2.38	762	15,76%		
	#76- 66h	27,760	25,590		8,266	5,815		75,46	18,47		1,953	0,855			
Level 2 (50mm)	Distri-bution	0-6	786	17,68%	4-8	1667	37,50%	88.1-92.0	584	13,14%	1,00-1,46	1400	31,50%	4445	4915
		12-18	614	13,81%	8-12	999	22,47%	84.1-88.1	522	11,74%	1,46-1,92	1290	29,02%		
		6-12	562	12,64%	0-4	951	21,39%	92.0-96.0	450	10,12%	1.92-2.38	802	18,04%		
	#118- 66h	29,370	27,130		8,999	6,876		73,44	19,81		2,043	0,922			
level 3 (100mm)	Distri-bution	0-6	683	17,62%	4-8	1325	34,18%	88,1-92,0	444	11,45%	1.00-1.46	1103	28,45%	3877	4287
		12-18	509	13,13%	8-12	852	21,98%	84.1-88.1	416	10,73%	1,46-1,92	1078	27,81%		
		6-12	464	11,97%	0-4	828	21,36%	80.2-84.1	357	9,21%	1.92-2.38	689	17,77%		
	#35- 68h	21,880	20,210		6,897	4,505		78,99	16,34		1,812	0,720			
Level 1 (10mm)	Distri-bution	0-6	948	19,34%	4-8	2158	44,02%	88.1-92.0	764	15,59%	1,00-1,46	1822	37,17%	4902	5421
		6-12	877	17,89%	0-4	1258	25,66%	92.0-96.0	632	12,89%	1,46-1,92	1478	30,15%		
		12-18	792	16,16%	8-12	999	20,38%	84.1-88.1	561	11,44%	1.92-2.38	820	16,73%		
	#77- 68h	27,830	24,140		8,341	5,633		75,38	17,93		1,960	0,868			
Level 2 (50mm)	Distri-bution	0-6	617	14,87%	4-8	1642	39,57%	88.1-92.0	528	12,72%	1,00-1,46	1283	30,92%	4150	4589
		18-24	573	13,81%	8-12	1010	24,34%	84.1-88.1	479	11,54%	1,46-1,92	1209	29,13%		
		12-18	561	13,52%	0-4	765	18,43%	80.2-84.1	417	10,05%	1.92-2.38	762	18,36%		
	#119- 68h	31,960	27,580		9,650	7,000		72,19	19,72		2,109	0,978			
level 3 (100mm)	Distri-bution	12-18	500	12,95%	4-8	1397	36,17%	88,1-92,0	453	11,73%	1.00-1.46	1050	27,19%	3862	4271
		18-24	478	12,38%	8-12	919	23,80%	84.1-88.1	394	10,20%	1,46-1,92	1018	26,36%		
		0-6	459	11,89%	0-4	594	15,38%	92.0-96.0	350	9,06%	1.92-2.38	696	18,02%		

Level 1 (10mm)	#36- 70h	26,500	23,380		7,618	4,976		78,58	17,49		1,749	0,690		4641	5132
	Distri-bution	6-12	719	15,49%	4-8	1958	42,19%	88.1-92.0	694	14,95%	1,00-1,46	1896	40,85%		
		0-6	703	15,15%	8-12	1024	22,06%	92.0-96.0	673	14,50%	1,46-1,92	1396	30,08%		
		12-18	647	13,94%	0-4	1008	21,72%	84.1-88.1	532	11,46%	1.92-2.38	714	15,38%		
Level 2 (50mm)	#78- 70h	30,640	26,300		8,641	5,813		75,80	18,10		1,877	0,771		4305	4760
	Distri-bution	18-24	550	12,78%	4-8	1733	40,26%	88.1-92.0	596	13,84%	1,00-1,46	1432	33,26%		
		0-6	541	12,57%	8-12	1043	24,23%	84.1-88.1	494	11,48%	1,46-1,92	1309	30,41%		
		12-18	535	12,43%	0-4	705	16,38%	92.0-96.0	469	10,89%	1.92-2.38	776	18,03%		
level 3 (100mm)	#120- 70h	33,850	28,530		9,948	7,136		72,05	19,70		2,106	0,984		3523	3896
	Distri-bution	12-18	457	12,97%	4-8	1270	36,05%	88,1-92,0	404	11,47%	1.00-1.46	993	28,19%		
		18-24	417	11,84%	8-12	866	24,58%	84.1-88.1	343	9,74%	1,46-1,92	935	26,54%		
		6-12	406	11,52%	0-4	480	13,62%	80.2-84.1	316	8,97%	1.92-2.38	590	16,75%		
Level 1 (10mm)	#37- 72h	24,570	22,160		7,313	4,668		78,76	16,61		1,789	0,707		4264	4715
	Distri-bution	6-12	724	16,98%	4-8	1836	43,06%	88.1-92.0	617	14,47%	1,00-1,46	1590	37,29%		
		0-6	715	16,77%	0-4	965	22,63%	92.0-96.0	566	13,27%	1,46-1,92	1336	31,33%		
		12-18	637	14,94%	8-12	960	22,51%	84.1-88.1	533	12,50%	1.92-2.38	710	16,65%		
Level 2 (50mm)	#79- 72h	28,860	25,200		8,574	5,822		74,96	18,40		1,976	0,871		3923	4338
	Distri-bution	12-18	563	14,35%	4-8	1561	39,79%	88.1-92.0	517	13,18%	1,00-1,46	1201	30,61%		
		0-6	532	13,56%	8-12	932	23,76%	84.1-88.1	443	11,29%	1,46-1,92	1140	29,06%		
		6-12	517	13,18%	0-4	683	17,41%	92.0-96.0	383	9,76%	1.92-2.38	695	17,72%		
level 3 (100mm)	#121- 72h	30,960	26,440		9,363	6,542		72,25	19,21		2,095	0,933		3774	4173
	Distri-bution	12-18	530	14,04%	4-8	1429	37,86%	88,1-92,0	417	11,05%	1.46-1.92	1031	27,32%		
		6-12	518	13,73%	8-12	929	24,62%	84.1-88.1	382	10,12%	1.00-1.46	1002	26,55%		
		18-24	436	11,55%	0-4	558	14,79%	80.2-84.1	345	9,14%	1.92-2.38	710	18,81%		
Level 1 (10mm)	#38- 74h	25,550	22,390		7,280	4,594		79,25	16,80		1,713	0,635		4408	4874
	Distri-bution	0-6	745	16,90%	4-8	1873	42,49%	88.1-92.0	692	15,70%	1,00-1,46	1830	41,52%		
		6-12	642	14,56%	8-12	1043	23,66%	92.0-96.0	618	14,02%	1,46-1,92	1427	32,37%		
		12-18	610	13,84%	0-4	993	22,53%	84.1-88.1	549	12,45%	1.92-2.38	630	14,29%		
Level 2 (50mm)	#80- 74h	31,560	26,460		8,829	5,914		75,23	18,17		1,855	0,772		4426	4894
	Distri-bution	12-18	551	12,45%	4-8	1692	38,23%	88.1-92.0	615	13,90%	1,00-1,46	1541	34,82%		
		18-24	539	12,18%	8-12	1156	26,12%	84.1-88.1	524	11,84%	1,46-1,92	1344	30,37%		
		0-6	518	11,70%	0-4	708	16,00%	92.0-96.0	434	9,81%	1.92-2.38	749	16,92%		
level 3 (100mm)	#122- 74h	35,950	30,450		10,080	7,402		72,47	19,63		2,036	0,903		3659	4046
	Distri-bution	0-6	439	12,00%	4-8	1180	32,25%	88,1-92,0	393	10,74%	1,00-1,46	1045	28,56%		
		18-24	398	10,88%	8-12	931	25,44%	84.1-88.1	365	9,98%	1,46-1,92	1036	28,31%		
		12-18	378	10,33%	0-4	560	15,30%	92.0-96.0	350	9,57%	1.92-2.38	652	17,82%		
Level 1 (10mm)	#39- 76h	23,150	20,820		6,992	4,533		79,81	16,83		1,705	0,660		4544	5025
	Distri-bution	0-6	806	17,74%	4-8	2020	44,45%	88.1-92.0	720	15,85%	1,00-1,46	1986	43,71%		
		6-12	798	17,56%	0-4	1107	24,36%	92.0-96.0	715	15,74%	1,46-1,92	1368	30,11%		
		12-18	724	15,93%	8-12	947	20,84%	84.1-88.1	560	12,32%	1.92-2.38	682	15,01%		
Level 2 (50mm)	#81- 76h	29,510	25,470		8,611	5,842		74,58	17,68		1,944	0,819		4248	4697
	Distri-bution	6-12	578	13,61%	4-8	1638	38,56%	88.1-92.0	506	11,91%	1.46-1.92	1303	30,67%		
		0-6	560	13,18%	8-12	1102	25,94%	84.1-88.1	487	11,46%	1.00-1.46	1278	30,08%		
		12-18	546	12,85%	0-4	725	17,07%	80.2-84.1	434	10,22%	1.92-2.38	773	18,20%		
level 3 (100mm)	#123- 76h	34,840	29,060		10,100	8,375		71,90	19,54		2,076	0,934		3581	3960
	Distri-bution	18-24	430	12,01%	4-8	1264	35,30%	88,1-92,0	386	10,78%	1.46-1.92	1010	28,20%		
		12-18	425	11,87%	8-12	868	24,24%	84.1-88.1	365	10,19%	1.00-1.46	956	26,70%		
		0-6	392	10,95%	0-4	485	13,54%	80.2-84.1	323	9,02%	1.92-2.38	664	18,54%		

Level 1 (10mm)	#40- 78h	23,480	20,750		6,968	4,433		79,91	16,33		1,676	0,598		4950	5474
	Distri-bution	6-12	857	17,31%	4-8	2224	44,93%	88.1-92.0	804	16,24%	1,00-1,46	2183	44,10%		
		0-6	840	16,97%	0-4	1188	24,00%	92.0-96.0	741	14,97%	1,46-1,92	1535	31,01%		
		12-18	743	15,01%	8-12	1045	21,11%	84.1-88.1	642	12,97%	1.92-2.38	719	14,53%		
Level 2 (50mm)	#82- 78h	31,560	27,020		8,999	6,317		73,92	18,93		1,913	0,808		4011	4435
	Distri-bution	0-6	542	13,51%	4-8	1440	35,90%	88.1-92.0	474	11,82%	1,00-1,46	1343	33,48%		
		12-18	466	11,62%	8-12	1070	26,68%	84.1-88.1	431	10,75%	1,46-1,92	1151	28,70%		
		6-12	453	11,29%	0-4	677	16,88%	92.0-96.0	378	9,42%	1.92-2.38	686	17,10%		
level 3 (100mm)	#124- 78h	36,030	30,310		10,200	7,422		70,79	20,42		2,037	0,927		3668	4056
	Distri-bution	0-6	493	13,44%	4-8	1127	30,73%	88,1-92,0	374	10,20%	1.46-1.92	1064	29,01%		
		18-24	386	10,52%	8-12	953	25,98%	84.1-88.1	370	10,09%	1.00-1.46	1020	27,81%		
		24-30	354	9,65%	0-4	569	15,51%	76.2-80.2	303	8,26%	1.92-2.38	684	18,65%		
Level 1 (10mm)	#41- 80h	26,000	22,850		7,432	4,813		79,23	17,50		1,721	0,670		4179	4621
	Distri-bution	0-6	654	15,65%	4-8	1769	42,33%	88.1-92.0	699	16,73%	1,00-1,46	1798	43,02%		
		6-12	621	14,86%	8-12	1014	24,26%	92.0-96.0	598	14,31%	1,46-1,92	1283	30,70%		
		12-18	607	14,53%	0-4	902	21,58%	84.1-88.1	540	12,92%	1.92-2.38	588	14,07%		
Level 2 (50mm)	#83- 80h	30,730	26,230		8,666	5,664		74,97	18,28		1,917	0,825		4104	4538
	Distri-bution	0-6	558	13,60%	4-8	1564	38,11%	88.1-92.0	504	12,28%	1,00-1,46	1336	32,55%		
		12-18	510	12,43%	8-12	1042	25,39%	84.1-88.1	459	11,18%	1,46-1,92	1201	29,26%		
		18-24	501	12,21%	0-4	697	16,98%	92.0-96.0	435	10,60%	1.92-2.38	735	17,91%		
level 3 (100mm)	#125- 80h	38,110	30,360		10,160	6,947		73,51	19,02		1,944	0,823		3267	3613
	Distri-bution	12-18	349	10,68%	4-8	1085	33,21%	88,1-92,0	416	12,73%	1,00-1,46	1025	31,37%		
		0-6	343	10,50%	8-12	860	26,32%	84.1-88.1	348	10,65%	1,46-1,92	974	29,81%		
		18-24	321	9,83%	0-4	418	12,79%	92.0-96.0	322	9,86%	1.92-2.38	532	16,28%		

Silicon Particles Analysis (Sr-modified)

Magnification:	1000 X	Field Area (µm2) :	5664	Updated:
No. of Fields:	40	Total Area (µm2) :	2,26572E+05	2005-09-30

Level	Sample ID	Area (µm2)			Length (µm)			Roundness (%)			Aspect Ratio			Total # Features	Si Particle Density
		Ave.	SD		Ave.	SD		Ave.	SD		Ave.	SD			
Level 1 (10mm)	#S1- 0h	1,163	1,939		1,568	1,363		75,24	20,64		1,806	0,662		26791	147806
	Distri-bution	Range	Qty.	Percent	Range	Qty.	Percent	Range	Qty.	Percent	Range	Qty.	Percent		
		0-2	22713	84,78%	0.5-1.0	8510	31,76%	96.0-100	5279	19,70%	1.96-2.12	4219	15,75%		
		2-4	2647	9,88%	1.0-1.5	5280	19,71%	80.2-84.1	2547	9,51%	1.48-1.64	3741	13,96%		
		4-6	752	2,81%	0-0.5	3552	13,26%	84.1-88.1	2384	8,90%	1.00-1.16	3302	12,33%		
Level 2 (50mm)	#S43- 0h	2,821	4,091		2,358	1,905		77,23	21,45		1,527	0,370		18043	79635
	Distri-bution	0-3	12976	71,92%	1.2-1.8	4462	24,73%	96.0-100	3287	18,22%	1.00-1.06	1608	8,91%		
		3-6	3112	17,25%	0.6-1.2	4007	22,21%	88.1-92.0	2407	13,34%	1.48-1.54	1546	8,57%		
		6-9	987	5,47%	1.8-2.4	2147	11,90%	92.0-96.0	2152	11,93%	1.30-1.36	1444	8,00%		
level 3 (100mm)	#S85- 0h	3,077	4,260		2,478	2,027		77,23	21,23		1,654	0,553		17801	78567
	Distri-bution	0-3	12035	67,61%	1.2-1.8	3871	21,75%	96.0-100	3449	19,38%	1.16-1.32	2769	15,56%		
		3-6	3447	19,36%	0.6-1.2	3554	19,97%	88.1-92.0	2120	11,91%	1.00-1.16	2616	14,70%		
		6-9	1190	6,69%	1.8-2.4	2131	11,97%	92.0-96.0	1941	10,90%	1.32-1.48	2612	14,67%		
Level 1 (10mm)	#S2- 2h	3,875	4,375		2,548	1,794		83,39	15,65		1,521	0,502		7047	31103
	Distri-bution	0-3	3864	54,83%	1.2-1.8	1427	20,25%	88.1-92.0	1349	19,14%	1.16-1.32	1539	21,84%		
		3-6	1798	25,51%	2.4-3.0	1145	16,25%	92.0-96.0	1227	17,41%	1.00-1.16	1390	19,72%		
		6-9	706	10,02%	0.6-1.2	1080	15,33%	96.0-100	1073	15,23%	1.32-1.48	1166	16,55%		
Level 2 (50mm)	#S44- 2h	4,164	4,466		2,662	1,768		85,35	13,93		1,491	0,447		7763	34263
	Distri-bution	0-3	3964	51,06%	1.2-1.8	1536	19,79%	88.1-92.0	1614	20,79%	1.16-1.32	1803	23,23%		
		3-6	2100	27,05%	2.4-3.0	1337	17,22%	92.0-96.0	1572	20,25%	1.00-1.16	1548	19,94%		
		6-9	882	11,36%	1.8-2.4	1149	14,80%	96.0-100	1339	17,25%	1.32-1.48	1314	16,93%		
level 3 (100mm)	#S86- 2h	4,623	4,685		2,839	1,857		85,52	13,91		1,486	0,447		8118	35830
	Distri-bution	0-3	3564	43,90%	2.4-3.0	1602	19,73%	92.0-96.0	1945	23,96%	1.16-1.32	1933	23,81%		
		3-6	2522	31,07%	1.2-1.8	1367	16,84%	88.1-92.0	1678	20,67%	1.00-1.16	1669	20,56%		
		6-9	1066	13,13%	1.8-2.4	1217	14,99%	96.0-100	1246	15,35%	1.32-1.48	1398	17,22%		
Level 1 (10mm)	#S3- 4h	4,127	4,923		2,588	1,831		83,80	13,83		1,505	0,443		5020	22156
	Distri-bution	0-3	2753	54,84%	1.2-1.8	1022	20,36%	84.1-88.1	983	19,58%	1.16-1.32	1119	22,29%		
		3-6	1134	22,59%	0.6-1.2	769	15,32%	92.0-96.0	766	15,26%	1.00-1.16	925	18,43%		
		6-9	562	11,20%	2.4-3.0	720	14,34%	96.0-100	739	14,72%	1.32-1.48	891	17,75%		
Level 2 (50mm)	#S45- 4h	4,969	5,661		2,885	1,929		84,76	13,53		1,507	0,453		6388	28194
	Distri-bution	0-3	2855	44,69%	2.4-3.0	1127	17,64%	88.1-92.0	1305	20,43%	1.16-1.32	1522	23,83%		
		3-6	1809	28,32%	1.2-1.8	1057	16,55%	92.0-96.0	1273	19,93%	1.00-1.16	1170	18,32%		
		6-9	798	12,49%	1.8-2.4	874	13,68%	84.1-88.1	907	14,20%	1.32-1.48	1095	17,14%		
level 3 (100mm)	#S87- 4h	5,088	5,911		2,975	2,050		82,96	14,87		1,568	0,508		6144	27117
	Distri-bution	0-3	2774	45,15%	2.4-3.0	1043	16,98%	88.1-92.0	1145	18,64%	1.16-1.32	1306	21,26%		
		3-6	1652	26,89%	1.2-1.8	956	15,56%	92.0-96.0	1060	17,25%	1.32-1.48	1032	16,80%		
		6-9	792	12,89%	1.8-2.4	835	13,59%	84.1-88.1	848	13,80%	1.00-1.16	1013	16,49%		

Level 1 (10mm)	#S4- 6h	5,175	5,826		2,801	1,938		83,89	15,71		1,440	0,416		5619	24800
	Distri-bution	0-3	2670	47,52%	1.2-1.8	971	17,28%	88.1-92.0	1100	19,58%	1.00-1.16	1359	24,19%		
		3-6	1244	22,14%	2.4-3.0	812	14,45%	92.0-96.0	1073	19,10%	1.16-1.32	1353	24,08%		
		6-9	660	11,75%	0.6-1.2	793	14,11%	96.0-100	964	17,16%	1.32-1.48	956	17,01%		
Level 2 (50mm)	#S46- 6h	6,120	6,577		3,136	2,021		83,90	14,10		1,441	0,414		5824	25705
	Distri-bution	0-3	2214	38,02%	2.4-3.0	940	16,14%	88.1-92.0	1174	20,16%	1.16-1.32	1559	26,77%		
		3-6	1466	25,17%	1.2-1.8	879	15,09%	92.0-96.0	1084	18,61%	1.00-1.16	1317	22,61%		
		6-9	885	15,20%	3.0-3.6	808	13,87%	84.1-88.1	783	13,44%	1.32-1.48	1029	17,67%		
level 3 (100mm)	#S88- 6h	5,997	6,443		3,170	2,078		84,00	13,40		1,497	0,441		5576	24610
	Distri-bution	0-3	2149	38,54%	2.4-3.0	905	16,23%	88.1-92.0	1122	20,12%	1.16-1.32	1343	24,09%		
		3-6	1432	25,68%	1.2-1.8	818	14,67%	92.0-96.0	947	16,98%	1.00-1.16	1070	19,19%		
		6-9	828	14,85%	3.0-3.6	745	13,36%	84.1-88.1	914	16,39%	1.32-1.48	936	16,79%		
Level 1 (10mm)	#S5- 8h	6,063	6,595		3,058	1,997		85,03	13,21		1,419	0,391		4160	18361
	Distri-bution	0-3	1727	41,51%	1.2-1.8	673	16,18%	88.1-92.0	908	21,83%	1.16-1.32	1140	27,40%		
		3-6	950	22,84%	2.4-3.0	608	14,62%	92.0-96.0	823	19,78%	1.00-1.16	988	23,75%		
		6-9	540	12,98%	3.0-3.6	509	12,24%	96.0-100	563	13,53%	1.32-1.48	718	17,26%		
Level 2 (50mm)	#S47- 8h	6,070	6,508		3,137	2,001		85,65	12,32		1,454	0,404		4838	21353
	Distri-bution	0-3	1887	39,00%	2.4-3.0	789	16,31%	88.1-92.0	1100	22,74%	1.16-1.32	1242	25,67%		
		3-6	1162	24,02%	1.2-1.8	744	15,38%	92.0-96.0	1035	21,39%	1.00-1.16	991	20,48%		
		6-9	732	15,13%	1.8-2.4	608	12,57%	84.1-88.1	714	14,76%	1.32-1.48	883	18,25%		
level 3 (100mm)	#S89- 8h	6,752	7,579		3,289	2,246		84,58	14,12		1,519	0,484		4753	20978
	Distri-bution	0-3	1741	36,63%	2.4-3.0	717	15,09%	88.1-92.0	973	20,47%	1.16-1.32	1082	22,76%		
		3-6	1106	23,27%	3.0-3.6	661	13,91%	92.0-96.0	962	20,24%	1.00-1.16	899	18,91%		
		6-9	755	15,88%	1.2-1.8	620	13,04%	96.0-100	649	13,65%	1.32-1.48	812	17,08%		
Level 1 (10mm)	#S6- 10h	5,924	6,322		3,022	1,999		85,67	12,51		1,437	0,390		4425	19530
	Distri-bution	0-3	1918	43,34%	1.2-1.8	687	15,53%	88.1-92.0	953	21,54%	1.16-1.32	1158	26,17%		
		3-6	950	21,47%	2.4-3.0	616	13,92%	92.0-96.0	872	19,71%	1.00-1.16	984	22,24%		
		6-9	546	12,34%	1,8-2,4	548	12,38%	96.0-100	654	14,78%	1.32-1.48	765	17,29%		
Level 2 (50mm)	#S48- 10h	5,789	6,356		3,048	2,000		85,65	12,63		1,476	0,426		5130	22642
	Distri-bution	0-3	2173	42,36%	1,2-1,8	845	16,47%	88.1-92.0	1163	22,67%	1.16-1.32	1302	25,38%		
		3-6	1187	23,14%	2,4-3,0	786	15,32%	92.0-96.0	1035	20,18%	1.00-1.16	973	18,97%		
		6-9	685	13,35%	1,8-2,4	638	12,44%	84.1-88.1	740	14,42%	1.32-1.48	900	17,54%		
level 3 (100mm)	#S90- 10h	6,524	7,071		3,262	2,180		85,08	13,39		1,507	0,470		5065	22355
	Distri-bution	0-3	1857	36,66%	2,4-3,0	759	14,99%	88.1-92.0	1051	20,75%	1.16-1.32	1183	23,36%		
		3-6	1184	23,38%	3,0-3,6	710	14,02%	92.0-96.0	1028	20,30%	1.00-1.16	1016	20,06%		
		6-9	812	16,03%	3,6-4,2	655	12,93%	96.0-100	714	14,10%	1.32-1.48	842	16,62%		
Level 1 (10mm)	#S7- 12h	6,426	7,004		3,152	2,083		85,80	11,91		1,441	0,393		4016	17725
	Distri-bution	0-3	1694	42,18%	1.2-1.8	651	16,21%	88.1-92.0	865	21,54%	1.16-1.32	1017	25,32%		
		3-6	823	20,49%	2.4-3.0	537	13,37%	92.0-96.0	809	20,14%	1.00-1.16	864	21,51%		
		6-9	504	12,55%	1,8-2,4	518	12,90%	96.0-100	559	13,92%	1.32-1.48	736	18,33%		
Level 2 (50mm)	#S49- 12h	6,925	7,250		3,308	2,108		86,27	11,97		1,429	0,388		4607	20333
	Distri-bution	0-3	1669	36,23%	1,2-1,8	696	15,11%	88.1-92.0	1097	23,81%	1.16-1.32	1232	26,74%		
		3-6	1012	21,97%	2,4-3,0	651	14,13%	92.0-96.0	1069	23,20%	1.00-1.16	1024	22,23%		
		6-9	705	15,30%	3,0-3,6	597	12,96%	84.1-88.1	643	13,96%	1.32-1.48	880	19,10%		
level 3 (100mm)	#S91- 12h	7,105	7,267		2,322	2,182		86,37	12,77		1,455	0,447		5187	22893
	Distri-bution	0-3	1750	33,74%	3,0-3,6	740	14,27%	92,0-96,0	1167	22,50%	1.16-1.32	1268	24,45%		
		3-6	1116	21,52%	2,4-3,0	706	13,61%	88,1-92,0	1104	21,28%	1.00-1.16	1235	23,81%		
		6-9	856	16,50%	1,2-1,8	593	11,43%	96.0-100	885	17,06%	1.32-1.48	889	17,14%		

Level 1 (10mm)	#S8- 14h	7,130	7,647		3,290	2,154		85,60	12,18		1,435	0,388		3846	16975
	Distri-bution	0-3	1433	37,26%	1.2-1.8	517	13,44%	88.1-92.0	842	21,89%	1.16-1.32	981	25,51%		
		3-6	801	20,83%	2.4-3.0	502	13,05%	92.0-96.0	771	20,05%	1.00-1.16	858	22,31%		
		6-9	510	13,26%	1,8-2,4	420	10,92%	84,1-88,1	522	13,57%	1.32-1.48	694	18,04%		
Level 2 (50mm)	#S50- 14h	7,343	7,781		3,352	2,124		85,06	13,25		1,443	0,412		4310	19023
	Distri-bution	0-3	1490	34,57%	2,4-3,0	618	14,34%	88.1-92.0	903	20,95%	1.16-1.32	1068	24,78%		
		3-6	955	22,16%	3,0-3,6	536	12,44%	92.0-96.0	861	19,98%	1.00-1.16	1015	23,55%		
		6-9	607	14,08%	1,2-1,8	505	11,72%	84.1-88.1	624	14,48%	1.32-1.48	741	17,19%		
level 3 (100mm)	#S92- 14h	7,320	7,475		3,386	2,160		85,42	12,39		1,463	0,436		4402	19429
	Distri-bution	0-3	1502	34,12%	2,4-3,0	614	13,95%	88.1-92.0	985	22,38%	1.16-1.32	1069	24,28%		
		3-6	899	20,42%	3,0-3,6	533	12,11%	92.0-96.0	895	20,33%	1.00-1.16	984	22,35%		
		6-9	680	15,45%	1,2-1,8	518	11,77%	84.1-88.1	614	13,95%	1.32-1.48	788	17,90%		
Level 1 (10mm)	#S9- 16h	8,554	9,006		3,659	2,293		84,49	12,43		1,451	0,389		3509	15487
	Distri-bution	0-3	1064	30,32%	2,4-3,0	484	13,79%	88.1-92.0	783	22,31%	1.16-1.32	868	24,74%		
		3-6	775	22,09%	3,0-3,6	434	12,37%	92.0-96.0	655	18,67%	1.00-1.16	723	20,60%		
		6-9	486	13,85%	1,2-1,8	399	11,37%	84,1-88,1	516	14,71%	1.32-1.48	666	18,98%		
Level 2 (50mm)	#S51- 16h	8,036	8,004		3,579	2,207		85,57	12,15		1,443	0,399		3947	17421
	Distri-bution	0-3	1221	30,93%	2,4-3,0	566	14,34%	88.1-92.0	932	23,61%	1.16-1.32	1025	25,97%		
		3-6	859	21,76%	3,0-3,6	515	13,05%	92.0-96.0	867	21,97%	1.00-1.16	866	21,94%		
		6-9	572	14,49%	1,2-1,8	482	12,21%	84.1-88.1	583	14,77%	1.32-1.48	690	17,48%		
level 3 (100mm)	#S93- 16h	8,203	8,133		3,594	2,111		86,12	11,29		1,438	0,395		3928	17337
	Distri-bution	0-3	1143	29,10%	3,0-3,6	571	14,54%	88.1-92.0	940	23,93%	1.16-1.32	1031	26,25%		
		3-6	859	21,87%	2,4-3,0	549	13,98%	92.0-96.0	848	21,59%	1.00-1.16	872	22,20%		
		6-9	623	15,86%	1,2-1,8	466	11,86%	84.1-88.1	634	16,14%	1.32-1.48	686	17,46%		
Level 1 (10mm)	#S10- 18h	8,236	9,243		3,504	2,359		85,33	12,19		1,413	0,392		3320	14653
	Distri-bution	0-3	1161	34,97%	1.2-1.8	439	13,22%	88.1-92.0	717	21,60%	1.16-1.32	831	25,03%		
		3-6	668	20,12%	2.4-3.0	419	12,62%	92.0-96.0	596	17,95%	1.00-1.16	760	22,89%		
		6-9	428	12,89%	3.0-3.6	382	11,51%	84,1-88,1	490	14,76%	1.32-1.48	611	18,40%		
Level 2 (50mm)	#S52- 18h	7,771	8,451		3,389	2,270		85,47	12,57		1,450	0,416		3825	16882
	Distri-bution	0-3	1319	34,48%	2,4-3,0	491	12,84%	88.1-92.0	832	21,75%	1.16-1.32	956	24,99%		
		3-6	767	20,05%	3,0-3,6	449	11,74%	92.0-96.0	673	17,59%	1.00-1.16	879	22,98%		
		6-9	536	14,01%	1,2-1,8	424	11,08%	96.0-100	576	15,06%	1.32-1.48	643	16,81%		
level 3 (100mm)	#S94- 18h	7,285	8,099		3,286	2,301		84,18	14,09		1,488	0,476		4535	20016
	Distri-bution	0-3	1683	37,11%	2.4-3.0	589	12,99%	88.1-92.0	844	18,61%	1.16-1.32	1094	24,12%		
		3-6	901	19,87%	3.0-3.6	547	12,06%	92.0-96.0	723	15,94%	1.00-1.16	1021	22,51%		
		6-9	589	12,99%	1.2-1.8	452	9,97%	96.0-100	713	15,72%	1.32-1.48	721	15,90%		
Level 1 (10mm)	#S11- 20h	8,032	8,737		3,477	2,140		85,41	11,80		1,395	0,340		2812	12411
	Distri-bution	0-3	924	32,86%	2.4-3.0	421	14,97%	88.1-92.0	707	25,14%	1.16-1.32	742	26,39%		
		3-6	633	22,51%	1.2-1.8	364	12,94%	92.0-96.0	527	18,74%	1.00-1.16	683	24,29%		
		6-9	375	13,34%	3.0-3.6	320	11,38%	84,1-88,1	411	14,62%	1.32-1.48	530	18,85%		
Level 2 (50mm)	#S53- 20h	8,664	8,760		3,626	2,230		85,70	12,55		1,419	0,393		3979	17562
	Distri-bution	0-3	1168	29,35%	2,4-3,0	549	13,80%	88.1-92.0	885	22,24%	1.16-1.32	1043	26,21%		
		3-6	779	19,58%	3,0-3,6	465	11,69%	92.0-96.0	860	21,61%	1.00-1.16	979	24,60%		
		6-9	627	15,76%	1,2-1,8	407	10,23%	84.1-88.1	570	14,33%	1.32-1.48	713	17,92%		
level 3 (100mm)	#S95- 20h	8,730	8,751		3,695	2,331		85,21	12,55		1,478	0,453		3896	17195
	Distri-bution	0-3	1146	29,41%	3.0-3.6	484	12,42%	88.1-92.0	864	22,18%	1.16-1.32	974	25,00%		
		3-6	739	18,97%	2.4-3.0	480	12,32%	92.0-96.0	767	19,69%	1.00-1.16	795	20,41%		
		6-9	581	14,91%	4.2-4.8	411	10,55%	84.1-88.1	537	13,78%	1.32-1.48	691	17,74%		

Level 1 (10mm)	#S12- 22h	7,097	8,920		3,025	2,357		86,39	12,35		1,434	0,431		3808	16807
	Distri-bution	0-3	1690	44,38%	0.6-1.2	566	14,86%	96.0-100	831	21,82%	1.00-1.16	1003	26,34%		
		3-6	643	16,89%	0.0-0.6	447	11,74%	88.1-92.0	720	18,91%	1.16-1.32	886	23,27%		
		6-9	450	11,82%	2.4-3.0	442	11,61%	92.0-96.0	587	15,41%	1.32-1.48	613	16,10%		
Level 2 (50mm)	#S54- 22h	7,873	9,055		3,287	2,370		86,64	11,70		1,438	0,413		4307	19009
	Distri-bution	0-3	1664	38,63%	0.6-1.2	501	11,63%	88.1-92.0	937	21,76%	1.16-1.32	1068	24,80%		
		3-6	756	17,55%	2.4-3.0	499	11,59%	92.0-96.0	788	18,30%	1.00-1.16	1030	23,91%		
		6-9	523	12,14%	3.0-3.6	482	11,19%	96.0-100	759	17,62%	1.32-1.48	746	17,32%		
level 3 (100mm)	#S96- 22h	7,375	9,597		3,045	2,595		86,15	13,11		1,477	0,454		5357	23644
	Distri-bution	0-3	2466	46,03%	0.6-1.2	949	17,72%	96.0-100	1288	24,04%	1.00-1.16	1358	25,35%		
		3-6	741	13,83%	0.0-0.6	800	14,93%	88.1-92.0	972	18,14%	1.16-1.32	1059	19,77%		
		6-9	524	9,78%	2.4-3.0	501	9,35%	92.0-96.0	731	13,65%	1.32-1.48	810	15,12%		
Level 1 (10mm)	#S13- 24h	8,724	9,851		3,500	2,426		85,37	13,95		1,417	0,435		3808	16807
	Distri-bution	0-3	1193	31,33%	2.4-3.0	463	12,16%	88.1-92.0	723	18,99%	1.00-1.16	997	26,18%		
		3-6	714	18,75%	3.0-3.6	398	10,45%	92.0-96.0	664	17,44%	1.16-1.32	877	23,03%		
		6-9	438	11,50%	0.6-1.2	342	8,98%	96.0-100	620	16,28%	1.32-1.48	560	14,71%		
Level 2 (50mm)	#S55- 24h	9,695	10,680		3,665	2,528		85,61	13,16		1,418	0,400		4307	19009
	Distri-bution	0-3	1313	30,49%	3.0-3.6	434	10,08%	88.1-92.0	793	18,41%	1.00-1.16	1039	24,12%		
		3-6	611	14,19%	0.6-1.2	422	9,80%	92.0-96.0	764	17,74%	1.16-1.32	1017	23,61%		
		6-9	526	12,21%	2.4-3.0	410	9,52%	96.0-100	672	15,60%	1.32-1.48	673	15,63%		
level 3 (100mm)	#S97- 24h	12,060	10,940		4,315	2,444		86,64	12,56		1,393	0,379		5357	23644
	Distri-bution	0-3	673	12,56%	2.4-3.0	439	8,19%	92.0-96.0	984	18,37%	1.16-1.32	1043	19,47%		
		3-6	624	11,65%	3.0-3.6	429	8,01%	88.1-92.0	895	16,71%	1.00-1.16	942	17,58%		
		6-9	518	9,67%	4.2-4.8	387	7,22%	96.0-100	452	8,44%	1.32-1.48	646	12,06%		
Level 1 (10mm)	#S14- 26h	8,457	10,310		3,363	2,571		84,94	13,34		1,466	0,448		3685	16264
	Distri-bution	0-3	1505	40,84%	0.6-1.2	501	13,60%	88.1-92.0	709	19,24%	1.00-1.16	896	24,31%		
		3-6	560	15,20%	2.4-3.0	385	10,45%	96.0-100	706	19,16%	1.16-1.32	826	22,42%		
		6-9	406	11,02%	0.0-0.6	377	10,23%	92.0-96.0	520	14,11%	1.32-1.48	594	16,12%		
Level 2 (50mm)	#S56- 26h	9,561	10,190		3,728	2,505		85,81	13,17		1,423	0,411		4088	18043
	Distri-bution	0-3	1273	31,14%	2.4-3.0	459	11,23%	88.1-92.0	884	21,62%	1.00-1.16	1043	25,51%		
		3-6	679	16,61%	3.0-3.6	459	11,23%	92.0-96.0	857	20,96%	1.16-1.32	1028	25,15%		
		6-9	547	13,38%	0.6-1.2	379	9,27%	96.0-100	634	15,51%	1.32-1.48	697	17,05%		
level 3 (100mm)	#S98- 26h	8,555	9,434		3,524	2,485		84,31	13,41		1,494	0,459		4551	20086
	Distri-bution	0-3	1617	35,53%	0.6-1.2	487	10,70%	92.0-96.0	867	19,05%	1.16-1.32	1037	22,79%		
		3-6	738	16,22%	3.0-3.6	487	10,70%	88.1-92.0	696	15,29%	1.00-1.16	968	21,27%		
		6-9	570	12,52%	2.4-3.0	482	10,59%	96.0-100	676	14,85%	1.32-1.48	780	17,14%		
Level 1 (10mm)	#S15- 28h	10,370	10,360		3,966	2,392		85,00	11,48		1,393	0,357		3002	13250
	Distri-bution	0-3	760	25,32%	2.4-3.0	378	12,59%	88.1-92.0	649	21,62%	1.16-1.32	841	28,01%		
		3-6	596	19,85%	3.0-3.6	353	11,76%	96.0-100	530	17,65%	1.00-1.16	756	25,18%		
		6-9	428	14,26%	1.8-2.4	294	9,79%	84.1-88.1	524	17,46%	1.32-1.48	529	17,62%		
Level 2 (50mm)	#S57- 28h	11,510	11,480		4,193	2,512		85,81	11,84		1,406	0,380		3208	14159
	Distri-bution	0-3	705	21,98%	2.4-3.0	410	12,78%	88.1-92.0	752	23,44%	1.16-1.32	864	26,93%		
		3-6	574	17,89%	3.0-3.6	362	11,28%	92.0-96.0	719	22,41%	1.00-1.16	806	25,12%		
		6-9	477	14,87%	4.2-4.8	315	9,82%	84.1-88.1	497	15,49%	1.32-1.48	567	17,67%		
level 3 (100mm)	#S99- 28h	10,250	11,850		3,754	2,799		84,89	14,03		1,483	0,464		4053	17888
	Distri-bution	0-3	1384	34,15%	0.6-1.2	492	12,14%	88.1-92.0	793	19,57%	1.16-1.32	946	23,34%		
		3-6	580	14,31%	2.4-3.0	401	9,89%	96.0-100	714	17,62%	1.00-1.16	926	22,85%		
		6-9	438	10,81%	3.0-3.6	359	8,86%	92.0-96.0	713	17,59%	1.32-1.48	636	15,69%		

Level 1 (10mm)	#S16- 30h	9,839	10,860		3,709	2,518		83,31	14,60		1,429	0,435		3415	15072
	Distri-bution	0-3	1100	32,21%	2.4-3.0	382	11,19%	88.1-92.0	620	18,16%	1.16-1.32	892	26,12%		
		3-6	533	15,61%	3.0-3.6	354	10,37%	92.0-96.0	555	16,25%	1.00-1.16	852	24,95%		
		6-9	444	13,00%	1.2-1.8	331	9,69%	96.0-100	482	14,11%	1.32-1.48	550	16,11%		
Level 2 (50mm)	#S58- 30h	10,230	10,640		2,822	2,500		85,69	12,75		1,418	0,415		3682	16251
	Distri-bution	0-3	1071	29,09%	2.4-3.0	435	11,81%	88.1-92.0	805	21,86%	1.00-1.16	968	26,29%		
		3-6	623	16,92%	3.0-3.6	370	10,05%	92.0-96.0	705	19,15%	1.16-1.32	951	25,83%		
		6-9	445	12,09%	4.2-4.8	336	9,13%	96.0-100	578	15,70%	1.32-1.48	603	16,38%		
level 3 (100mm)	#S100- 30h	10,480	11,030		3,931	2,594		85,38	12,61		1,468	0,437		3611	15938
	Distri-bution	0-3	1023	28,33%	3.0-3.6	394	10,91%	88.1-92.0	811	22,46%	1.16-1.32	865	23,95%		
		3-6	575	15,92%	2.4-3.0	381	10,55%	92.0-96.0	699	19,36%	1.00-1.16	794	21,99%		
		6-9	467	12,93%	0.6-1.2	326	9,03%	96.0-100	471	13,04%	1.32-1.48	630	17,45%		
Level 1 (10mm)	#S17- 32h	11,680	12,200		4,155	2,603		83,77	14,40		1,422	0,450		3087	13625
	Distri-bution	0-3	783	25,36%	2.4-3.0	371	12,02%	88.1-92.0	624	20,21%	1.00-1.16	827	26,79%		
		3-6	522	16,91%	3.0-3.6	328	10,63%	92.0-96.0	605	19,60%	1.16-1.32	817	26,47%		
		6-9	389	12,60%	4,2-4,8	284	9,20%	84,1-88,1	438	14,19%	1.32-1.48	516	16,72%		
Level 2 (50mm)	#S59- 32h	10,990	10,730		4,070	2,420		85,53	12,67		1,399	0,376		3540	15624
	Distri-bution	0-3	850	24,01%	2.4-3.0	399	11,27%	88.1-92.0	797	22,51%	1,16-1,32	996	28,14%		
		3-6	617	17,43%	3.0-3.6	396	11,19%	92.0-96.0	777	21,95%	1,00-1,16	900	25,42%		
		6-9	484	13,67%	4.2-4.8	353	9,97%	84,1-88,1	513	14,49%	1.32-1.48	594	16,78%		
level 3 (100mm)	#S101- 32h	12,480	11,580		4,416	2,528		84,38	13,27		1,427	0,402		3465	15293
	Distri-bution	0-3	694	20,03%	3.0-3.6	408	11,77%	88.1-92.0	776	22,40%	1.16-1.32	906	26,15%		
		3-6	524	15,12%	2.4-3.0	369	10,65%	92.0-96.0	727	20,98%	1.00-1.16	847	24,44%		
		6-9	493	14,23%	0.6-1.2	326	9,41%	84,1-88,1	495	14,29%	1.32-1.48	606	17,49%		
Level 1 (10mm)	#S18- 34h	9,934	10,700		3,829	2,508		84,20	13,66		1,429	0,420		3332	14706
	Distri-bution	0-3	1001	30,04%	2.4-3.0	426	12,79%	88.1-92.0	686	20,59%	1,16-1,32	852	25,57%		
		3-6	601	18,04%	3.0-3.6	366	10,98%	92.0-96.0	608	18,25%	1,00-1,16	848	25,45%		
		6-9	455	13,66%	1,2-1,8	321	9,63%	84,1-88,1	497	14,92%	1.32-1.48	553	16,60%		
Level 2 (50mm)	#S60- 34h	11,000	11,360		4,014	2,556		85,05	13,24		1,415	0,392		3708	16366
	Distri-bution	0-3	992	26,75%	2.4-3.0	419	11,30%	88.1-92.0	823	22,20%	1,16-1,32	983	26,51%		
		3-6	616	16,61%	3.0-3.6	415	11,19%	92.0-96.0	727	19,61%	1,00-1,16	917	24,73%		
		6-9	479	12,92%	3,6-4,2	325	8,76%	84,1-88,1	565	15,24%	1.32-1.48	663	17,88%		
level 3 (100mm)	#S102- 34h	12,600	12,590		4,257	2,749		85,45	12,68		1,438	0,414		3214	14185
	Distri-bution	0-3	826	25,70%	3.0-3.6	285	8,87%	88.1-92.0	709	22,06%	1.16-1.32	822	25,58%		
		3-6	429	13,35%	2.4-3.0	281	8,74%	92.0-96.0	579	18,01%	1.00-1.16	765	23,80%		
		6-9	353	10,98%	4,2-4,8	277	8,62%	84,1-88,1	528	16,43%	1.32-1.48	548	17,05%		
Level 1 (10mm)	#S19- 36h	9,292	9,890		3,728	2,406		84,10	13,78		1,427	0,390		3020	13329
	Distri-bution	0-3	944	31,26%	2.4-3.0	378	12,52%	88.1-92.0	618	20,46%	1,16-1,32	799	26,46%		
		3-6	562	18,61%	3.0-3.6	347	11,49%	92.0-96.0	539	17,85%	1,00-1,16	728	24,11%		
		6-9	407	13,48%	1.8-2.4	320	10,60%	84,1-88,1	489	16,19%	1.32-1.48	514	17,02%		
Level 2 (50mm)	#S61- 36h	10,140	10,420		3,949	2,478		85,19	11,87		1,437	0,404		3519	15531
	Distri-bution	0-3	942	26,77%	2.4-3.0	425	12,08%	88.1-92.0	786	22,34%	1,16-1,32	924	26,26%		
		3-6	643	18,27%	3.0-3.6	409	11,62%	92.0-96.0	709	20,15%	1,00-1,16	798	22,68%		
		6-9	482	13,70%	1.2-1.8	360	10,23%	84,1-88,1	537	15,26%	1.32-1.48	625	17,76%		
level 3 (100mm)	#S103- 36h	10,950	11,200		4,088	2,541		84,90	12,71		1,470	0,429		3537	15611
	Distri-bution	0-3	897	25,36%	2.4-3.0	398	11,25%	88.1-92.0	764	21,60%	1.16-1.32	869	24,57%		
		3-6	610	17,25%	3.0-3.6	397	11,22%	92.0-96.0	690	19,51%	1.00-1.16	753	21,29%		
		6-9	469	13,26%	3.6-4.2	307	8,68%	84,1-88,1	547	15,47%	1.32-1.48	631	17,84%		

Level 1 (10mm)	#S20- 38h	9,358	11,000		3,626	2,586		82,65	13,70		1,450	0,429		3334	14715
	Distri-bution	0-3	1142	34,25%	2.4-3.0	411	12,33%	88.1-92.0	565	16,95%	1,16-1,32	855	25,64%		
		3-6	589	17,67%	3.0-3.6	342	10,26%	84.1-88.1	499	14,97%	1,00-1,16	784	23,52%		
		6-9	419	12,57%	0.6-1.2	341	10,23%	96.0-100	449	13,47%	1.32-1.48	541	16,23%		
Level 2 (50mm)	#S62- 38h	10,040	11,240		3,789	2,670		84,01	13,38		1,474	0,452		3369	14869
	Distri-bution	0-3	1082	32,12%	2.4-3.0	364	10,80%	88.1-92.0	654	19,41%	1,16-1,32	791	23,48%		
		3-6	549	16,30%	3.0-3.6	352	10,45%	92.0-96.0	522	15,49%	1,00-1,16	771	22,89%		
		6-9	412	12,23%	0.6-1.2	329	9,77%	84,1-88,1	473	14,04%	1.32-1.48	551	16,36%		
level 3 (100mm)	#S104- 38h	9,948	11,280		3,739	2,666		83,37	14,12		1,493	0,463		3902	17222
	Distri-bution	0-3	1326	33,98%	3.0-3.6	401	10,28%	88.1-92.0	721	18,48%	1.16-1.32	873	22,37%		
		3-6	570	14,61%	0.6-1.2	390	9,99%	96.0-100	570	14,61%	1.00-1.16	856	21,94%		
		6-9	446	11,43%	2.4-3.0	384	9,84%	84.1-88.1	551	14,12%	1.32-1.48	639	16,38%		
Level 1 (10mm)	#S21- 40h	11,010	12,070		3,975	2,696		84,37	15,03		1,443	0,502		2972	13117
	Distri-bution	0-3	521	17,53%	2.4-3.0	411	13,83%	88.1-92.0	565	19,01%	1,16-1,32	855	28,77%		
		3-6	589	19,82%	3.0-3.6	342	11,51%	84.1-88.1	499	16,79%	1,00-1,16	784	26,38%		
		6-9	419	14,10%	0.6-1.2	341	11,47%	96.0-100	449	15,11%	1.32-1.48	541	18,20%		
Level 2 (50mm)	#S63- 40h	10,960	11,670		3,980	2,623		85,52	12,82		1,422	0,398		3490	15403
	Distri-bution	0-3	1082	31,00%	2.4-3.0	364	10,43%	88.1-92.0	654	18,74%	1,16-1,32	791	22,66%		
		3-6	549	15,73%	3.0-3.6	352	10,09%	92.0-96.0	522	14,96%	1,00-1,16	771	22,09%		
		6-9	412	11,81%	0.6-1.2	329	9,43%	84,1-88,1	473	13,55%	1.32-1.48	551	15,79%		
level 3 (100mm)	#S105- 40h	12,530	11,890		4,350	2,620		85,28	12,91		1,435	0,412		3400	15006
	Distri-bution	0-3	1326	39,00%	3.0-3.6	401	11,79%	88.1-92.0	721	21,21%	1.16-1.32	873	25,68%		
		3-6	570	16,76%	0.6-1.2	390	11,47%	96.0-100	570	16,76%	1.00-1.16	856	25,18%		
		6-9	446	13,12%	2.4-3.0	384	11,29%	84.1-88.1	551	16,21%	1.32-1.48	639	18,79%		
Level 1 (10mm)	#S22- 42h	9,819	11,010		3,759	2,551		84,23	12,98		1,446	0,406		3574	15774
	Distri-bution	0-3	1175	32,88%	2.4-3.0	418	11,70%	88.1-92.0	711	19,89%	1,16-1,32	862	24,12%		
		3-6	611	17,10%	3.0-3.6	399	11,16%	92.0-96.2	579	16,20%	1,00-1,16	828	23,17%		
		6-9	453	12,67%	1.2-1.8	379	10,60%	84.1-88.1	559	15,64%	1.32-1.48	635	17,77%		
Level 2 (50mm)	#S64- 42h	9,770	10,960		3,766	2,544		84,45	13,04		1,453	0,414		3885	17147
	Distri-bution	0-3	1265	32,56%	3.0-3.6	431	11,09%	88.1-92.0	778	20,03%	1,16-1,32	963	24,79%		
		3-6	657	16,91%	1.2-1.8	407	10,48%	92.0-96.0	639	16,45%	1,00-1,16	873	22,47%		
		6-9	478	12,30%	2.4-3.0	407	10,48%	84,1-88,1	616	15,86%	1.32-1.48	666	17,14%		
level 3 (100mm)	#S106- 42h	10,620	11,350		3,923	2,635		83,79	13,60		1,467	0,429		3672	16207
	Distri-bution	0-3	1118	30,45%	2.4-3.0	371	10,10%	88.1-92.0	760	20,70%	1.16-1.32	875	23,83%		
		3-6	536	14,60%	3.0-3.6	357	9,72%	92.0-96.0	576	15,69%	1.00-1.16	797	21,70%		
		6-9	452	12,31%	0.6-1.2	352	9,59%	84.1-88.1	535	14,57%	1.32-1.48	647	17,62%		
Level 1 (10mm)	#S23- 44h	9,190	10,680		3,564	2,508		84,77	13,67		1,458	0,457		3754	16569
	Distri-bution	0-3	1390	37,03%	0.6-1.2	454	12,09%	88.1-92.0	781	20,80%	1,16-1,32	925	24,64%		
		3-6	612	16,30%	2.4-3.0	429	11,43%	92.0-96.0	635	16,92%	1,00-1,16	877	23,36%		
		6-9	394	10,50%	1.2-1.8	393	10,47%	96.0-100	577	15,37%	1.32-1.48	629	16,76%		
Level 2 (50mm)	#S65- 44h	10,410	11,450		3,836	2,612		84,68	13,65		1,448	0,437		3834	16922
	Distri-bution	0-3	1205	31,43%	2.4-3.0	423	11,03%	88.1-92.0	767	20,01%	1,16-1,32	976	25,46%		
		3-6	619	16,15%	3.0-3.6	415	10,82%	92.0-96.0	727	18,96%	1,00-1,16	919	23,97%		
		6-9	470	12,26%	0.6-1.2	352	9,18%	96.0-100	560	14,61%	1.32-1.48	620	16,17%		
level 3 (100mm)	#S107- 44h	10,710	11,030		3,983	2,563		84,91	12,38		1,459	0,423		3589	15840
	Distri-bution	0-3	1042	29,03%	3.0-3.6	376	10,48%	88.1-92.0	793	22,10%	1.16-1.32	880	24,52%		
		3-6	540	15,05%	2.4-3.0	356	9,92%	92.0-96.0	632	17,61%	1.00-1.16	797	22,21%		
		6-9	446	12,43%	1.2-1.8	329	9,17%	84.1-88.1	491	13,68%	1.32-1.48	614	17,11%		

Level 1 (10mm)	**#S24- 46h**	11,140	12,280		3,990	2,712		84,43	13,40		1,451	0,439		3069	13545
	Distri-bution	0-3	898	29,26%	2.4-3.0	334	10,88%	88.1-92.0	631	20,56%	1,16-1,32	769	25,06%		
		3-6	475	15,48%	3.0-3.6	312	10,17%	92.0-96.0	529	17,24%	1,00-1,16	743	24,21%		
		6-9	399	13,00%	0.6-1.2	279	9,09%	84.1-88.1	440	14,34%	1.32-1.48	493	16,06%		
Level 2 (50mm)	**#S66- 46h**	11,600	12,130		4,143	2,606		85,48	12,44		1,421	0,369		3255	14366
	Distri-bution	0-3	791	24,30%	3.0-3.6	372	11,43%	88.1-92.0	714	21,94%	1,16-1,32	836	25,68%		
		3-6	543	16,68%	2.4-3.0	371	11,40%	92.0-96.0	657	20,18%	1,00-1,16	775	23,81%		
		6-9	463	14,22%	4.2-4.8	300	9,22%	84.1-88.1	492	15,12%	1.32-1.48	587	18,03%		
level 3 (100mm)	**#S108- 46h**	12,500	11,680		4,381	2,558		85,71	11,67		1,424	0,381		3108	13717
	Distri-bution	0-3	637	20,50%	3.0-3.6	370	11,90%	88.1-92.0	788	25,35%	1.16-1.32	836	26,90%		
		3-6	474	15,25%	2.4-3.0	324	10,42%	92.0-96.0	630	20,27%	1.00-1.16	728	23,42%		
		6-9	415	13,35%	4.2-4.8	318	10,23%	84.1-88.1	487	15,67%	1.32-1.48	544	17,50%		
Level 1 (10mm)	**#S25- 48h**	10,200	12,300		3,669	2,827		84,31	14,53		1,465	0,479		3717	16405
	Distri-bution	0-3	1356	36,48%	0.0-0.6	438	11,78%	96.0-100	706	18,99%	1.00-1.16	954	25,67%		
		3-6	543	14,61%	0.6-1.2	424	11,41%	88.1-92.0	672	18,08%	1.16-1.32	862	23,19%		
		6-9	381	10,25%	2.4-3.0	400	10,76%	84.1-88.1	541	14,55%	1.32-1.48	555	14,93%		
Level 2 (50mm)	**#S67- 48h**	10,680	11,580		3,905	2,652		85,07	12,36		1,441	0,413		3274	14450
	Distri-bution	0-3	947	28,92%	2.4-3.0	390	11,91%	88.1-92.0	690	21,08%	1,16-1,32	868	26,51%		
		3-6	592	18,08%	3.0-3.6	329	10,05%	92.0-96.0	556	16,98%	1,00-1,16	769	23,49%		
		6-9	371	11,33%	0.6-1.2	293	8,95%	84.1-88.1	499	15,24%	1.32-1.48	536	16,37%		
level 3 (100mm)	**#S109- 48h**	11,430	11,670		4,152	2,658		84,61	12,12		1,470	0,428		3072	13559
	Distri-bution	0-3	791	25,75%	2.4-3.0	326	10,61%	88.1-92.0	651	21,19%	1.16-1.32	761	24,77%		
		3-6	479	15,59%	3.0-3.6	319	10,38%	92.0-96.0	518	16,86%	1.00-1.16	654	21,29%		
		6-9	382	12,43%	4.8-5.4	271	8,82%	84.1-88.1	495	16,11%	1.32-1.48	489	15,92%		
Level 1 (10mm)	**#S26- 50h**	9,869	10,350		3,891	2,475		84,83	12,49		1,436	0,392		3414	15068
	Distri-bution	0-3	966	28,30%	2,4-3,0	455	13,33%	88,1-92,0	744	21,79%	1,16-1,32	896	26,24%		
		3-6	658	19,27%	3,0-3,6	370	10,84%	92,0-96,0	659	19,30%	1,00-1,16	764	22,38%		
		6-9	446	13,06%	1,2-1,8	356	10,43%	84,1-88,1	479	14,03%	1.32-1.48	601	17,60%		
Level 2 (50mm)	**#S68- 50h**	9,766	9,947		3,850	2,372		84,87	12,16		1,434	0,387		3634	16039
	Distri-bution	0-3	1007	27,71%	2.4-3.0	490	13,48%	88.1-92.0	783	21,55%	1,16-1,32	957	26,33%		
		3-6	706	19,43%	3.0-3.6	404	11,12%	92.0-96.0	680	18,71%	1,00-1,16	808	22,23%		
		6-9	476	13,10%	1,2-1,8	396	10,90%	84.1-88.1	525	14,45%	1.32-1.48	652	17,94%		
level 3 (100mm)	**#S110- 50h**	10,480	10,320		4,064	2,451		84,10	12,56		1,462	0,424		3439	15178
	Distri-bution	0-3	834	24,25%	2.4-3.0	408	11,86%	88.1-92.0	736	21,40%	1.16-1.32	901	26,20%		
		3-6	645	18,76%	3.0-3.6	389	11,31%	92.0-96.0	609	17,71%	1.00-1.16	695	20,21%		
		6-9	467	13,58%	3,6-4,0	334	9,71%	84.1-88.1	535	15,56%	1.32-1.48	613	17,82%		
Level 1 (10mm)	**#S27- 52h**	9,752	10,440		3,859	2,443		84,19	12,74		1,438	0,396		3429	15134
	Distri-bution	0-3	1001	29,19%	2,4-3,0	450	13,12%	88,1-92,0	738	21,52%	1,16-1,32	907	26,45%		
		3-6	666	19,42%	1,2-1,8	384	11,20%	92,0-96,0	617	17,99%	1,00-1,16	781	22,78%		
		6-9	472	13,76%	3,0-3,6	380	11,08%	84,1-88,1	489	14,26%	1.32-1.48	573	16,71%		
Level 2 (50mm)	**#S69- 52h**	10,300	10,680		3,951	2,475		85,80	12,02		1,430	0,375		3494	15421
	Distri-bution	0-3	926	26,50%	2.4-3.0	442	12,65%	88.1-92.0	813	23,27%	1,16-1,32	909	26,02%		
		3-6	647	18,52%	3.0-3.6	398	11,39%	92.0-96.0	760	21,75%	1,00-1,16	774	22,15%		
		6-9	506	14,48%	1,2-1,8	355	10,16%	84.1-88.1	468	13,39%	1.32-1.48	651	18,63%		
level 3 (100mm)	**#S111- 52h**	10,290	9,969		4,012	2,356		86,00	11,29		1,438	0,395		3543	15637
	Distri-bution	0-3	866	24,44%	3,0-3,6	438	12,36%	88.1-92.0	836	23,60%	1.16-1.32	918	25,91%		
		3-6	641	18,09%	2,4-3,0	419	11,83%	92.0-96.0	797	22,50%	1.00-1.16	809	22,83%		
		6-9	522	14,73%	1,2-1,8	377	10,64%	84.1-88.1	549	15,50%	1.32-1.48	653	18,43%		

Level 1 (10mm)	**#S28- 54h**	11,040	12,290		4,053	2,703		83,42	15,66		1,469	0,512		3466	15298
	Distri-bution	0-3	946	27,29%	2,4-3,0	429	12,38%	92,0-96,0	672	19,39%	1,16-1,32	872	25,16%		
		3-6	658	18,98%	3,0-3,6	392	11,31%	88,1-92,0	661	19,07%	1,00-1,16	825	23,80%		
		6-9	424	12,23%	1,2-1,8	327	9,43%	84,1-88,1	473	13,65%	1.32-1.48	598	17,25%		
Level 2 (50mm)	**#S70- 54h**	11,150	11,560		4,104	2,543		85,58	12,22		1,420	0,380		3488	15395
	Distri-bution	0-3	876	25,11%	2.4-3.0	447	12,82%	88.1-92.0	799	22,91%	1,16-1,32	919	26,35%		
		3-6	652	18,69%	3.0-3.6	395	11,32%	92.0-96.0	780	22,36%	1,00-1,16	830	23,80%		
		6-9	457	13,10%	1,2-1,8	353	10,12%	84.1-88.1	469	13,45%	1.32-1.48	608	17,43%		
level 3 (100mm)	**#S112- 54h**	12,050	11,200		4,324	2,454		86,01	11,84		1,406	0,378		3400	15006
	Distri-bution	0-3	685	20,15%	3,0-3,6	387	11,38%	88.1-92.0	839	24,68%	1.16-1.32	970	28,53%		
		3-6	564	16,59%	2,4-3,0	354	10,41%	92.0-96.0	767	22,56%	1.00-1.16	808	23,76%		
		6-9	474	13,94%	4,2-4,8	353	10,38%	84.1-88.1	495	14,56%	1.32-1.48	597	17,56%		
Level 1 (10mm)	**#S29- 56h**	11,120	12,060		4,423	2,860		83,19	14,10		1,410	0,461		3034	13391
	Distri-bution	0-3	863	28,44%	3,0-3,6	355	11,70%	88,1-92,0	640	21,09%	1,16-1,32	810	26,70%		
		3-6	479	15,79%	2,4-3,0	325	10,71%	92,0-96,0	537	17,70%	1,00-1,16	733	24,16%		
		6-9	414	13,65%	1,2-1,8	290	9,56%	84,1-88,1	507	16,71%	1.32-1.48	532	17,53%		
Level 2 (50mm)	**#S71- 56h**	12,380	12,440		4,525	2,885		84,01	13,50		1,399	0,408		3370	14874
	Distri-bution	0-3	764	22,67%	2.4-3.0	395	11,72%	88.1-92.0	798	23,68%	1,16-1,32	921	27,33%		
		3-6	518	15,37%	3.0-3.6	351	10,42%	92.0-96.0	652	19,35%	1,00-1,16	720	21,36%		
		6-9	448	13,29%	1,2-1,8	325	9,64%	84.1-88.1	489	14,51%	1.32-1.48	570	16,91%		
level 3 (100mm)	**#S113- 56h**	11,720	10,820		4,324	2,454		84,74	12,42		1,422	0,388		3328	14688
	Distri-bution	0-3	622	18,70%	2,4-3,0	420	12,61%	88.1-92.0	791	23,77%	1.16-1.32	984	29,57%		
		3-6	579	17,39%	3,0-3,6	362	10,87%	92.0-96.0	643	19,32%	1.00-1.16	709	21,30%		
		6-9	492	14,78%	3,6-4,2	340	10,22%	84.1-88.1	546	16,41%	1.32-1.48	695	20,88%		
Level 1 (10mm)	**#S30- 58h**	10,630	11,320		4,535	2,954		82,78	15,35		1,421	0,524		3088	13629
	Distri-bution	0-3	824	26,68%	2,4-3,0	415	13,45%	88,1-92,0	628	20,34%	1,16-1,32	876	28,36%		
		3-6	597	19,33%	3,0-3,6	363	11,76%	92,0-96,0	626	20,27%	1,00-1,16	701	22,69%		
		6-9	428	13,87%	1,8-2,4	318	10,29%	84,1-88,1	472	15,28%	1.32-1.48	506	16,39%		
Level 2 (50mm)	**#S72- 58h**	11,253	12,270		4,628	2,975		83,77	14,19		1,405	0,401		3383	14931
	Distri-bution	0-3	904	26,71%	2.4-3.0	343	10,14%	88.1-92.0	741	21,90%	1,16-1,32	876	25,88%		
		3-6	434	12,84%	3.0-3.6	301	8,90%	92.0-96.0	697	20,60%	1,00-1,16	784	23,19%		
		6-9	385	11,39%	3,6-4,2	294	8,70%	84.1-88.1	469	13,86%	1.32-1.48	574	16,98%		
level 3 (100mm)	**#S114- 58h**	12,460	11,280		4,592	2,832		82,18	12,97		1,433	0,401		3016	13311
	Distri-bution	0-3	705	23,39%	3,0-3,6	363	12,03%	88.1-92.0	588	19,50%	1.16-1.32	766	25,39%		
		3-6	423	14,03%	4,2-4,8	302	10,02%	84,1-88,1	577	19,13%	1.00-1.16	705	23,39%		
		6-9	376	12,47%	2,4-3,0	262	8,69%	92,0-96,0	403	13,36%	1.32-1.48	551	18,26%		
Level 1 (10mm)	**#S31- 60h**	10,630	11,320		4,255	2,764		82,57	12,93		1,445	0,380		2648	11687
	Distri-bution	0-3	853	32,20%	2,4-3,0	327	12,35%	88,1-92,0	534	20,17%	1,16-1,32	686	25,91%		
		3-6	417	15,74%	3,0-3,6	269	10,17%	84,1-88,1	461	17,41%	1,00-1,16	628	23,73%		
		6-9	289	10,90%	1,8-2,4	250	9,44%	88,1-92,0	398	15,03%	1.32-1.48	417	15,74%		
Level 2 (50mm)	**#S73- 60h**	11,253	12,270		4,250	2,819		83,99	12,92		1,445	0,382		2995	13219
	Distri-bution	0-3	866	28,92%	2,4-3,0	337	11,24%	88.1-92.0	676	22,57%	1,16-1,32	722	24,10%		
		3-6	616	20,55%	3,6-4,2	353	11,77%	92.0-96.0	545	18,20%	1,00-1,16	686	22,91%		
		6-9	385	12,84%	3,0-3,6	321	10,70%	84.1-88.1	485	16,19%	1.32-1.48	571	19,05%		
level 3 (100mm)	**#S115- 60h**	10,840	11,700		4,575	3,091		82,12	13,35		1,488	0,422		3028	13364
	Distri-bution	0-3	815	26,91%	3,0-3,6	353	11,66%	88.1-92.0	618	20,41%	1.16-1.32	686	22,65%		
		3-6	489	16,14%	2,4-3,0	319	10,54%	84,1-88,1	511	16,88%	1.00-1.16	625	20,63%		
		6-9	414	13,68%	4,2-4,8	306	10,09%	92,0-96,0	416	13,74%	1.32-1.48	523	17,26%		

Level 1 (10mm)	**#S32- 62h**	10,590	11,980		3,925	2,739		82,71	15,25		1,463	0,459		3820	16860
	Distri-bution	0-3	1225	32,07%	2,4-3,0	400	10,47%	88.1-92.0	681	17,83%	1,16-1,32	918	24,03%		
		3-6	596	15,60%	3,0-3,6	390	10,21%	92.0-96.0	587	15,37%	1,00-1,16	895	23,43%		
		6-9	459	12,02%	1,2-1,8	366	9,58%	96,0-100	527	13,80%	1.32-1.48	609	15,94%		
Level 2 (50mm)	**#S74- 62h**	11,800	12,060		4,237	2,692		84,08	12,90		1,434	0,388		3402	15015
	Distri-bution	0-3	863	25,37%	2,4-3,0	392	11,52%	88.1-92.0	716	21,05%	1,16-1,32	828	24,34%		
		3-6	569	16,73%	3,6-4,2	350	10,29%	92.0-96.0	605	17,78%	1,00-1,16	802	23,57%		
		6-9	408	11,99%	1,2-1,8	308	9,05%	84.1-88.1	525	15,43%	1.32-1.48	606	17,81%		
level 3 (100mm)	**#S116- 62h**	14,100	13,170		4,685	2,780		84,13	13,03		1,436	0,386		3250	14344
	Distri-bution	0-3	626	19,26%	3,0-3,6	317	9,75%	88.1-92.0	695	21,38%	1.16-1.32	840	25,85%		
		3-6	459	14,12%	4,2-4,8	307	9,45%	92,0-96,0	610	18,77%	1.00-1.16	731	22,49%		
		6-9	395	12,15%	2,4-3,0	302	9,29%	84,1-88,1	510	15,69%	1.32-1.48	561	17,26%		
Level 1 (10mm)	**#S33- 64h**	11,080	12,470		3,995	2,793		83,66	13,79		1,443	0,423		3242	14309
	Distri-bution	0-3	986	30,41%	2,4-3,0	366	11,29%	88.1-92.0	615	18,97%	1,16-1,32	808	24,92%		
		3-6	539	16,63%	3,0-3,6	338	10,43%	92.0-96.0	501	15,45%	1,00-1,16	758	23,38%		
		6-9	393	12,12%	1,2-1,8	288	8,88%	84,1-88,1	479	14,77%	1.32-1.48	580	17,89%		
Level 2 (50mm)	**#S75- 64h**	12,140	12,310		4,229	2,701		84,71	12,71		1,422	0,393		3299	14560
	Distri-bution	0-3	795	24,10%	2,4-3,0	357	10,82%	88.1-92.0	753	22,83%	1,16-1,32	860	26,07%		
		3-6	542	16,43%	3,0-3,6	351	10,64%	92.0-96.0	545	16,52%	1,00-1,16	812	24,61%		
		6-9	413	12,52%	4,2-4,8	291	8,82%	84.1-88.1	471	14,28%	1.32-1.48	567	17,19%		
level 3 (100mm)	**#S117- 64h**	11,350	12,110		4,006	2,741		84,05	13,01		1,463	0,411		3514	15509
	Distri-bution	0-3	1016	28,91%	3,0-3,6	346	9,85%	88.1-92.0	661	18,81%	1.16-1.32	808	22,99%		
		3-6	497	14,14%	4,2-4,8	337	9,59%	84,1-88,1	552	15,71%	1.00-1.16	793	22,57%		
		6-9	407	11,58%	2,4-3,0	317	9,02%	96,0-100	506	14,40%	1.32-1.48	578	16,45%		
Level 1 (10mm)	**#S34- 66h**	11,250	12,650		4,106	2,757		81,75	14,96		1,456	0,419		3322	14662
	Distri-bution	0-3	964	29,02%	2,4-3,0	383	11,53%	88.1-92.0	586	17,64%	1,16-1,32	823	24,77%		
		3-6	579	17,43%	3,0-3,6	355	10,69%	92.0-96.0	489	14,72%	1,00-1,16	705	21,22%		
		6-9	420	12,64%	1,2-1,8	327	9,84%	84,1-88,1	472	14,21%	1.32-1.48	599	18,03%		
Level 2 (50mm)	**#S76- 66h**	12,670	13,000		4,329	2,755		83,31	13,74		1,435	0,406		3244	14318
	Distri-bution	0-3	792	24,41%	2,4-3,0	353	10,88%	88.1-92.0	664	20,47%	1,16-1,32	829	25,55%		
		3-6	498	15,35%	3,0-3,6	310	9,56%	92.0-96.0	528	16,28%	1,00-1,16	761	23,46%		
		6-9	379	11,68%	4,2-4,8	273	8,42%	84.1-88.1	508	15,66%	1.32-1.48	545	16,80%		
level 3 (100mm)	**#S118- 66h**	12,870	12,920		4,391	2,722		83,46	13,36		1,460	0,415		3271	14437
	Distri-bution	0-3	791	24,18%	3,0-3,6	344	10,52%	88.1-92.0	705	21,55%	1.16-1.32	798	24,40%		
		3-6	453	13,85%	2,4-3,0	296	9,05%	92,0-96,0	521	15,93%	1.00-1.16	727	22,23%		
		6-9	425	12,99%	4,2-4,8	277	8,47%	84,1-88,1	514	15,71%	1.32-1.48	533	16,29%		
Level 1 (10mm)	**#S35- 68h**	12,090	13,440		4,208	2,738		82,84	13,10		1,431	0,372		2958	13055
	Distri-bution	0-3	770	26,03%	2,4-3,0	357	12,07%	88.1-92.0	553	18,70%	1,16-1,32	712	24,07%		
		3-6	507	17,14%	3,0-3,6	333	11,26%	92.0-96.0	439	14,84%	1,00-1,16	687	23,23%		
		6-9	401	13,56%	3,6-4,2	244	8,25%	84,1-88,1	433	14,64%	1.32-1.48	519	17,55%		
Level 2 (50mm)	**#S77- 68h**	12,040	12,780		4,223	2,684		83,97	12,73		1,426	0,365		3152	13912
	Distri-bution	0-3	807	25,60%	2,4-3,0	341	10,82%	88.1-92.0	699	22,18%	1,16-1,32	822	26,08%		
		3-6	528	16,75%	3,0-3,6	327	10,37%	84,1-88,1	511	16,21%	1,00-1,16	713	22,62%		
		6-9	387	12,28%	1,2-1,8	285	9,04%	92,0-96,0	493	15,64%	1.32-1.48	556	17,64%		
level 3 (100mm)	**#S119- 68h**	13,080	12,690		4,472	2,676		84,80	12,10		1,446	0,409		2830	12491
	Distri-bution	0-3	614	21,70%	3,0-3,6	305	10,78%	88.1-92.0	657	23,22%	1.16-1.32	739	26,11%		
		3-6	404	14,28%	2,4-3,0	284	10,04%	92,0-96,0	509	17,99%	1.00-1.16	617	21,80%		
		6-9	366	12,93%	4,8-5,4	250	8,83%	84,1-88,1	459	16,22%	1.32-1.48	512	18,09%		

Level 1 (10mm)	#S36- 70h	12,100	13,010		4,253	2,699		80,59	13,92		1,433	0,426		2499	11030
	Distri-bution	0-3	604	24,17%	2,4-3,0	308	12,32%	88.1-92.0	375	15,01%	1,16-1,32	626	25,05%		
		3-6	449	17,97%	3,0-3,6	269	10,76%	84,1-92,0	360	14,41%	1,00-1,16	617	24,69%		
		6-9	320	12,81%	3,6-4,2	227	9,08%	92,0-96,0	306	12,24%	1.32-1.48	430	17,21%		
Level 2 (50mm)	#S78- 70h	13,060	13,320		4,462	2,793		84,40	12,48		1,442	0,402		2687	11859
	Distri-bution	0-3	611	22,74%	2,4-3,0	307	11,43%	88.1-92.0	574	21,36%	1,16-1,32	746	27,76%		
		3-6	430	16,00%	3,0-3,6	275	10,23%	92,0-96,0	499	18,57%	1,00-1,16	584	21,73%		
		6-9	326	12,13%	4,2-4,8	236	8,78%	84,1-88,1	422	15,71%	1.32-1.48	441	16,41%		
level 3 (100mm)	#S120- 70h	14,110	13,300		4,658	2,667		85,40	11,53		1,435	0,402		2572	11352
	Distri-bution	0-3	457	17,77%	2,4-3,0	284	11,04%	88.1-92.0	650	25,27%	1.16-1.32	706	27,45%		
		3-6	381	14,81%	3,0-3,6	261	10,15%	92,0-96,0	540	21,00%	1.00-1.16	583	22,67%		
		6-9	331	12,87%	4,2-4,8	255	9,91%	84,1-88,1	377	14,66%	1.32-1.48	467	18,16%		
Level 1 (10mm)	#S37- 72h	13,360	13,550		4,490	2,811		84,86	12,66		1,423	0,374		2541	11215
	Distri-bution	0-3	563	22,16%	2,4-3,0	277	10,90%	88.1-92.0	549	21,61%	1,16-1,32	683	26,88%		
		3-6	404	15,90%	3,0-3,6	276	10,86%	92,0-96,0	488	19,21%	1,00-1,16	577	22,71%		
		6-9	322	12,67%	4,2-4,8	214	8,42%	84,1-88,1	407	16,02%	1.32-1.48	448	17,63%		
Level 2 (50mm)	#S79- 72h	12,660	12,650		4,417	2,701		84,10	12,65		1,446	0,380		2640	11652
	Distri-bution	0-3	597	22,61%	2,4-3,0	296	11,21%	88.1-92.0	555	21,02%	1,16-1,32	687	26,02%		
		3-6	423	16,02%	3,0-3,6	284	10,76%	92,0-96,0	459	17,39%	1,00-1,16	541	20,49%		
		6-9	359	13,60%	4,2-4,8	234	8,86%	84,1-88,1	442	16,74%	1.32-1.48	482	18,26%		
level 3 (100mm)	#S121- 72h	14,860	14,350		4,806	2,889		83,80	12,69		1,459	0,424		2245	9909
	Distri-bution	0-3	402	17,91%	4,2-4,8	217	9,67%	88.1-92.0	493	21,96%	1.16-1.32	558	24,86%		
		3-6	319	14,21%	2,4-3,0	212	9,44%	92,0-96,0	376	16,75%	1.00-1.16	495	22,05%		
		6-9	274	12,20%	3,0-3,6	210	9,35%	84,1-88,1	362	16,12%	1.32-1.48	409	18,22%		
Level 1 (10mm)	#S38- 74h	12,370	12,830		4,358	2,727		82,89	13,08		1,444	0,374		2498	11025
	Distri-bution	0-3	579	23,18%	2,4-3,0	296	11,85%	88.1-92.0	532	21,30%	1,16-1,32	671	26,86%		
		3-6	429	17,17%	3,0-3,6	250	10,01%	84,1-88,1	416	16,65%	1,00-1,16	486	19,46%		
		6-9	324	12,97%	1,2-1,8	232	9,29%	92,0-96,2	377	15,09%	1.32-1.48	466	18,65%		
Level 2 (50mm)	#S80- 74h	12,960	12,890		4,438	2,693		86,36	12,02		1,425	0,381		2746	12120
	Distri-bution	0-3	589	21,45%	2,4-3,0	297	10,82%	88.1-92.0	656	23,89%	1,16-1,32	732	26,66%		
		3-6	438	15,95%	3,0-3,6	286	10,42%	92,0-96,0	587	21,38%	1,00-1,16	633	23,05%		
		6-9	339	12,35%	3,6-4,2	265	9,65%	84,1-88,1	387	14,09%	1.32-1.48	479	17,44%		
level 3 (100mm)	#S122- 74h	13,210	12,450		4,500	2,578		83,69	12,03		1,449	0,396		2682	11837
	Distri-bution	0-3	523	19,50%	2,4-3,0	289	10,78%	88.1-92.0	591	22,04%	1.16-1.32	705	26,29%		
		3-6	422	15,73%	3,0-3,6	271	10,10%	84,1-88,1	439	16,37%	1.00-1.16	551	20,54%		
		6-9	361	13,46%	3,6-4,2	248	9,25%	92,0-96,2	400	14,91%	1.32-1.48	496	18,49%		
Level 1 (10mm)	#S39- 76h	12,070	12,840		4,233	2,744		82,79	14,78		1,450	0,451		2995	13219
	Distri-bution	0-3	792	26,44%	2,4-3,0	309	10,32%	88.1-92.0	600	20,03%	1,16-1,32	769	25,68%		
		3-6	460	15,36%	3,0-3,6	299	9,98%	84,1-88,1	478	15,96%	1,00-1,16	683	22,80%		
		6-9	377	12,59%	3,6-4,2	279	9,32%	92,0-96,2	456	15,23%	1.32-1.48	522	17,43%		
Level 2 (50mm)	#S81- 76h	12,970	13,460		4,373	2,831		83,93	13,91		1,442	0,454		3118	13762
	Distri-bution	0-3	750	24,05%	3,0-3,6	317	10,17%	88.1-92.0	614	19,69%	1,16-1,32	797	25,56%		
		3-6	453	14,53%	2,4-3,0	311	9,97%	92,0-96,0	531	17,03%	1,00-1,16	780	25,02%		
		6-9	402	12,89%	3,6-4,2	276	8,85%	84,1-88,1	488	15,65%	1.32-1.48	527	16,90%		
level 3 (100mm)	#S123- 76h	12,310	12,600		4,323	2,817		82,30	13,73		1,498	0,437		3108	13717
	Distri-bution	0-3	796	25,61%	2,4-3,0	293	9,43%	88.1-92.0	545	17,54%	1.16-1.32	697	22,43%		
		3-6	453	14,58%	4,2-4,8	288	9,27%	84,1-88,1	480	15,44%	1.00-1.16	606	19,50%		
		6-9	360	11,58%	3,0-3,6	280	9,01%	92,0-96,2	408	13,13%	1.32-1.48	546	17,57%		

Level 1 (10mm)	#S40- 78h	11,450	13,140		4,056	2,837		82,71	14,33		1,462	0,428		3080	13594
	Distri-bution	0-3	928	30,13%	2,4-3,0	339	11,01%	88.1-92.0	588	19,09%	1,16-1,32	765	24,84%		
		3-6	487	15,81%	3,0-3,6	314	10,19%	84,1-88,1	464	15,06%	1,00-1,16	670	21,75%		
		6-9	372	12,08%	4,2-4,8	270	8,77%	96,0-100	396	12,86%	1.32-1.48	517	16,79%		
Level 2 (50mm)	#S82- 78h	13,070	12,970		4,459	2,694		84,04	12,24		1,428	0,391		2881	12716
	Distri-bution	0-3	636	22,08%	2,4-3,0	311	10,79%	88.1-92.0	606	21,03%	1,16-1,32	746	25,89%		
		3-6	452	15,69%	3,0-3,6	303	10,52%	92,0-96,0	501	17,39%	1,00-1,16	645	22,39%		
		6-9	377	13,09%	4,2-4,8	271	9,41%	84,1-88,1	462	16,04%	1.32-1.48	569	19,75%		
level 3 (100mm)	#S124- 78h	13,980	12,990		4,669	2,713		84,22	12,63		1,427	0,389		2889	12751
	Distri-bution	0-3	539	18,66%	3,0-3,6	302	10,45%	88.1-92.0	689	23,85%	1.16-1.32	779	26,96%		
		3-6	425	14,71%	2,4-3,0	292	10,11%	92,0-96,0	518	17,93%	1.00-1.16	676	23,40%		
		6-9	344	11,91%	4,2-4,8	267	9,24%	84,1-88,1	436	15,09%	1.32-1.48	490	16,96%		
Level 1 (10mm)	#S41- 80h	12,130	12,960		4,274	2,724		83,18	13,07		1,424	0,382		2956	13047
	Distri-bution	0-3	715	24,19%	2,4-3,0	362	12,25%	88.1-92.0	587	19,86%	1,16-1,32	813	27,50%		
		3-6	521	17,63%	3,0-3,6	321	10,86%	84,1-88,1	479	16,20%	1,00-1,16	671	22,70%		
		6-9	396	13,40%	3,6-4,2	249	8,42%	92,0-96,0	453	15,32%	1.32-1.48	509	17,22%		
Level 2 (50mm)	#S83- 80h	12,020	12,490		4,251	2,711		82,91	13,79		1,447	0,396		3193	14093
	Distri-bution	0-3	817	25,59%	2,4-3,0	344	10,77%	88.1-92.0	627	19,64%	1,16-1,32	829	25,96%		
		3-6	494	15,47%	3,0-3,6	326	10,21%	92,0-96,0	478	14,97%	1,00-1,16	683	21,39%		
		6-9	403	12,62%	3,6-4,2	281	8,80%	84,1-88,1	454	14,22%	1.32-1.48	549	17,19%		
level 3 (100mm)	#S125- 80h	12,940	12,720		4,502	2,713		83,07	13,38		1,459	0,418		2897	12786
	Distri-bution	0-3	608	20,99%	2,4-3,0	309	10,67%	88.1-92.0	644	22,23%	1.16-1.32	721	24,89%		
		3-6	444	15,33%	3,0-3,6	295	10,18%	84,1-88,1	461	15,91%	1.00-1.16	622	21,47%		
		6-9	371	12,81%	4,2-4,8	271	9,35%	92,0-96,0	429	14,81%	1.32-1.48	547	18,88%		

Silicon Particles Analysis (SuperHeat)

Magnification:	1000 X	Field Area (µm2) :	5664	Updated:	
No. of Fields:	40	Total Area (µm2) :	2,26572E+05	2005-09-30	

Level	Sample ID	Area (µm2)			Length (µm)			Roundness (%)			Aspect Ratio			Total # Features	Si Particle Density
		Ave.	SD		Ave.	SD		Ave.	SD		Ave.	SD			
	S1- 0 0h	1,619	3,369		1,942	2,040		74,76	22,84		1,848	0,781			
		Range	Qty.	Percent	Range	Qty.	Percent	Range	Qty.	Percent	Range	Qty.	Percent		
Level 1 (10mm)	Distri-bution	0-3.2	16010	89,30%	0-1.2	8076	45,05%	96.0-100	3457	19,28%	1.00-1.36	5587	31,16%	17928	79127
		3.2-6.4	1212	6,76%	1.2-2.4	5648	31,50%	88.1-92.0	1825	10,18%	1.36-1.72	4167	23,24%		
		6.4-9.6	334	1,86%	2.4-3.6	2148	11,98%	84.1-88.1	1784	9,95%	1.72-2.08	3591	20,03%		
	S2-0 0h	2,803	4,447		2,623	2,539		74,78	23,20		1,787	0,751			
Level 2 (50mm)	Distri-bution	0-3.2	11111	76,32%	1.2-2.4	5677	39,00%	96.0-100	2319	15,93%	1.00-1.36	4988	34,26%	14558	64253
		3.2-6.4	2131	14,64%	0-1.2	3602	24,74%	88.1-92.0	1836	12,61%	1.36-1.72	3656	25,11%		
		6.4-9.6	614	4,22%	2.4-3.6	2458	16,88%	92.0-96.0	1620	11,13%	1.72-2.08	2445	16,79%		
	S3-0- 0h	4,403	6,202		3,287	2,955		73,43	23,77		1,786	0,723			
level 3 (100mm)	Distri-bution	0-3.2	6785	59,42%	1.2-2.4	4026	35,26%	96-100	1590	13,93%	1.00-1.36	3709	32,48%	11418	50395
		3.2-6.4	2478	21,70%	2.4-3.6	2305	20,19%	88.1-92.0	1464	12,82%	1.36-1.72	2964	25,96%		
		6.4-9.6	999	8,75%	0-1.2	1729	15,14%	92.0-96.0	1409	12,34%	1.72-2.08	1929	16,89%		
	S1-1 8h	7,192	8,313		3,476	2,634		82,29	15,71		1,573	0,678			
Level 1 (10mm)	Distri-bution	0-3.2	1724	40,21%	2.4-3.6	1036	24,16%	88.1-92.0	762	17,77%	1.00-1.36	2044	47,67%	4288	18926
		3.2-6.4	882	20,57%	1.2-2.4	1028	23,97%	92.0-96.0	707	16,49%	1.36-1.72	1153	26,89%		
		6.4-9.6	600	13,99%	3.6-4.8	666	15,53%	96.0-100	578	13,48%	1.72-2.08	586	13,67%		
	S2-1 8h	7,711	8,420		3,591	2,651		84,58	14,53		1,496	0,476			
Level 2 (50mm)	Distri-bution	0-3.2	1721	35,53%	2.4-3.6	1224	25,27%	92.0-96.0	992	20,48%	1.00-1.36	2452	50,62%	4844	21380
		3.2-6.4	1072	22,13%	1.2-2.4	1056	21,80%	88.1-92.0	965	19,92%	1.36-1.72	1278	26,38%		
		6.4-9.6	703	14,51%	3.6-4.8	766	15,81%	96.0-100	773	15,96%	1.72-2.08	657	13,56%		
	S3-1 8h	7,833	8,482		3,703	2,750		83,48	14,82		1,496	0,479			
level 3 (100mm)	Distri-bution	0-3.2	1614	33,29%	2.4-3.6	1341	27,66%	88.1-92.0	981	20,24%	1.00-1.36	2489	51,34%	4848	21397
		3.2-6.4	1117	23,04%	1.2-2.4	1071	22,09%	92.0-96.0	922	19,02%	1.36-1.72	1279	26,38%		
		6.4-9.6	778	16,05%	3.6-4.8	784	16,17%	84.1-88.1	623	12,85%	1.72-2.08	623	12,85%		
	S1-2 16h	8,605	9,577		3,776	2,745		82,99	14,71		1,516	0,526			
Level 1 (10mm)	Distri-bution	0-3.2	1238	35,25%	2.4-3.6	822	23,41%	88.1-92.0	657	18,71%	1.00-1.36	1766	50,28%	3512	15501
		3.2-6.4	689	19,62%	1.2-2.4	787	22,41%	92.0-96.0	582	16,57%	1.36-1.72	925	26,34%		
		6.4-9.6	484	13,78%	3.6-4.8	534	15,21%	84.1-88.1	496	14,12%	1.72-2.08	466	13,27%		
	S2-2 16h	8,957	9,374		3,862	2,701		84,27	13,85		1,467	0,470			
Level 2 (50mm)	Distri-bution	0-3.2	1130	30,90%	2.4-3.6	898	24,56%	88.1-92.0	756	20,67%	1.00-1.36	1995	54,55%	3657	16141
		3.2-6.4	725	19,82%	1.2-2.4	768	21,00%	92.0-96.0	747	20,43%	1.36-1.72	925	25,29%		
		6.4-9.6	559	15,29%	3.6-4.8	650	17,77%	84.1-88.1	480	13,13%	1.72-2.08	426	11,65%		
	S3-2 16h	9,455	9,524		4,076	2,867		83,41	14,32		1,503	0,503			
level 3 (100mm)	Distri-bution	0-3.2	1061	26,74%	2.4-3.6	1005	25,33%	88.1-92.0	776	19,56%	1.00-1.36	1982	49,95%	3968	17513
		3.2-6.4	837	21,09%	3.6-4.8	765	19,28%	92.0-96.0	720	18,15%	1.36-1.72	1097	27,65%		
		6.4-9.6	660	16,63%	1.2-2.4	717	18,07%	84.1-88.1	577	14,54%	1.72-2.08	530	13,36%		

Level 1 (10mm)	**S1-3 24h**	10,510	10,680		4,228	2,856		82,76	13,34		1,496	0,455		2424	10699
	Distri-bution	0-3.2	653	26,94%	2.4-3.6	551	22,73%	88.1-92.0	474	19,55%	1.00-1.36	1186	48,93%		
		3.2-6.4	470	19,39%	1.2-2.4	445	18,36%	84.1-88.1	381	15,72%	1.36-1.72	697	28,75%		
		6.4-9.6	335	13,82%	3.6-4.8	445	18,36%	92.0-96.0	377	15,55%	1.72-2.08	315	13,00%		
Level 2 (50mm)	**S2-3 24h**	10,71	11,000		4,284	2,969		83,04	13,78		1,496	0,475		2920	12888
	Distri-bution	0-3.2	806	27,60%	2.4-3.6	690	23,63%	88.1-92.0	586	20,07%	1.00-1.36	1459	49,97%		
		3.2-6.4	533	18,25%	1.2-2.4	538	18,42%	84.1-88.1	466	15,96%	1.36-1.72	821	28,12%		
		6.4-9.6	394	13,49%	3.6-4.8	496	16,99%	92.0-96.0	464	15,89%	1.72-2.08	353	12,09%		
level 3 (100mm)	**S3-3 24h**	10,930	11,240		4,285	2,963		83,29	13,44		1,508	0,523		3194	14097
	Distri-bution	0-3.2	814	25,49%	2.4-3.6	752	23,54%	88.1-92.0	641	20,07%	1.00-1.36	1611	50,44%		
		3.2-6.4	619	19,38%	3.6-4.8	569	17,81%	92.0-96.0	533	16,69%	1.36-1.72	864	27,05%		
		6.4-9.6	472	14,78%	1.2-2.4	505	15,81%	84.1-88.1	453	14,18%	1.72-2.08	411	12,87%		
Level 1 (10mm)	**S1-4 32h**	12,650	13,070		4,496	3,111		81,75	15,23		1,486	0,519		2312	10204
	Distri-bution	0-3.2	578	25,00%	2.4-3.6	449	19,42%	88.1-92.0	426	18,43%	1.00-1.36	1212	52,42%		
		3.2-6.4	359	15,53%	3.6-4.8	418	18,08%	92.0-96.0	332	14,36%	1.36-1.72	632	27,34%		
		6.4-9.6	298	12,89%	4.8-6.0	310	13,41%	84.1-88.1	313	13,54%	1.72-2.08	286	12,37%		
Level 2 (50mm)	**S2-4 32h**	12,44	13,790		4,526	3,462		79,24	15,86		1,505	0,555		2650	11696
	Distri-bution	0-3.2	754	28,45%	2.4-3.6	518	19,55%	88.1-92.0	395	14,91%	1.00-1.36	1351	50,98%		
		3.2-6.4	415	15,66%	1.2-2.4	429	16,19%	84.1-88.1	364	13,74%	1.36-1.72	735	27,74%		
		6.4-9.6	327	12,34%	3.6-4.8	415	15,66%	92.0-96.0	287	10,83%	1.72-2.08	332	12,53%		
level 3 (100mm)	**S3-4 32h**	12,030	12,340		4,455	3,194		79,45	14,92		1,492	0,489		3264	14406
	Distri-bution	0-3.2	870	26,65%	2.4-3.6	680	20,83%	88.1-92.0	431	13,20%	1.00-1.36	1657	50,77%		
		3.2-6.4	543	16,64%	3.6-4.8	557	17,06%	84.1-88.1	411	12,59%	1.36-1.72	925	28,34%		
		6.4-9.6	400	12,25%	1.2-2.4	475	14,55%	92.0-96.0	377	11,55%	1.72-2.08	398	12,19%		
Level 1 (10mm)	**S1-5 40h**	12,250	13,540		4,384	3,393		79,13	18,03		1,698	1,046		2182	9630
	Distri-bution	0-3.2	681	31,21%	3.6-4.8	417	19,11%	88.1-92.0	325	14,89%	1.00-1.36	1049	48,08%		
		3.2-6.4	318	14,57%	0-1.2	364	16,68%	92.0-96.0	294	13,47%	1.36-1.72	551	25,25%		
		6.4-9.6	232	10,63%	3.6-4.8	308	14,12%	84.1-88.1	282	12,92%	1.72-2.08	267	12,24%		
Level 2 (50mm)	**S2-5 40h**	12,42	12,820		4,600	3,331		82,28	14,47		1,515	0,551		2493	11003
	Distri-bution	0-3.2	610	24,47%	2.4-3.6	514	20,62%	88.1-92.0	457	18,33%	1.00-1.36	1231	49,38%		
		3.2-6.4	435	17,45%	3.6-4.8	400	16,04%	92.0-96.0	386	15,48%	1.36-1.72	686	27,52%		
		6.4-9.6	300	12,03%	1.2-2.4	357	14,32%	84.1-88.1	343	13,76%	1.72-2.08	347	13,92%		
level 3 (100mm)	**S3-5 40h**	11,700	12,500		4,408	3,071		76,18	22,00		1,762	1,360		2976	13135
	Distri-bution	0-3.2	895	30,07%	2.4-3.6	600	20,16%	88.1-92.0	462	15,52%	1.00-1.36	1368	45,97%		
		3.2-6.4	433	14,55%	1.2-2.4	516	17,34%	92.0-96.0	407	13,68%	1.36-1.72	695	23,35%		
		6.4-9.6	318	10,69%	3.6-4.8	496	16,67%	84.1-88.1	375	12,60%	1.72-2.08	389	13,07%		
Level 1 (10mm)	**S1-6 48h**	13,840	14,530		4,820	3,515		81,98	14,38		1,490	0,459		2085	9202
	Distri-bution	0-3.2	499	23,93%	2.4-3.6	416	19,95%	88.1-92.0	371	17,79%	1.00-1.36	1040	49,88%		
		3.2-6.4	326	15,64%	3.6-4.8	323	15,49%	84.1-88.1	306	14,68%	1.36-1.72	586	28,11%		
		6.4-9.6	239	11,46%	4.8-6.0	271	13,00%	92.0-96.0	292	14,00%	1.72-2.08	277	13,29%		
Level 2 (50mm)	**S2-6 48h**	13,56	14,560		4,680	3,560		81,58	14,89		1,502	0,500		2430	10725
	Distri-bution	0-3.2	683	28,11%	2.4-3.6	421	17,33%	88.1-92.0	414	17,04%	1.00-1.36	1208	49,71%		
		3.2-6.4	327	13,46%	3.6-4.8	362	14,90%	84.1-88.1	379	15,60%	1.36-1.72	691	28,44%		
		6.4-9.6	247	10,16%	0-1.2	359	14,77%	96.0-100	286	11,77%	1.72-2.08	297	12,22%		
level 3 (100mm)	**S3-6 48h**	14,310	14,770		4,880	3,502		82,35	13,79		1,491	0,462		2735	12071
	Distri-bution	0-3.2	655	23,95%	2.4-3.6	508	18,57%	88.1-92.0	496	18,14%	1.00-1.36	1384	50,60%		
		3.2-6.4	369	13,49%	3.6-4.8	443	16,20%	92.0-96.0	417	15,25%	1.36-1.72	738	26,98%		
		6.4-9.6	321	11,74%	1.2-2.4	366	13,38%	84.1-88.1	412	15,06%	1.72-2.08	358	13,09%		

Level 1 (10mm)	S1-7 56h	14,500	14,090		5,030	3,498		79,94	14,88		1,523	0,564		1790	7900
	Distri-bution	0-3.2	387	21,62%	2.4-3.6	329	18,38%	88.1-92.0	278	15,53%	1.00-1.36	887	49,55%		
		3.2-6.4	270	15,08%	3.6-4.8	282	15,75%	84.1-88.1	265	14,80%	1.36-1.72	465	25,98%		
		6.4-9.6	198	11,06%	1.2-2.4	234	13,07%	92.0-96.0	234	13,07%	1.72-2.08	258	14,41%		
Level 2 (50mm)	S2-7 56h	15,56	14,530		5,248	3,491		79,97	14,11		1,496	0,466		1933	8532
	Distri-bution	0-3.2	341	17,64%	2.4-3.6	378	19,56%	88.1-92.0	309	15,99%	1.00-1.36	964	49,87%		
		3.2-6.4	286	14,80%	3.6-4.8	330	17,07%	84.1-88.1	284	14,69%	1.36-1.72	546	28,25%		
		6.4-9.6	257	13,30%	4.8-6.0	255	13,19%	92.0-96.0	235	12,16%	1.72-2.08	234	12,11%		
level 3 (100mm)	S3-7 56h	15,230	14,850		5,169	3,632		80,37	15,78		1,598	0,866		2006	8854
	Distri-bution	0-3.2	403	20,09%	3.6-4.8	355	17,70%	88.1-92.0	364	18,15%	1.00-1.36	988	49,25%		
		3.2-6.4	270	13,46%	2.4-3.6	348	17,35%	84.1-88.1	303	15,10%	1.36-1.72	550	27,42%		
		6.4-9.6	241	12,01%	4.8-6.0	258	12,86%	92.0-96.0	276	13,76%	1.72-2.08	248	12,36%		
Level 1 (10mm)	S1-8 64h	15,910	15,240		5,195	3,385		82,34	13,43		1,489	0,470		1799	7940
	Distri-bution	0-3.2	317	17,62%	2.4-3.6	343	19,07%	88.1-92.0	347	19,29%	1.00-1.36	895	49,75%		
		3.2-6.4	260	14,45%	3.6-4.8	305	16,95%	84.1-88.1	287	15,95%	1.36-1.72	530	29,46%		
		6.4-9.6	220	12,23%	4.8-6.0	266	14,79%	92.0-96.0	244	13,56%	1.72-2.08	231	12,84%		
Level 2 (50mm)	S2-8 64h	15,99	15,710		5,176	3,692		83,31	13,57		1,502	0,484		1986	8765
	Distri-bution	0-3.2	445	22,41%	2.4-3.6	325	16,36%	88.1-92.0	341	17,17%	1.00-1.36	979	49,30%		
		3.2-6.4	243	12,24%	3.6-4.8	284	14,30%	92.0-96.0	326	16,41%	1.36-1.72	543	27,34%		
		6.4-9.6	213	10,73%	1.2-2.4	242	12,19%	84.1-88.1	300	15,11%	1.72-2.08	286	14,40%		
level 3 (100mm)	S3-8 64h	16,240	14,820		5,245	3,235		83,75	11,81		1,471	0,429		2175	9600
	Distri-bution	0-3.2	350	16,09%	3.6-4.8	382	17,56%	88.1-92.0	439	20,18%	1.00-1.36	1117	51,36%		
		3.2-6.4	300	13,79%	2.4-3.6	378	17,38%	92.0-96.0	366	16,83%	1.36-1.72	616	28,32%		
		6.4-9.6	260	11,95%	4.8-6.0	321	14,76%	84.1-88.1	356	16,37%	1.72-2.08	264	12,14%		
Level 1 (10mm)	S1-9 72h	16,610	16,440		5,314	3,759		80,05	14,96		1,514	0,552		1798	7936
	Distri-bution	0-3.2	364	20,24%	2.4-3.6	299	16,63%	88.1-92.0	255	14,18%	1.00-1.36	921	51,22%		
		3.2-6.4	217	12,07%	3.6-4.8	278	15,46%	80.2-84.1	249	13,85%	1.36-1.72	466	25,92%		
		6.4-9.6	210	11,68%	4.8-6.0	229	12,74%	84.1-88.1	242	13,46%	1.72-2.08	243	13,52%		
Level 2 (50mm)	S2-9 72h	15,91	14,950		5,298	3,490		80,80	14,08		1,505	0,537		1971	8699
	Distri-bution	0-3.2	338	17,15%	2.4-3.6	381	19,33%	88.1-92.0	340	17,25%	1.00-1.36	997	50,58%		
		3.2-6.4	318	16,13%	3.6-4.8	304	15,42%	84.1-88.1	318	16,13%	1.36-1.72	540	27,40%		
		6.4-9.6	216	10,96%	6.0-7.2	263	13,34%	92.0-96.0	247	12,53%	1.72-2.08	253	12,84%		
level 3 (100mm)	S3-9 72h	15,870	15,280		5,246	3,598		82,76	12,62		1,470	0,446		1977	8726
	Distri-bution	0-3.2	352	17,80%	2.4-3.6	384	19,42%	88.1-92.0	364	18,41%	1.00-1.36	1070	54,12%		
		3.2-6.4	278	14,06%	3.6-4.8	345	17,45%	84.1-88.1	311	15,73%	1.36-1.72	497	25,14%		
		6.4-9.6	250	12,65%	4.8-6.0	269	13,61%	92.0-96.0	292	14,77%	1.72-2.08	257	13,00%		
Level 1 (10mm)	S1-10 80h	15,430	16,300		4,998	3,549		77,70	19,37		1,692	1,241		1718	7583
	Distri-bution	0-3.2	443	25,79%	2.4-3.6	297	17,29%	88.1-92.0	291	16,94%	1.00-1.36	853	49,65%		
		3.2-6.4	211	12,28%	3.6-4.8	264	15,37%	84.1-88.1	259	15,08%	1.36-1.72	437	25,44%		
		6.4-9.6	183	10,65%	1.2-2.4	234	13,62%	92.0-96.0	210	12,22%	1.72-2.08	195	11,35%		
Level 2 (50mm)	S2-10 80h	17,18	16,370		5,468	3,755		81,77	13,62		1,468	0,445		1757	7755
	Distri-bution	0-3.2	344	19,58%	2.4-3.6	302	17,19%	88.1-92.0	306	17,42%	1.00-1.36	920	52,36%		
		3.2-6.4	214	12,18%	3.6-4.8	246	14,00%	92.0-96.0	252	14,34%	1.36-1.72	486	27,66%		
		6.4-9.6	199	11,33%	6.0-7.2	226	12,86%	84.1-88.1	251	14,29%	1.72-2.08	207	11,78%		
level 3 (100mm)	S3-10 80h	16,460	15,980		5,290	3,628		81,31	15,34		1,584	0,827		2061	9096
	Distri-bution	0-3.2	435	21,11%	2.4-3.6	337	16,35%	88.1-92.0	400	19,41%	1.00-1.36	1004	48,71%		
		3.2-6.4	238	11,55%	3.6-4.8	324	15,72%	84.1-88.1	320	15,53%	1.36-1.72	584	28,34%		
		6.4-9.6	219	10,63%	6.0-7.2	265	12,86%	92.0-96.0	279	13,54%	1.72-2.08	261	12,66%		

Silicon Particles Analysis (MTT)

Magnification:	**1000 X**	**Field Area (µm2) :**	**5664**	**Updated:**	
No. of Fields:	**40**	**Total Area (µm2) :**	**2,26572E+05**		**2005-09-30**

Level	Sample ID	Area (µm2) Ave.	SD		Length (µm) Ave.	SD		Roundness (%) Ave.	SD		Aspect Ratio Ave.	SD		Total # Features	Si Particle Density
Level 1 (10mm)	M1-0 0h	2,941	4,558		3,196	3,213		56,96	27,34		2,511	1,332		7049	38889
	Distri-bution	Range	Qty.	Percent	Range	Qty.	Percent	Range	Qty.	Percent	Range	Qty.	Percent		
		0-3.2	5137	72,88%	0-1.2	2090	29,65%	96.0-100	951	13,49%	1.72-2.08	1260	17,87%		
		3.2-6.4	1046	14,84%	1.2-2.4	1704	24,17%	60.4-64.3	386	5,48%	1.36-1.72	1123	15,93%		
		6.4-9.6	377	5,35%	2.4-3.6	1054	14,95%	24.7-28.7	346	4,91%	1.00-1.36	1103	15,65%		
Level 2 (50mm)	M2-0 0h	5,037	8,477		4,417	5,110		55,26	29,51		2,907	1,624		5183	22876
	Distri-bution	0-3.2	3294	63,55%	0-1.2	1715	33,09%	96.0-100	880	16,98%	1.72-2.08	852	16,44%		
		3.2-6.4	668	12,89%	1.2-2.4	852	16,44%	16.8-20.8	267	5,15%	1.00-1.36	702	13,54%		
		6.4-9.6	388	7,49%	2.4-3.6	578	11,15%	64.3-68.3	262	5,05%	1.36-1.72	620	11,96%		
level 3 (100mm)	M3-0 0h	8,980	12,950		6,109	6,219		51,16	29,97		2,760	1,521		3469	15311
	Distri-bution	0-3.2	1644	47,39%	0-1.2	800	23,06%	96.0-100	426	12,28%	1.72-2.08	561	16,17%		
		3.2-6.4	492	14,18%	1.2-2.4	478	13,78%	12.8-16.8	230	6,63%	1.00-1.36	522	15,05%		
		6.4-9.6	280	8,07%	2.4-3.6	378	10,90%	16.8-20.8	222	6,40%	1.36-1.72	446	12,86%		
Level 1 (10mm)	M1-1 8h	9,308	9,592		4,491	3,482		76,05	18,99		1,868	0,788		3089	13634
	Distri-bution	0-3.2	860	27,84%	2.4-3.6	645	20,88%	88.1-92.0	371	12,01%	1.00-1.36	857	27,74%		
		3.2-6.4	618	20,01%	3.6-4.8	571	18,48%	84.1-88.1	349	11,30%	1.36-1.72	806	26,09%		
		6.4-9.6	520	16,83%	0-1.2	446	14,44%	96.0-100	339	10,97%	1.72-2.08	614	19,88%		
Level 2 (50mm)	M2-1 8h	11,210	11,330		5,543	4,378		65,93	22,78		2,307	1,194		2639	11648
	Distri-bution	0-3.2	649	24,59%	3.6-4.8	447	16,94%	96.0-100	222	8,41%	1.36-1.72	496	18,79%		
		3.2-6.4	443	16,79%	2.4-3.6	415	15,73%	88.1-92.0	198	7,50%	1.00-1.36	494	18,72%		
		6.4-9.6	395	14,97%	0-1.2	329	12,47%	84.1-88.1	193	7,31%	1.72-2.08	477	18,08%		
level 3 (100mm)	M3-1 8h	14,070	13,830		6,609	5,328		63,92	23,16		2,430	1,291		2333	10297
	Distri-bution	0-3.2	509	21,82%	2.4-3.0	324	13,89%	96.0-100	162	6,94%	1.00-1.36	408	17,49%		
		3.2-6.4	325	13,93%	3.6-4.8	299	12,82%	88.1-92.0	156	6,69%	1.36-1.72	395	16,93%		
		6.4-9.6	277	11,87%	0-1.2	271	11,62%	84.1-88.1	154	6,60%	1.72-2.08	395	16,93%		
Level 1 (10mm)	M1-2 16h	10,840	9,995		4,788	3,203		76,68	17,22		1,814	0,746		2474	10919
	Distri-bution	0-3.2	548	22,15%	2.4-3.6	491	19,85%	88.1-92.0	344	13,90%	1.00-1.36	737	29,79%		
		3.2-6.4	429	17,34%	3.6-4.8	483	19,52%	84.1-88.1	298	12,05%	1.36-1.72	646	26,11%		
		6.4-9.6	394	15,93%	4.8-6.0	341	13,78%	92.0-96.0	240	9,70%	1.72-2.08	466	18,84%		
Level 2 (50mm)	M2-2 16h	14,120	13,930		5,910	4,518		71,48	20,12		2,021	0,867		2279	10059
	Distri-bution	0-3.2	518	22,73%	2.4-3.6	329	14,44%	80.2-84.1	230	10,09%	1.00-1.36	533	23,39%		
		3.2-6.4	279	12,24%	3.6-4.8	310	13,60%	84.1-88.1	201	8,82%	1.36-1.72	500	21,94%		
		6.4-9.6	277	12,15%	4.8-6.0	293	12,86%	96.0-100	187	8,21%	1.72-2.08	450	19,75%		
level 3 (100mm)	M3-2 16h	16,870	15,040		7,076	5,307		67,54	21,91		2,233	1,102		1908	8421
	Distri-bution	0-3.2	314	16,46%	3.6-4.8	263	13,78%	88.1-92.0	160	8,39%	1.36-1.72	379	19,86%		
		6.4-9.6	215	11,27%	4.8-6.0	219	11,48%	84.1-88.1	158	8,28%	1.00-1.36	370	19,39%		
		9.6-12.8	212	11,11%	6.0-7.2	214	11,22%	80.2-84.1	137	7,18%	1.72-2.08	333	17,45%		

Level 1 (10mm)	M1-3 24h	11,500	10,380		4,737	3,065		78,48	16,32		1,743	0,706		2332	10293
	Distri-bution	0-3.2	489	20,97%	2.4-3.6	488	20,93%	88.1-92.0	341	14,62%	1.00-1.36	771	33,06%		
		3.2-6.4	392	16,81%	3.6-4.8	438	18,78%	84.1-88.1	301	12,91%	1.36-1.72	657	28,17%		
		6.4-9.6	351	15,05%	4.8-6.0	319	13,68%	80.2-84.1	246	10,55%	1.72-2.08	419	17,97%		
Level 2 (50mm)	M2-3 24h	16,660	15,080		6,472	4,726		71,54	19,55		2,009	0,898		2037	8991
	Distri-bution	0-3.2	359	17,62%	4.8-6.0	305	14,97%	80.2-84.1	187	9,18%	1.00-1.36	496	24,35%		
		9.6-12.8	232	11,39%	3.6-4.8	269	13,21%	88.1-92.0	181	8,89%	1.36-1.72	473	23,22%		
		6.4-9.6	216	10,60%	6.0-7.2	239	11,73%	84.1-88.1	179	8,79%	1.72-2.08	369	18,11%		
level 3 (100mm)	M3-3 24h	18,670	16,180		7,046	5,188		69,67	20,83		2,095	1,005		1779	7852
	Distri-bution	0-3.2	293	16,47%	3.6-4.8	233	13,10%	80.2-84.1	169	9,50%	1.36-1.72	407	22,88%		
		9.6-12.8	183	10,29%	4.8-6.0	218	12,25%	84.1-88.1	142	7,98%	1.00-1.36	391	21,98%		
		6.4-9.6	170	9,56%	6.0-7.2	211	11,86%	96.0-100	142	7,98%	1.72-2.08	313	17,59%		
Level 1 (10mm)	M1-4 32h	13,960	13,370		5,122	3,645		75,44	18,69		1,767	0,902		2241	9891
	Distri-bution	0-3.2	509	22,71%	3.6-4.8	363	16,20%	88.1-92.0	257	11,47%	1.00-1.36	810	36,14%		
		6.4-9.6	273	12,18%	4.8-6.0	336	14,99%	84.1-88.1	242	10,80%	1.36-1.72	576	25,70%		
		9.6-12.8	250	11,16%	2.4-3.6	322	14,37%	80.2-84.1	233	10,40%	1.72-2.08	414	18,47%		
Level 2 (50mm)	M2-4 32h	14,740	15,770		5,536	4,736		74,82	18,97		1,872	0,816		2205	9732
	Distri-bution	0-3.2	683	30,98%	0-1.2	464	21,04%	96.0-100	302	13,70%	1.00-1.36	643	29,16%		
		6.4-9.6	204	9,25%	3.6-4.8	286	12,97%	80.2-84.1	215	9,75%	1.36-1.72	544	24,67%		
		9.6-12.8	195	8,84%	4.8-6.0	235	10,66%	84.1-88.1	214	9,71%	1.72-2.08	429	19,46%		
level 3 (100mm)	M3-4 32h	19,170	16,480		7,444	5,206		67,33	20,15		2,252	1,087		1434	6329
	Distri-bution	0-3.2	185	12,90%	3.6-4.8	206	14,37%	80.2-84.1	115	8,02%	1.72-2.08	282	19,67%		
		6.4-9.6	163	11,37%	4.8-6.0	185	12,90%	84.1-88.1	114	7,95%	1.00-1.36	277	19,32%		
		9.6-12.8	147	10,25%	6.0-7.2	158	11,02%	72.2-76.2	108	7,53%	1.36-1.72	250	17,43%		
Level 1 (10mm)	M1-5 40h	11,970	11,110		4,828	3,157		78,35	16,40		1,803	0,880		2033	8973
	Distri-bution	0-3.2	441	21,69%	2.4-3.6	376	18,49%	88.1-92.0	304	14,95%	1.00-1.36	652	32,07%		
		3.2-6.4	325	15,99%	3.6-4.8	368	18,10%	84.1-88.1	256	12,59%	1.36-1.72	574	28,23%		
		6.4-9.6	294	14,46%	4.8-6.0	311	15,30%	80.2-84.1	230	11,31%	1.72-2.08	354	17,41%		
Level 2 (50mm)	M2-5 40h	18,310	15,240		6,781	4,524		72,30	17,46		1,965	0,827		1635	7216
	Distri-bution	0-3.2	217	13,27%	3.6-4.8	246	15,05%	84.1-88.1	183	11,19%	1.36-1.72	411	25,14%		
		9.6-12.8	189	11,56%	4.8-6.0	241	14,74%	80.2-84.1	183	11,19%	1.00-1.36	390	23,85%		
		6.4-9.6	188	11,50%	6.0-7.2	209	12,78%	76.2-80.2	158	9,66%	1.72-2.08	305	18,65%		
level 3 (100mm)	M3-5 40h	20,780	16,720		7,637	5,028		69,10	19,00		2,177	1,001		1377	6078
	Distri-bution	0-3.2	170	12,35%	6.0-7.2	189	13,73%	84.1-88.1	134	9,73%	1.36-1.72	281	20,41%		
		9.6-12.8	151	10,97%	4.8-6.0	159	11,55%	88.1-92.0	118	8,57%	1.00-1.36	261	18,95%		
		12.8-16.0	122	8,86%	3.6-4.8	159	11,55%	76.2-80.2	118	8,57%	1.72-2.08	246	17,86%		
Level 1 (10mm)	M1-6 48h	13,300	12,960		4,998	3,534		78,20	15,89		1,728	0,656		2139	9441
	Distri-bution	0-3.2	545	25,48%	3.6-4.8	344	16,08%	84.1-88.1	270	12,62%	1.00-1.36	702	32,82%		
		9.6-12.8	249	11,64%	4.8-6.0	304	14,21%	88.1-92.0	269	12,58%	1.36-1.72	626	29,27%		
		6.4-9.6	241	11,27%	2.4-3.6	283	13,23%	80.2-84.1	246	11,50%	1.72-2.08	371	17,34%		
Level 2 (50mm)	M2-6 48h	17,750	16,470		6,435	4,825		73,84	18,18		1,959	0,850		1792	7909
	Distri-bution	0-3.2	411	22,94%	0-1.2	244	13,62%	84.1-88.1	183	10,21%	1.00-1.36	433	24,16%		
		6.4-9.6	140	7,81%	6.0-7.2	206	11,50%	80.2-84.1	180	10,04%	1.36-1.72	425	23,72%		
		3.2-6.4	135	7,53%	3.6-4.8	199	11,10%	96.0-100	168	9,38%	1.72-2.08	377	21,04%		
level 3 (100mm)	M3-6 48h	19,320	17,060		7,225	5,343		69,81	19,62		2,122	0,977		1663	7340
	Distri-bution	0-3.2	315	18,94%	4.8-6.0	191	11,49%	84.1-88.1	170	10,22%	1.36-1.72	365	21,95%		
		9.6-12.8	150	9,02%	3.6-4.8	181	10,88%	76.2-80.2	148	8,90%	1.00-1.36	335	20,14%		
		6.4-9.6	137	8,24%	6.0-7.2	180	10,82%	80.2-84.1	146	8,78%	1.72-2.08	295	17,74%		

Level 1 (10mm)	M1-7 56h	15,050	14,090		5,385	3,646		78,37	15,33		1,705	0,620		1812	7997
	Distri-bution	0-3.2	372	20,53%	4.8-6.0	285	15,73%	84.1-88.1	241	13,30%	1.00-1.36	634	34,99%		
		3.2-6.4	204	11,26%	2.4-3.6	269	14,85%	88.1-92.0	230	12,69%	1.36-1.72	470	25,94%		
		6.4-9.6	201	11,09%	3.6-4.8	260	14,35%	80.2-84.1	203	11,20%	1.72-2.08	352	19,43%		
Level 2 (50mm)	M2-7 56h	19,550	17,130		6,927	4,951		73,26	17,29		1,962	0,804		1486	6559
	Distri-bution	0-3.2	256	17,23%	4.8-6.0	199	13,39%	88.1-92.0	153	10,30%	1.36-1.72	376	25,30%		
		9.6-12.8	139	9,35%	6.0-7.2	190	12,79%	84.1-88.1	152	10,23%	1.00-1.36	327	22,01%		
		12.8-16.0	136	9,15%	3.6-4.8	178	11,98%	80.2-84.1	152	10,23%	1.72-2.08	301	20,26%		
level 3 (100mm)	M3-7 56h	20,630	17,950		7,220	5,112		71,35	18,30		2,026	0,823		1462	6453
	Distri-bution	0-3.2	272	18,60%	4.8-6.0	175	11,97%	76.2-80.2	142	9,71%	1.36-1.72	340	23,26%		
		9.6-12.8	127	8,69%	6.0-7.2	168	11,49%	80.2-84.1	130	8,89%	1.00-1.36	314	21,48%		
		12.8-16.0	111	7,59%	3.6-4.8	143	9,78%	84.1-88.1	122	8,34%	1.72-2.08	283	19,36%		
Level 1 (10mm)	M1-8 64h	15,780	14,030		5,432	3,382		80,18	14,04		1,641	0,548		1641	7243
	Distri-bution	0-3.2	268	16,33%	3.6-4.8	292	17,79%	88.1-92.0	258	15,72%	1.00-1.36	608	37,05%		
		6.4-9.6	208	12,68%	4.8-6.0	252	15,36%	84.1-88.1	244	14,87%	1.36-1.72	479	29,19%		
		3.2-6.4	200	12,19%	2.4-3.6	236	14,38%	80.2-84.1	200	12,19%	1.72-2.08	291	17,73%		
Level 2 (50mm)	M2-8 64h	20,710	16,910		6,887	4,423		73,85	17,77		1,877	0,821		1668	7362
	Distri-bution	0-3.2	240	14,39%	6.0-7.2	241	14,45%	84.1-88.1	196	11,75%	1.36-1.72	464	27,82%		
		12.8-16.0	144	8,63%	4.8-6.0	209	12,53%	80.2-84.1	180	10,79%	1.00-1.36	423	25,36%		
		9.6-12.8	131	7,85%	3.6-4.8	183	10,97%	76.2-80.2	170	10,19%	1.72-2.08	327	19,60%		
level 3 (100mm)	M3-8 64h	20,980	18,820		7,144	5,156		72,74	18,64		1,984	0,862		1664	7344
	Distri-bution	0-3.2	327	19,65%	0-1.2	223	13,40%	96.0-100	166	9,98%	1.36-1.72	388	23,32%		
		19.2-22.4	121	7,27%	6.0-7.2	214	12,86%	84.1-88.1	153	9,19%	1.00-1.36	379	22,78%		
		16.0-19.2	119	7,15%	7.2-8.4	162	9,74%	80.2-84.1	142	8,53%	1.72-2.08	343	20,61%		
Level 1 (10mm)	M1-9 72h	15,770	14,220		5,327	3,359		80,60	14,46		1,637	0,650		1674	7388
	Distri-bution	0-3.2	315	18,82%	3.6-4.8	264	15,77%	88.1-92.0	250	14,93%	1.00-1.36	675	40,32%		
		6.4-9.6	186	11,11%	4.8-6.0	253	15,11%	84.1-88.1	240	14,34%	1.36-1.72	465	27,78%		
		3.2-6.4	175	10,45%	6.0-7.2	230	13,74%	80.2-84.1	203	12,13%	1.72-2.08	285	17,03%		
Level 2 (50mm)	M2-9 72h	19,670	16,090		6,735	4,251		71,42	17,73		2,045	1,032		1491	6581
	Distri-bution	0-3.2	236	15,83%	6.0-7.2	212	14,22%	76.2-80.2	156	10,46%	1.36-1.72	379	25,42%		
		12.8-16.0	134	8,99%	4.8-6.0	189	12,68%	80.2-84.1	149	9,99%	1.00-1.36	311	20,86%		
		16.0-19.2	128	8,58%	3.6-4.8	176	11,80%	84.1-88.1	146	9,79%	1.72-2.08	297	19,92%		
level 3 (100mm)	M3-9 72h	19,180	18,820		6,548	5,208		71,80	19,45		2,029	0,993		1533	6766
	Distri-bution	0-3.2	215	14,02%	6.0-7.2	262	17,09%	96.0-100	167	10,89%	1.00-1.36	358	23,35%		
		12.8-16.0	168	10,96%	4.8-6.0	192	12,52%	80.2-84.1	148	9,65%	1.72-2.08	341	22,24%		
		16.0-19.2	128	8,35%	3.6-4.8	171	11,15%	84.1-88.1	135	8,81%	1.36-1.72	327	21,33%		
Level 1 (10mm)	M1-10 80h	16,760	15,140		5,695	3,623		79,21	14,21		1,642	0,595		1685	7437
	Distri-bution	0-3.2	271	16,08%	3.6-4.8	297	17,63%	88.1-92.0	255	15,13%	1.00-1.36	652	38,69%		
		6.4-9.6	201	11,93%	2.4-3.6	251	14,90%	80.2-84.1	216	12,82%	1.36-1.72	494	29,32%		
		3.2-6.4	191	11,34%	4.8-6.0	220	13,06%	84.1-88.1	210	12,46%	1.72-2.08	260	15,43%		
Level 2 (50mm)	M2-10 80h	21,960	16,700		7,347	4,416		72,66	16,13		1,973	0,767		1443	6369
	Distri-bution	0-3.2	156	10,81%	6.0-7.2	213	14,76%	72.2-76.2	149	10,33%	1.36-1.72	317	21,97%		
		16.0-19.2	136	9,42%	4.8-6.0	178	12,34%	80.2-84.1	143	9,91%	1.00-1.36	315	21,83%		
		12.8-16.0	123	8,52%	7.2-8.4	154	10,67%	84.1-88.1	141	9,77%	1.72-2.08	309	21,41%		
level 3 (100mm)	M3-10 80h	22,100	18,120		7,321	4,940		73,40	17,38		1,926	0,754		1304	5755
	Distri-bution	0-3.2	199	15,26%	6.0-7.2	189	14,49%	80.2-84.1	143	10,97%	1.36-1.72	330	25,31%		
		12.8-16.0	113	8,67%	4.8-6.0	155	11,89%	68.3-72.2	124	9,51%	1.00-1.36	302	23,16%		
		16.0-19.2	100	7,67%	0-1.2	135	10,35%	88.1-92.0	116	8,90%	1.72-2.08	264	20,25%		

Silicon Particles Analysis (SrMTT)

Magnification:	**1000 X**	**Field Area (µm2) :**	**5664**	**Updated:**
No. of Fields:	**40**	**Total Area (µm2) :**	**2,26572E+05**	**2005-09-30**

Level	Sample ID	Area (µm2)			Length (µm)			Roundness (%)			Aspect Ratio			Total # Features	Si Particle Density
		Ave.	SD		Ave.	SD		Ave.	SD		Ave.	SD			
	M1-0 0h	0,9392	1,846		1,399	1,280		78,87	20,35		1,814	0,666			
		Range	Qty.	Percent	Range	Qty.	Percent	Range	Qty.	Percent	Range	Qty.	Percent		
Level 1 (10mm)	Distri-bution	0-3.0	24955	93,98%	0.6-1.2	11193	42,15%	96.0-100	7745	29,17%	1.96-2.12	4798	18,07%	26554	146499
		3.0-6.0	1085	4,09%	1.2-1.8	5096	19,19%	88.1-92.0	2226	8,38%	1.48-1.64	3878	14,60%		
		6.0-9.0	266	1,00%	0-0.6	4692	17,67%	84.1-88.1	2193	8,26%	1.00-1.16	3685	13,88%		
	M2-0 0h	1,383	2,438		1,742	1,595		77,32	20,87		1,827	0,692			
Level 2 (50mm)	Distri-bution	0-3.0	21365	89,60%	0.6-1.2	8711	36,53%	96.0-100	5518	23,14%	1.96-2.12	3433	14,40%	23846	105247
		3.0-6.0	1631	6,84%	1.2-1.8	5402	22,65%	88.1-92.0	2300	9,65%	1.48-1.64	3429	14,38%		
		6.0-9.0	447	1,87%	0-0.6	2735	11,47%	84.1-88.1	2180	9,14%	1.00-1.16	2867	12,02%		
	M3-0 0h	1,531	2,696		1,865	1,719		75,81	21,48		1,873	0,720			
level 3 (100mm)	Distri-bution	0-3.0	18752	88,09%	0.6-1.2	7085	33,28%	96.0-100	4412	20,73%	1.96-2.12	2978	13,99%	21288	93957
		3.0-6.0	1651	7,76%	1.2-1.8	5002	23,50%	88.1-92.0	2045	9,61%	1.48-1.64	2885	13,55%		
		6.0-9.0	441	2,07%	0-0.6	2303	10,82%	84.1-88.1	1964	9,23%	1.00-1.16	2400	11,27%		
	M1-1 8h	6,407	6,735		3,264	2,247		84,21	15,81		1,545	0,814			
Level 1 (10mm)	Distri-bution	0-3.2	2462	39,80%	2.4-3.6	1678	27,13%	92.0-96.0	1437	23,23%	1.00-1.36	3276	52,96%	6186	27303
		3.2-6.4	1468	23,73%	1.2-2.4	1672	27,03%	88.1-92.0	1249	20,19%	1.36-1.72	1595	25,78%		
		6.4-9.6	916	14,81%	3.6-4.8	967	15,63%	96.0-100	881	14,24%	1.72-2.08	702	11,35%		
	M2-1 8h	7,344	7,607		3,529	2,461		85,41	14,11		1,467	0,471			
Level 2 (50mm)	Distri-bution	0-3.2	2101	34,65%	2.4-3.6	1746	28,79%	92.0-96.0	1527	25,18%	1.00-1.36	3309	54,57%	6064	26764
		3.2-6.4	1415	23,33%	1.2-2.4	1516	25,00%	88.1-92.0	1310	21,60%	1.36-1.72	1618	26,68%		
		6.4-9.6	974	16,06%	3.6-4.8	999	16,47%	96.0-100	844	13,92%	1.72-2.08	628	10,36%		
	M3-1 8h	6,811	6,683		3,360	2,106		86,02	12,94		1,430	0,396			
level 3 (100mm)	Distri-bution	0-3.2	2279	33,63%	2.4-3.6	2109	31,12%	92.0-96.0	1683	24,83%	1.00-1.36	3780	55,78%	6777	29911
		3.2-6.4	1815	26,78%	1.2-2.4	1648	24,32%	88.1-92.0	1503	22,18%	1.36-1.72	1838	27,12%		
		6.4-9.6	1114	16,44%	3.6-4.8	1173	17,31%	96.0-100	920	13,58%	1.72-2.08	719	10,61%		
	M1-2 16h	8,516	9,465		3,644	2,652		84,07	14,13		1,466	0,455			
Level 1 (10mm)	Distri-bution	0-3.2	1355	35,69%	2.4-3.6	878	23,12%	88.1-92.0	795	20,94%	1.00-1.36	2058	54,20%	3797	16758
		3.2-6.4	679	17,88%	1.2-2.4	757	19,94%	92.0-96.0	663	17,46%	1.36-1.72	1000	26,34%		
		6.4-9.6	565	14,88%	3.6-4.8	661	17,41%	96.0-100	517	13,62%	1.72-2.08	444	11,69%		
	M2-2 16h	7,822	8,230		3,579	2,396		84,86	12,79		1,474	0,421			
Level 2 (50mm)	Distri-bution	0-3.2	1537	35,04%	2.4-3.6	1137	25,92%	88.1-92.0	975	22,22%	1.00-1.36	2201	50,17%	4387	19362
		3.2-6.4	934	21,29%	1.2-2.4	995	22,68%	92.0-96.0	867	19,76%	1.36-1.72	1287	29,34%		
		6.4-9.6	658	15,00%	3.6-4.8	770	17,55%	84.1-88.1	619	14,11%	1.72-2.08	538	12,26%		
	M3-2 16h	8,446	8,932		3,801	2,676		84,46	13,30		1,508	0,486			
level 3 (100mm)	Distri-bution	0-3.2	1244	31,44%	2.4-3.6	1052	26,59%	88.1-92.0	829	20,95%	1.00-1.36	1943	49,10%	3957	17465
		3.2-6.4	841	21,25%	1.2-2.4	813	20,55%	92.0-96.0	799	20,19%	1.36-1.72	1141	28,83%		
		6.4-9.6	670	16,93%	3.6-4.8	759	19,18%	84.1-88.1	609	15,39%	1.72-2.08	488	12,33%		

Level 1 (10mm)	M1-3 24h	10,150	10,420		4,013	2,648		85,46	12,70		1,433	0,432			
	Distri-bution	0-3.2	881	28,14%	2.4-3.6	754	24,08%	88.1-92.0	709	22,64%	1.00-1.36	1763	56,31%	3131	13819
		3.2-6.4	596	19,04%	1.2-2.4	596	19,04%	92.0-96.0	671	21,43%	1.36-1.72	828	26,45%		
		6.4-9.6	473	15,11%	3.6-4.8	560	17,89%	84.1-88.1	449	14,34%	1.72-2.08	343	10,95%		
Level 2 (50mm)	M2-3 24h	9,459	9,916		3,915	2,582		84,92	12,44		1,459	0,434			
	Distri-bution	0-3.2	1034	28,60%	2.4-3.6	957	26,47%	88.1-92.0	794	21,96%	1.00-1.36	1893	52,35%	3616	15960
		3.2-6.4	757	20,93%	1.2-2.4	700	19,36%	92.0-96.0	737	20,38%	1.36-1.72	1049	29,01%		
		6.4-9.6	560	15,49%	3.6-4.8	624	17,26%	84.1-88.1	542	14,99%	1.72-2.08	404	11,17%		
level 3 (100mm)	M3-3 24h	10,000	10,410		4,086	2,819		85,06	12,70		1,476	0,450			
	Distri-bution	0-3.2	1009	27,56%	2.4-3.6	913	24,94%	88.1-92.0	844	23,05%	1.00-1.36	1898	51,84%	3661	16158
		3.2-6.4	742	20,27%	1.2-2.4	697	19,04%	92.0-96.0	753	20,57%	1.36-1.72	1034	28,24%		
		6.4-9.6	522	14,26%	3.6-4.8	685	18,71%	84.1-88.1	549	15,00%	1.72-2.08	424	11,58%		
Level 1 (10mm)	M1-4 32h	11,290	11,700		4,229	2,806		84,16	13,78		1,453	0,490			
	Distri-bution	0-3.2	779	26,49%	2.4-3.6	721	24,52%	88.1-92.0	632	21,49%	1.00-1.36	1619	55,05%	2941	12980
		6.4-9.6	577	19,62%	1.2-2.4	505	17,17%	92.0-96.0	564	19,18%	1.36-1.72	804	27,34%		
		9.6-12.8	377	12,82%	3.6-4.8	492	16,73%	84.1-88.1	440	14,96%	1.72-2.08	328	11,15%		
Level 2 (50mm)	M2-4 32h	10,940	11,280		4,193	2,765		83,47	12,84		1,458	0,428			
	Distri-bution	0-3.2	854	26,86%	2.4-3.6	739	23,25%	88.1-92.0	617	19,41%	1.00-1.36	1672	52,60%	3179	14031
		6.4-9.6	612	19,25%	1.2-2.4	565	17,77%	92.0-96.0	520	16,36%	1.36-1.72	892	28,06%		
		9.6-12.8	408	12,83%	3.6-4.8	538	16,92%	84.1-88.1	491	15,45%	1.72-2.08	385	12,11%		
level 3 (100mm)	M3-4 32h	11,040	11,100		4,239	2,801		83,45	12,86		1,485	0,487			
	Distri-bution	0-3.2	825	26,35%	2.4-3.6	677	21,62%	88.1-92.0	664	21,21%	1.00-1.36	1627	51,96%	3131	13819
		6.4-9.6	539	17,21%	3.6-4.8	578	18,46%	92.0-96.0	550	17,57%	1.36-1.72	867	27,69%		
		9.6-12.8	443	14,15%	1.2-2.4	525	16,77%	84.1-88.1	519	16,58%	1.72-2.08	366	11,69%		
Level 1 (10mm)	M1-5 40h	11,160	11,930		4,123	2,782		80,35	15,17		1,560	0,841			
	Distri-bution	0-3.2	737	29,20%	2.4-3.6	529	20,96%	88.1-92.0	406	16,09%	1.00-1.36	1290	51,11%	2524	11140
		3.2-6.4	418	16,56%	3.6-4.8	422	16,72%	84.1-88.1	368	14,58%	1.36-1.72	708	28,05%		
		6.4-9.6	344	13,63%	1.2-2.4	410	16,24%	92.0-96.0	289	11,45%	1.72-2.08	292	11,57%		
Level 2 (50mm)	M2-5 40h	11,780	12,310		4,294	2,824		83,18	13,14		1,436	0,392			
	Distri-bution	0-3.2	704	26,09%	2.4-3.6	618	22,91%	88.1-92.0	507	18,79%	1.00-1.36	1447	53,63%	2698	11908
		3.2-6.4	496	18,38%	3.6-4.8	460	17,05%	84.1-88.1	444	16,46%	1.36-1.72	775	28,72%		
		6.4-9.6	338	12,53%	1.2-2.4	444	16,46%	92.0-96.0	428	15,86%	1.72-2.08	310	11,49%		
level 3 (100mm)	M3-5 40h	12,090	12,610		4,426	3,059		82,48	13,84		1,508	0,525			
	Distri-bution	0-3.2	733	26,40%	2.4-3.6	590	21,25%	88.1-92.0	555	19,99%	1.00-1.36	1429	51,46%	2777	12257
		3.2-6.4	451	16,24%	3.6-4.8	456	16,42%	84.1-88.1	418	15,05%	1.36-1.72	741	26,68%		
		6.4-9.6	334	12,03%	1.2-2.4	417	15,02%	92.0-96.0	417	15,02%	1.72-2.08	347	12,50%		
Level 1 (10mm)	M1-6 48h	12,270	12,820		4,328	2,837		85,46	11,79		1,409	0,356			
	Distri-bution	0-3.2	614	24,80%	2.4-3.6	551	22,25%	88.1-92.0	563	22,74%	1.00-1.36	1402	56,62%	2476	10928
		3.2-6.4	446	18,01%	3.6-4.8	426	17,21%	92.0-96.0	515	20,80%	1.36-1.72	674	27,22%		
		6.4-9.6	308	12,44%	1.2-2.4	406	16,40%	84.1-88.1	387	15,63%	1.72-2.08	282	11,39%		
Level 2 (50mm)	M2-6 48h	13,160	13,810		4,584	3,315		81,59	16,02		1,547	0,826			
	Distri-bution	0-3.2	679	26,56%	2.4-3.6	513	20,07%	88.1-92.0	524	20,50%	1.00-1.36	1353	52,93%	2556	11281
		3.2-6.4	399	15,61%	1.2-2.4	417	16,31%	92.0-96.0	393	15,38%	1.36-1.72	662	25,90%		
		6.4-9.6	282	11,03%	3.6-4.8	400	15,65%	84.1-88.1	385	15,06%	1.72-2.08	298	11,66%		
level 3 (100mm)	M3-6 48h	13,560	13,740		4,622	3,105		81,52	15,06		1,523	0,674			
	Distri-bution	0-3.2	636	24,31%	2.4-3.6	525	20,07%	88.1-92.0	517	19,76%	1.00-1.36	1345	51,41%	2616	11546
		3.2-6.4	407	15,56%	3.6-4.8	403	15,41%	92.0-96.0	391	14,95%	1.36-1.72	725	27,71%		
		6.4-9.6	312	11,93%	1.2-2.4	356	13,61%	84.1-88.1	381	14,56%	1.72-2.08	300	11,47%		

Level 1 (10mm)	M1-7 56h	13,700	13,440		4,739	3,126		83,82	12,95		1,441	0,420		2076	9163
	Distri-bution	0-3.2	434	20,91%	2.4-3.6	428	20,62%	88.1-92.0	453	21,82%	1.00-1.36	1147	55,25%		
		3.2-6.4	337	16,23%	3.6-4.8	381	18,35%	92.0-96.0	346	16,67%	1.36-1.72	584	28,13%		
		6.4-9.6	261	12,57%	1.2-2.4	286	13,78%	84.1-88.1	342	16,47%	1.72-2.08	221	10,65%		
Level 2 (50mm)	M2-7 56h	14,140	14,160		4,778	3,190		82,88	12,44		1,463	0,436		2300	10151
	Distri-bution	0-3.2	535	23,26%	2.4-3.6	439	19,09%	88.1-92.0	451	19,61%	1.00-1.36	1183	51,43%		
		3.2-6.4	320	13,91%	3.6-4.8	378	16,43%	84.1-88.1	377	16,39%	1.36-1.72	686	29,83%		
		6.4-9.6	302	13,13%	1.2-2.4	322	14,00%	92.0-96.0	330	14,35%	1.72-2.08	272	11,83%		
level 3 (100mm)	M3-7 56h	15,230	14,400		5,077	3,355		83,13	12,81		1,465	0,410		2246	9913
	Distri-bution	0-3.2	441	19,63%	2.4-3.6	404	17,99%	88.1-92.0	452	20,12%	1.00-1.36	1180	52,54%		
		3.2-6.4	304	13,54%	3.6-4.8	353	15,72%	84.1-88.1	366	16,30%	1.36-1.72	608	27,07%		
		6.4-9.6	264	11,75%	4.8-6.0	317	14,11%	92.0-96.0	354	15,76%	1.72-2.08	298	13,27%		
Level 1 (10mm)	M1-8 64h	15,880	15,310		5,017	3,279		83,87	12,34		1,435	0,430		1985	8761
	Distri-bution	0-3.2	443	22,32%	2.4-3.6	314	15,82%	88.1-92.0	375	18,89%	1.00-1.36	1098	55,31%		
		3.2-6.4	225	11,34%	3.6-4.8	314	15,82%	84.1-88.1	343	17,28%	1.36-1.72	563	28,36%		
		6.4-9.6	203	10,23%	4.8-6.0	281	14,16%	92.0-96.0	303	15,26%	1.72-2.08	207	10,43%		
Level 2 (50mm)	M2-8 64h	16,080	15,900		5,148	3,678		78,59	17,78		1,697	1,235		2094	9242
	Distri-bution	0-3.2	481	22,97%	2.4-3.6	344	16,43%	88.1-92.0	354	16,91%	1.00-1.36	1080	51,58%		
		3.2-6.4	265	12,66%	3.6-4.8	323	15,43%	84.1-88.1	313	14,95%	1.36-1.72	512	24,45%		
		6.4-9.6	222	10,60%	1.2-2.4	256	12,23%	92.0-96.0	263	12,56%	1.72-2.08	218	10,41%		
level 3 (100mm)	M3-8 64h	17,960	16,260		5,568	3,526		83,35	13,07		1,470	0,486		1947	8593
	Distri-bution	0-3.2	305	15,67%	2.4-3.6	325	16,69%	88.1-92.0	446	22,91%	1.00-1.36	1037	53,26%		
		3.2-6.4	232	11,92%	3.6-4.8	323	16,59%	92.0-96.0	323	16,59%	1.36-1.72	546	28,04%		
		6.4-9.6	213	10,94%	4.8-6.0	283	14,54%	84.1-88.1	288	14,79%	1.72-2.08	219	11,25%		
Level 1 (10mm)	M1-9 72h	15,710	15,150		5,036	3,270		82,91	12,29		1,425	0,389		1801	7949
	Distri-bution	0-3.2	355	19,71%	2.4-3.6	342	18,99%	88.1-92.0	343	19,04%	1.00-1.36	1023	56,80%		
		3.2-6.4	258	14,33%	3.6-4.8	301	16,71%	84.1-88.1	297	16,49%	1.36-1.72	461	25,60%		
		6.4-9.6	210	11,66%	4.8-6.0	244	13,55%	92.0-96.0	244	13,55%	1.72-2.08	216	11,99%		
Level 2 (50mm)	M2-9 72h	14,800	15,550		4,766	3,466		81,23	15,78		1,566	0,937		2214	9772
	Distri-bution	0-3.2	594	26,83%	2.4-3.6	348	15,72%	88.1-92.0	412	18,61%	1.00-1.36	1202	54,29%		
		3.2-6.4	269	12,15%	3.6-4.8	331	14,95%	84.1-88.1	327	14,77%	1.36-1.72	539	24,35%		
		6.4-9.6	223	10,07%	0-1.2	309	13,96%	92.0-96.0	281	12,69%	1.72-2.08	271	12,24%		
level 3 (100mm)	M3-9 72h	16,840	16,950		5,231	3,889		83,01	14,14		1,510	0,552		2143	9458
	Distri-bution	0-3.2	499	23,29%	3.6-4.8	322	15,03%	88.1-92.0	412	19,23%	1.00-1.36	1083	50,54%		
		6.4-9.6	224	10,45%	0-1.2	310	14,47%	92.0-96.0	302	14,09%	1.36-1.72	571	26,64%		
		3.2-6.4	218	10,17%	2.4-3.6	307	14,33%	84.1-88.1	301	14,05%	1.72-2.08	316	14,75%		
Level 1 (10mm)	M1-10 80h	14,430	15,420		4,621	3,355		83,00	15,43		1,490	0,615		1965	8673
	Distri-bution	0-3.2	535	27,23%	2.4-3.6	345	17,56%	88.1-92.0	361	18,37%	1.00-1.36	1073	54,61%		
		3.2-6.4	251	12,77%	0-1.2	316	16,08%	92.0-96.0	303	15,42%	1.36-1.72	487	24,78%		
		6.4-9.6	222	11,30%	3.6-4.8	303	15,42%	84.1-88.1	290	14,76%	1.72-2.08	258	13,13%		
Level 2 (50mm)	M2-10 80h	15,360	15,140		4,919	3,465		83,29	12,92		1,446	0,446		2108	9304
	Distri-bution	0-3.2	518	24,57%	2.4-3.6	318	15,09%	88.1-92.0	397	18,83%	1.00-1.36	1177	55,83%		
		3.2-6.4	243	11,53%	3.6-4.8	310	14,71%	84.1-88.1	325	15,42%	1.36-1.72	554	26,28%		
		6.4-9.6	209	9,91%	4.8-6.0	277	13,14%	92.0-96.0	281	13,33%	1.72-2.08	246	11,67%		
level 3 (100mm)	M3-10 80h	18,630	17,110		5,642	3,734		82,66	13,19		1,488	0,544		1876	8280
	Distri-bution	0-3.2	350	18,66%	3.6-4.8	282	15,03%	88.1-92.0	395	21,06%	1.00-1.36	982	52,35%		
		3.2-6.4	193	10,29%	4.8-6.0	264	14,07%	92.0-96.0	300	15,99%	1.36-1.72	503	26,81%		
		9.6-12.8	179	9,54%	2.4-3.6	249	13,27%	84.1-88.1	284	15,14%	1.72-2.08	242	12,90%		