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Experimental exploration of the aluminum tube drawing process for producing variable wall thickness components used in light structural applications

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ABSTRACT

Tube drawing is a well known process involving at room temperature the reduction of diameter and wall thickness to obtain specified values. The initial tube is drawn into a die of a smaller opening and its thickness achieved by use of a mandrel. Usually, the mandrel has a land area which diameter defines by sizing the inside diameter of the final tube.

Some structural components found in cars, aircrafts and other vehicles require bent or hydroformed tubes of lower weight. It is of interest to have tubes of varying axial or circumferential thickness so that to reduce overweight in low stressed areas and reinforce it otherwise. However, the production of tubes of varying thickness is more difficult in reason notably of higher metal flow stresses in the deformation zone and the need to control precisely the mandrel position during drawing. Axial thickness variation is obtained using a mandrel with stepped lands or with a slight taper while circumferential variation is achieved with a mandrel of desired internal or external shape (e.g. oval).

In this paper, two techniques for axial tube wall thickness variation and one technique for circumferential variations are introduced and tested. First, the techniques to produce drawn tubes with thickness variations are presented. For testing, a small (335 kN) instrumented tube drawing machine is used. Details on this machine, process lubrication, monitored data and on the tooling implemented are also presented. Initial tubes are mainly AA6063 extrusions of 63.5mm O.D. and 2.6mm thick and the final outside diameter, i.e. the inside diameter of the die, is about 47.5 mm. AA6061 tubes are also drawn. Starting with drawing tests without mandrel, the natural flow of the tube and the drawing force involved are measured. Secondly, tubes of 4 different thicknesses are produced with a stepped mandrel and the strain hardening effect on mechanical properties established. Using a tapered mandrel, tubes of continuously varying wall thickness are tested. Higher local pressure in the die corner radius restricts proper lubrication in certain conditions but results are promising in most cases. We also study the effect of thickness rate of change along the tube. Finally, tests with a stepped oval mandrel provided good results for circumferential thickness variations. The dimensional quality is measured using a coordinate measuring machine and mechanical properties obtained from tensile tests in both initial and drawn tubes. Finally, despite some minor problems, the techniques proposed can efficiently produce tubes with thickness variations and have a very strong potential for industrial use.

INTRODUCTION

As illustrated in Figure 1 (see also ref. [1]), an aluminum bloom, i.e. a tube that is produced generally by hot extrusion is drawn in one or more passes to achieve desired final diameter and thickness. Between drawing passes, annealing treatment may be required. To initiate drawing, the tube is crimped at one end, placed into a tapered annular die and clamped in a set of jaws. The die opening diameter defines also the drawn tube outside diameter. A mandrel fixed to a rod at the opposite end produces the inside diameter and thus, the wall thickness of the drawn tube. The jaw mechanism pulls the tube through the die which is also sized by the mandrel.

For tube producers, several reasons justify the use of the tube drawing process. First, with a limited variety of large blooms, a wide range of tube diameters and thicknesses can be achieved. Second, the quality, namely the tolerances and surface finish, is generally better than common extrusions. At last, the mechanical and metallurgical properties (e.g. strength, hardness, grain elongation) are usually significantly increased by work hardening and surface sizing. Because this process generates large material deformations, attention must be paid in each pass to the reduction ratio and initial material ductility which otherwise would lead to tube breakage [2]. Although other drawing methods (e.g. with floating mandrel [3]) can be found in practice, the fixed or position controlled mandrel technique illustrated in Figure 1 will be applied in this paper.

The idea of making tubes of variable wall thickness comes essentially from the need to adjust the tube properties, notably its bending strength, for a given application while minimizing weight. For example, bicycle frame tubing, certain automotive hydroformed components and landing gears of small aircrafts can benefit from variable wall thickness to improve strength where it is needed and reduce weight elsewhere. Compared to a tube of constant thickness, a tube of variable thickness can reduce by more than 25% the weight of the parts illustrated in Figure 2. After drawing, these tubes of variable thickness can be bent, formed or hydroformed to produce the final part.

The production of different wall thicknesses within the same tube can be obtained in industry using a stepped mandrel as shown in Figure 3b. Even though these stepped mandrels are rather used to reduce the number of tooling components (e.g. for a given tube outside diameter several thicknesses can be achieved with only one stepped mandrel) they can also produce different wall thicknesses along a single tube. However, the thickness variations produced are not progressive and often generates stress concentration at the steps. Calhoun et al. [4] proposed another method for producing stepped wall tubing using more than

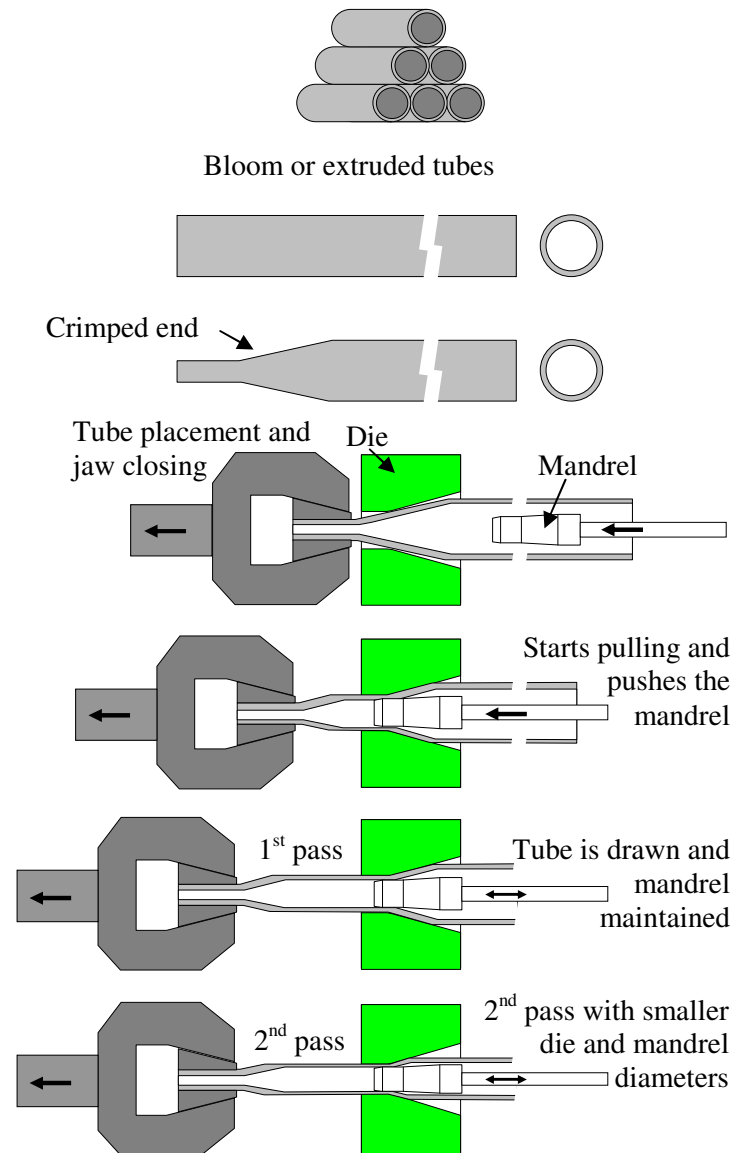


Figure 1 – Schematic of the tube drawing process using a fixed standard mandrel

one mandrel. Alexoff [5] also patented a technique using back pushing and no mandrel to vary wall thicknesses. Although interesting, these techniques are still limited in flexibility.

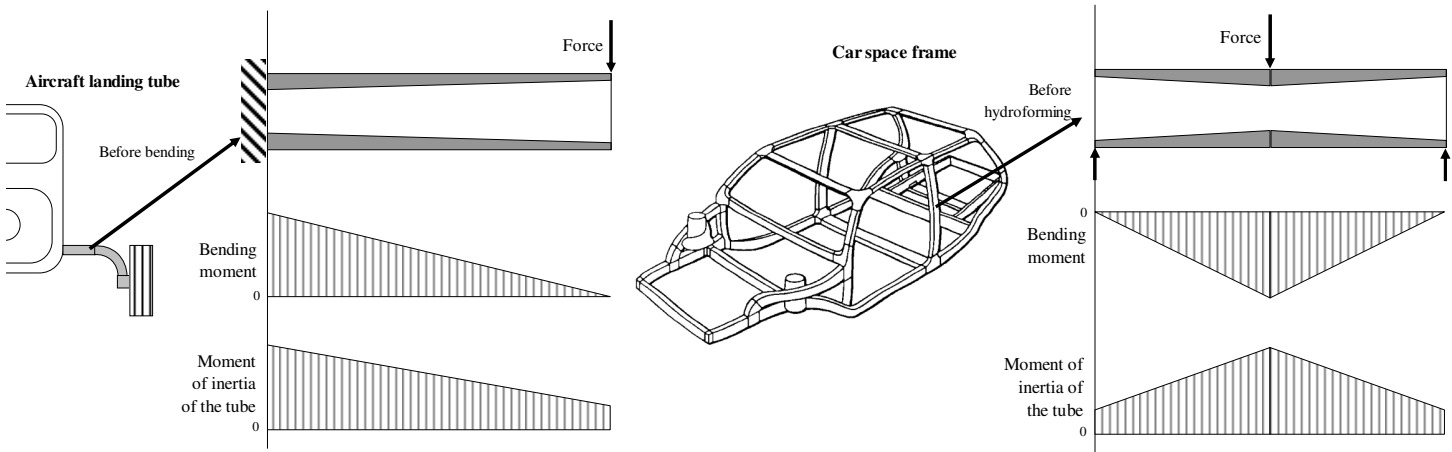


Figure 2 – Examples where tubes of variable thickness can be useful to withstand bending moments.

As illustrated in Figure 3a with a common mandrel for constant thickness, tube drawing generates three deformation zones, first tube sinking with no contact with the mandrel, second tube drawing where the contact with the mandrel reduces the wall thickness and third, a sizing zone to improve final tube dimensions and surface finish. For axial thickness variations, a stepped mandrel or a tapered mandrel can be used as shown respectively in Figures 3b and c. With a stepped mandrel, sinking, drawing and sizing is similar to the classic mandrel but the sizing zone can be shorter and defined more by the mandrel design than the die design. The tapered transitions between the steps in (b) are relatively short with a small angle (e.g. 3 degrees). Finally, the tapered mandrel of Figure 3c provides continuously adjustable wall thickness. This thickness is adjusted by moving axially the mandrel for a desired gap between the die corner radius and mandrel tapered face. However, it has no sizing zone and produces a peak of pressure at the corner radius of the die. Care will be required in selecting the mandrel taper angle and die corner radius. The tube produced with tapered mandrel will also be checked carefully for final dimension and surface finish.

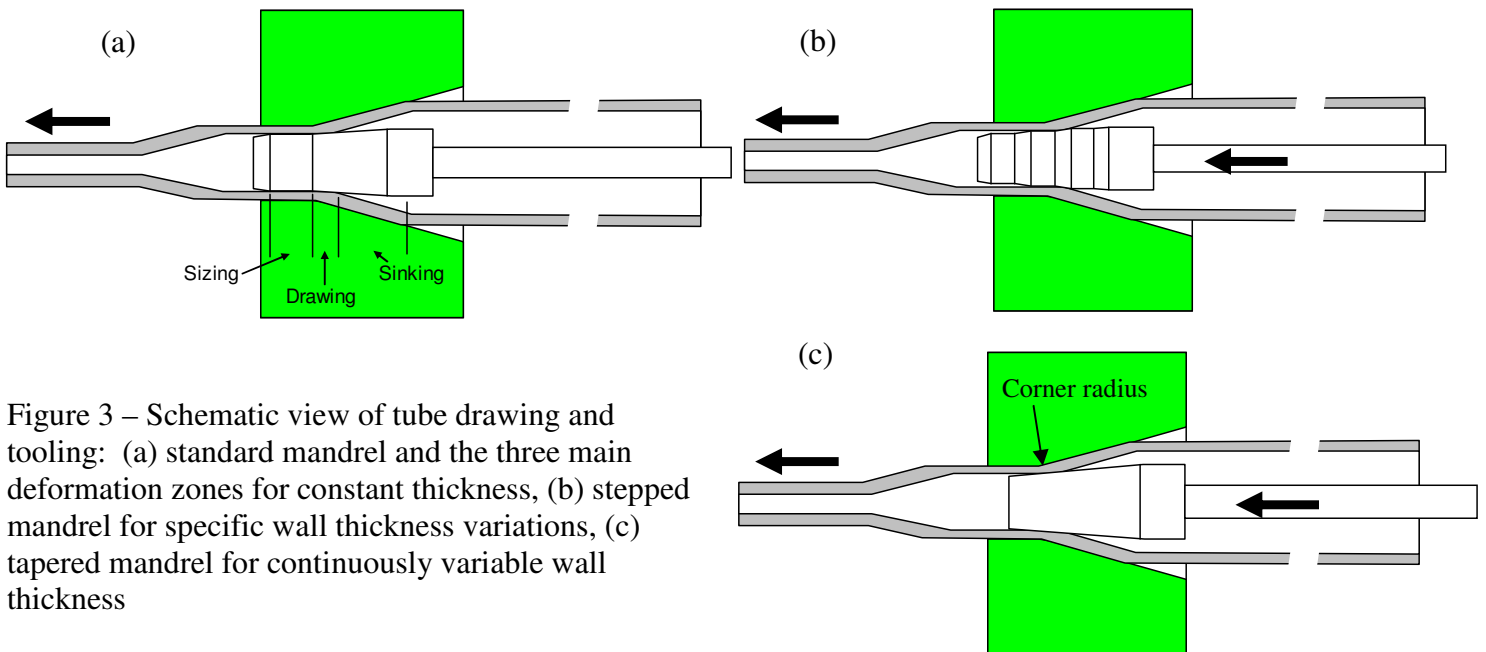
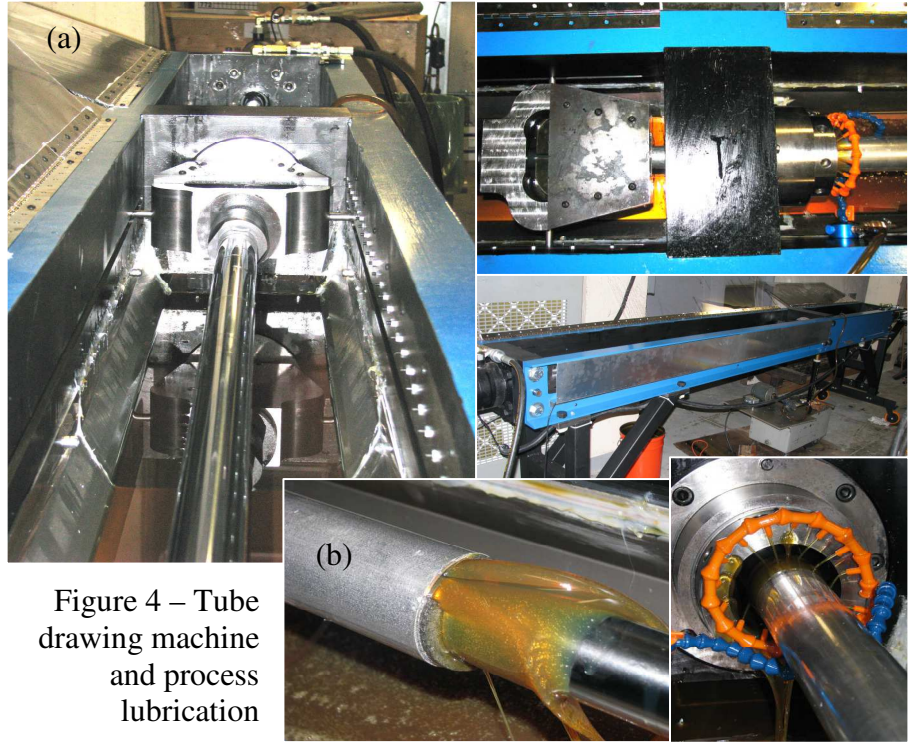


Figure 3 – Schematic view of tube drawing and tooling: (a) standard mandrel and the three main deformation zones for constant thickness, (b) stepped mandrel for specific wall thickness variations, (c) tapered mandrel for continuously variable wall thickness

EXPERIMENTAL SET-UP

Drawing tests have been realized using a small hydraulic tube drawing machine illustrated in Figure 4. Its pulling axis has a capacity of 335kN and 2.1m stroke and the mandrel axis can sustain 135kN over a 1.5m stroke. The tube crimped end is clamped into a self closing jaw of the pulling axis. Optical and magnetic encoders detect the position of each axis while electronic pressure gages installed on both sides of each hydraulic cylinder are used to monitor the force involved. The dimensions of the tooling used for the tests are illustrated in Figure 5. For these tests, no separate sinker was used. Drawing lubrication is ensured inside the tube (mandrel) by filling the tube of oil, and outside the tube (die), using multi-jets around the tube before the die as shown in Figure 4b. The lubricant utilized for all the tests is Magnus CAL 70-2 drawing oil. For the tests, the machine operated at a low drawing speed of 6 mm/s allowing time to change the thickness along the tube.



Finally, two batches of tubes will be used in conditions as received from the tube drawing manufacturer: a batch of AA6063 tubes of 63.5mm O.D. and 2.6mm wall thickness, and a batch of AA6061 tubes of 76.2mm O.D. 3.1 mm thick. These tubes have been inspected on CMM and tensile tests were made on standard samples. The results are presented in Table 1 and in Figure 6. Although they are supposed to be in full annealing (“O”) condition, the tensile tests confirm that some stresses were still present in regard of the slightly lower ductility and higher yield and ultimate strengths observed and compared to usual handbook data for AA6063-O and AA6061-O.

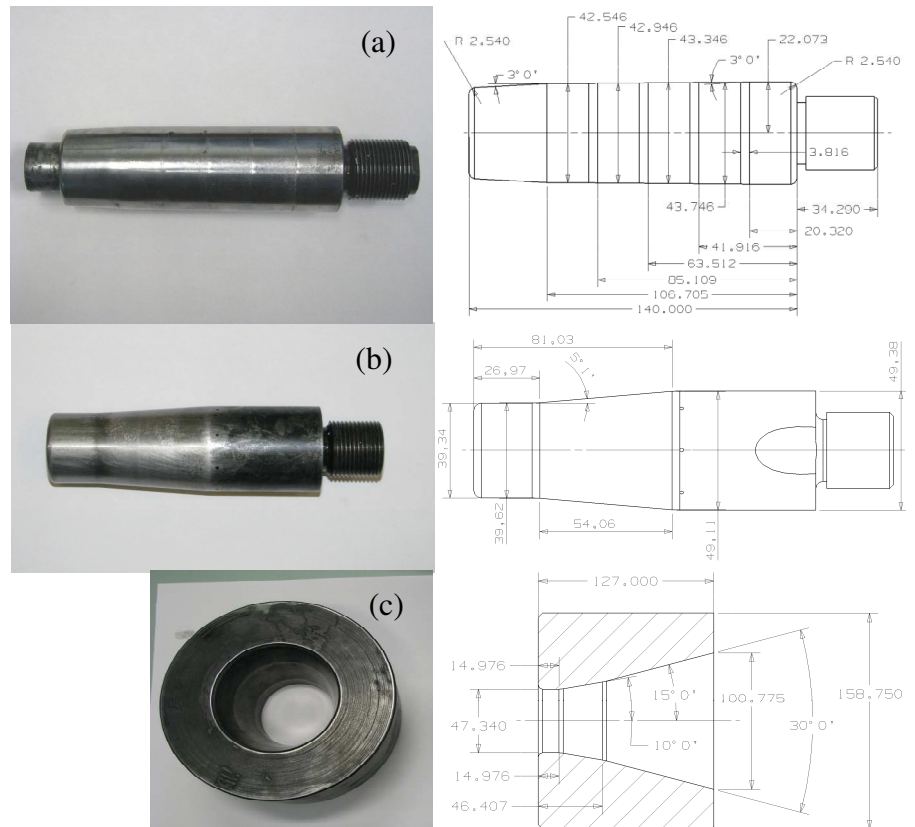


Table 1 – Extruded tube characteristics

Aluminum alloy	Initial geometry								Material properties		
	O.D.		I.D.		Wall thickness		Surface finish (avg Ra)		Tensile test		
	Ave	Roundness	Ave	Roundness	Ave	Std.Dev.	Inside	Outside	Yield stress	Ult. stress	Elongation
	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(μm)	(μm)	(MPa)	(MPa)	(%)
AA6063	63,481	0,014	58,233	0,010	2,623	0,007	0,74	0,75	60,0	117,0	15,6
AA6061	76,150	0,028	70,150	0,036	3,088	0,012	0,15	0,12	86,0	203,2	16,0

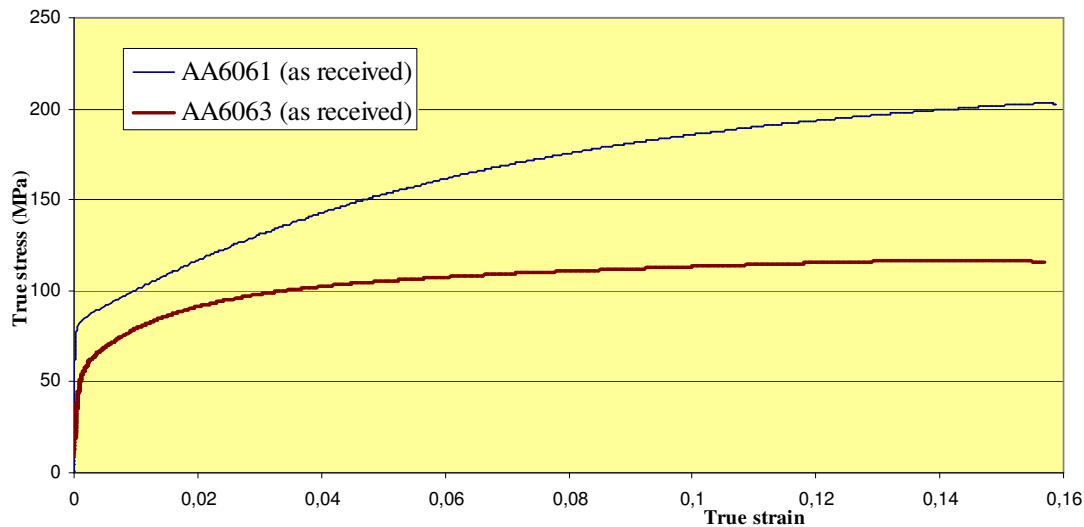


Figure 6 – Stress-strain curve from tensile tests on original tubes as received in partly annealed conditions

EXPERIMENTS AND RESULTS

Drawing without mandrel. In the first test both AA6063 and AA6061 tubes were drawn in the die without mandrel. Even though this is not common practice, these tests will be used to establish the final thickness and drawing force without mandrel. Later the effect of the mandrel alone will be separated from the overall forces. The results are presented in Table 2. It is interesting to observe that a relatively large drawing force is required for sinking only and that the wall thickness initially of 2.62mm and 3.09mm respectively for AA6063 and AA6061 tubes remain almost the same after sinking which indicate that most of the deformation is taken in the axial direction.

Table 2 – Results of tube drawing without mandrel (tube sinking)

Aluminum alloy	Final geometry						Monitored data
	O.D.		I.D.		Wall thickness		Drawing force
	Ave	Roundness	Ave	Roundness	Ave	Std.Dev.	
	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	
AA6063	48,111	0,017	42,527	0,025	2,805	0,012	26,27
AA6061	47,904	0,043	41,463	0,084	3,158	0,048	89,59

Tube drawing with the stepped cylindrical mandrel. Using the stepped mandrel of Figure 5a tests have been done with AA6063 tubes. The results illustrated in Table 3 are for different wall thicknesses obtained by aligning the mandrel cylindrical area to the die land providing a sizing length of about 15mm. Transition between steps is achieved progressively to avoid peaks in the drawing forces. Once the mandrel reaches its final position, a tube length of 150mm was produced at constant wall thickness. The tube broke when

attempting to reduce the wall thickness to 1.8mm. According to calculation [6], the minimum thickness to fracture was estimated at 1.9mm. With the stepped mandrel, the inside surface finish was very good and glossy while the outside finish remains to its original state. All dimensions were constant and repeatable. Tube expansion at the die output was limited to 0.3 mm of the outside diameter. The thinner the wall the lower is the elastic expansion. The drawing force ranged between 30.7 to 35.1kN. Compared to the sinking force of Table 2, the use of a mandrel increased the total drawing force by 4.5kN for 2.5mm wall thickness to 8.8kN for 1.895mm thickness. The presence of a mandrel increases by 17 to 33% the total drawing force. The mandrel force is relatively small and negative, i.e. a force must be applied to avoid the mandrel to enter into the die opening.

After tube drawing, samples taken in areas of constant thickness have been tested in tension and the corresponding stress-strain curves are illustrated in Figure 7 below. As expected, the alloy works hardened more with thickness reduction, its strength increases while its elongation is reduced.

Table 3 – Results of AA6063 tube drawing using the cylindrical stepped mandrel

Aluminum alloy	Final geometry								Monitored data		Material properties		
	O.D.		I.D.		Wall thickness		Surface finish (avg Ra)		Drawing force (kN)	Mandrel force (kN)	Tensile test		
	Ave	Roundness	Ave	Roundness	Ave	Std.Dev.	Inside	Outside			Yield stress	Ult. stress	Elongation
	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(μ m)	(μ m)			(MPa)	(MPa)	(%)
AA6063	47,639	0,049	42,670	0,044	2,500	0,031	0.06 to 0.15	0.52 to 0.64	30,770	-4,322	128,0	131,3	5,1
	47,583	0,044	43,037	0,034	2,286	0,028			33,544	-5,884	130,5	136,3	4,0
	47,569	0,030	43,408	0,035	2,081	0,006			33,926	-5,223	137,8	140,9	2,5
	47,479	0,072	43,671	0,055	1,895	0,041			35,072	-5,740	142,5	143,7	1,2

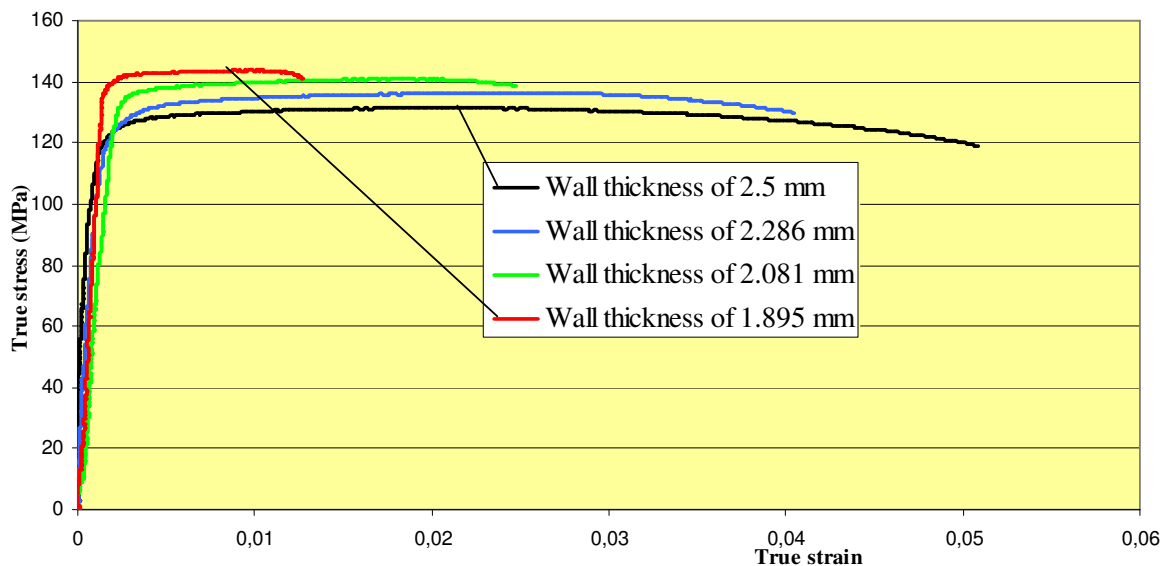


Figure 7 – Stress-strain curve (tensile tests) of AA6063 tubes after drawing at different thicknesses to observe the effect of work hardening

Tube drawing with the tapered mandrel. The taper mandrel is positioned axially according to a calibration curve obtained prior to the test. This calibration curve provides the axial position of the mandrel as a function of the wall thickness required. In a first drawing test the mandrel position was continuously changed to reduce progressively the wall thickness until tube breakage. This is illustrated in Figure 8 for both AA6063 and AA6061 tubes. The drawing force monitored during drawing is almost constant during tube sinking and increases as the mandrel comes into contact to reduce wall thickness.

The minimum thickness achieved immediately before tube breakage was about 2,1 mm for the AA6063 tube which is slightly thicker than the minimum thickness of 1,89mm observed with the stepped mandrel. This is due to the increase of drawing force after tube sinking that reaches by 57% for the tapered mandrel compared to 33% for the stepped mandrel. This higher drawing force with the tapered mandrel is in turn caused by the lower area of contact and the higher pressure in the die corner radius area where the lubricant becomes less effective. This effect is more important with the AA6061 where some aluminum depositions have been observed at the corner radius of the die which indicates the presence of some surface sticking. The surface finish of the tube using the stepped mandrel was also better.

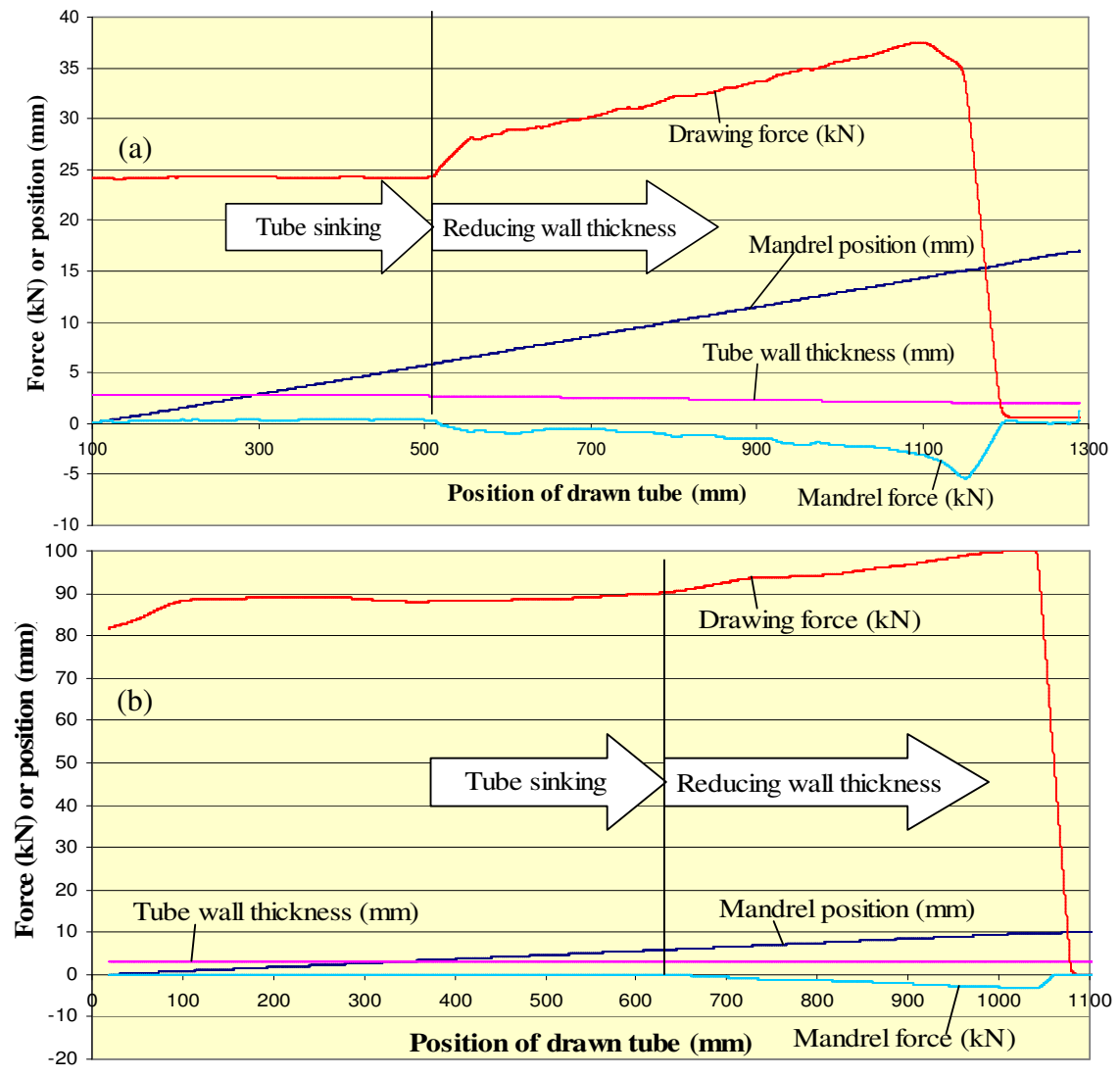


Figure 8 – Monitoring results during tube drawing with progressive wall thickness reduction using the tapered mandrel with both (a) AA6063 and (b) AA6061 tubes.

The second test comprises 4 different thicknesses made in the same tube using 50mm transitions and 150mm constant tube thickness areas. The results are provided in Table 4. The surface finish inside is relatively good although not glossy since no sizing zone is present. The observed drawing force was slightly higher than with continuous reduction of wall thickness of Figure 8. Indeed, as the mandrel position is stabilized for a given thickness, the drawing force slightly increases before stabilization. With drawing forces from 34.6 to 42.6kN,

the addition of the mandrel increases by up to 62% the drawing force. This increase is again higher than the increase observed with the stepped mandrel.

Table 4 – Results of constant thickness AA6063 tube drawing using the tapered mandrel

Aluminum alloy	Final geometry								Monitored data	
	O.D.		I.D.		Wall thickness		Surface finish (avg Ra)		Drawing force	Mandrel force
	Ave (mm)	Roundness (mm)	Ave (mm)	Roundness (mm)	Ave (mm)	Std.Dev. (mm)	Inside (μm)	Outside (μm)		
AA6063	48,009	0,047	43,172	0,039	2,440	0,017	0,17	0.52 to 0.62	34,591	-2,926
	47,983	0,037	43,570	0,035	2,231	0,020	0,11		38,793	-4,596
	47,512	0,058	43,514	0,044	2,020	0,024	0,29		40,745	-4,886
	47,579	0,063	43,604	0,042	2,013	0,027	0,30		42,634	-7,304

Testing the maximum rate of change of wall thickness. As shown in Figure 9, thickness reduction is obtained by moving the tapered mandrel in the die. The rate of change of wall thickness is a measure of the change of thickness per unit length of tube drawn. Two series of tests which details are not reported in this paper have been done with different rates of change. It was found that as long as the tube drawing speed is significantly higher (two to three times) than the mandrel speed during transitions, the drawing force depends mostly on the current wall thickness independently of the thickness rate of change. The maximum thickness reduction rates thus depend on mandrel taper angle. Obviously, this applies only as the wall thickness is reduced, thickness can be increased at any rate.

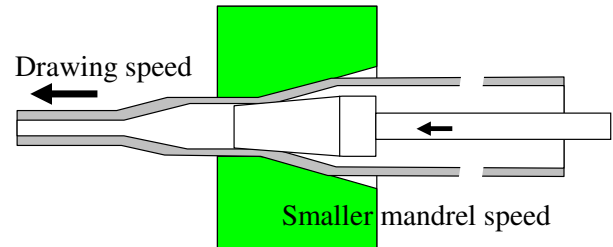


Figure 9 – Rate of change of tube wall thickness

Tube drawing with the oval stepped mandrel. The oval stepped mandrel utilized in the following tests is dimensionally identical to the cylindrical stepped mandrel of Figure 5a except for the cylindrical steps that are made oval. The major diameter of the oval is indicated in the drawing of Figure 5a and the minor diameter is 0.76mm smaller. This oval stepped mandrel has been tested in conditions similar to those used with the cylindrical stepped mandrel and reported in Table 3.

Table 5 – Results of AA6063 tube drawing using the oval stepped mandrel

Aluminum alloy	Final geometry								Monitored data	
	O.D.		Wall thick.(minor diam)		Wall thick.(major diam)		Surface finish (avg Ra)		Drawing force	Mandrel force
	Ave (mm)	Roundness (mm)	Ave (mm)	Std.Dev. (mm)	Ave (mm)	Std.Dev. (mm)	Inside (μm)	Outside (μm)		
AA6063	48,027	0,159	2,519	0,001	2,776	0,003	0,05	0.32 to 0.62	29,930	-3,819
	47,727	0,139	2,328	0,001	2,688	0,005	0,05		34,745	-4,551
	47,600	0,042	2,129	0,003	2,482	0,001	0,06		34,450	-3,614
	47,577	0,046	1,904	0,001	2,245	0,003	0,07		36,137	-4,066

The drawn tubes appear very good in both thin and thick areas of the oval and were drawn as easily as with the cylindrical stepped mandrel. Thicknesses at minor and major diameters do not show 0.38mm of variations but are closed with 0.34 to 0.36mm. For the first step, the mandrel minor diameter was too small and the thickness could not exceed 2.776mm. Indeed, Table 2 indicates that 2.8mm is the natural tube thickness without mandrel. The tube outside roundness is slightly degraded especially for thicker walls. Surface finish is still very good and no tearing or cracking is visible.

CONCLUSIONS

Tubes drawn with axial and circumferential thickness variations demonstrated the feasibility of the proposed technique and tooling. Using a stepped mandrel, excellent surface finish and dimensions are achieved for any thickness. Despite excessive pressure and poorer surface finish in certain conditions that could probably be corrected with a larger radius in the die transition between the land and tapered section, axial thickness variations can be achieved easily using the conical mandrel with both AA6063 and AA6061 alloys tested. The use of a sinker could improve even more the performance while reducing the pressure in the drawing zone between the mandrel and the die. Drawing tests with the oval stepped mandrel provided easily circumferential thickness variations. Obviously the gap variations between the die and mandrel can not be modified very significantly, but these limits are still to be explored especially with multi-pass reduction.

In further work, we intend to investigate not only the limits in circumferential thickness variations but also the effect of die corner radius and mandrel angle on the quality of drawn tubes using the conical mandrel, the benefit of using a sinker, the effect of pressurized lubricants both inside and outside the tube, the effect of other lubricants, and the control of the press to improved the quality of tubes drawn with variable thickness. Better models and finite element simulations like in [6] must be used to predict adequately tube breakage limits.

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