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Effect of Cross Section Reduction on the Mechanical Properties of Aluminium Tubes Drawn With Variable Wall Thickness

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Variable thickness tube drawing is a new process for the production of high performance tubes. In this study, experiments were conducted to evaluate the effect of cross section reduction on the microstructure and mechanical properties of variable thickness aluminium tubes drawn using two different position controlled mandrel techniques. Various tubes with three different outer diameters were subjected to cold drawing at room temperature from 11% to 41% cross section reduction. The local mechanical properties were determined from tensile tests carried out on specimens cut from different positions in the tubes parallel to their axes. The distributions of the Vickers hardness over the surfaces at 0 deg and 90 deg to the drawing direction were examined. It was found that the microhardness, yield strength, and ultimate tensile of the deformed samples increase and the corresponding elongation decreases with the increase of cross section reduction. Also, the anisotropy in microstructure and mechanical properties is more significant with increasing of cross section reduction. The evolution of mechanical properties of drawn tubes versus cross section reduction depends on the mandrel shapes and initial tube outer diameter. This study helps to further understand the microstructure and mechanical properties evolutions during tube drawing process with variable thickness. [DOI: 10.1115/1.4005040]

Keywords: tube drawing, variable thickness tube, mechanical properties inhomogeneity, anisotropy, AA6063

1 Introduction

It is well known that 6xxx series aluminium alloys are attractive to the industry for components requiring medium strength. Among the 6xxx series aluminium alloys, AA6063 is often used because of its high formability especially in the extrusion and drawing processes [1]. In addition, the formation of Mg₂Si intermetallic compound in this alloy during heat treatment process has beneficial effect on improving its casting, corrosion resistance property as well as its strength as reported by Siddiqui et al. [2].

Some structural components such as bicycle frame [3] or some sport articles [1] require bent or hydroformed tubes that are produced using tube drawing or extrusion processes. Tube drawing process is one of the mostly used processes to reduce diameter and wall thickness of tubes. This process can be modified to produce tubes with axially and/or circumferentially variable wall thickness. The variable wall thickness tube drawing process is being increasingly used to produce the lightweight tubes. Calhoun et al. [4] patented a method for production of stepped wall tubes using more than one mandrel. Newport et al. [5] also patented a method for fabrication of tubular structures from variable wall thickness tubes. Alexoff [6] proposed a technique using back pushing without mandrel to change tube wall thickness. Recently, several works focused on the production of variable thickness aluminium tubes for reduction of their weight to strength ratio. Guillot et al. [7] showed some applications of variable thickness tube in transportation purposes. They estimated that with application of these kinds of tubes, the weight of vehicle structures can be reduced up to 25%. Bihamta et al. [8] studied state of residual stresses in the variable thickness tubes. Bihamta et al. [9] devel-

oped an optimization procedure coupled with a finite element method (FEM) to study design specifications of this process. Bihamta et al. [10] studied effect of tube initial geometry on the minimum and maximum possible thicknesses in the production of variable thickness tubes using numerical and experimental. Also Bui et al. [11] investigated the forming limit of AA6063 tubes drawn with variable wall thickness using the upper bound method combined with the maximum drawing stress ratio forming criterion. However, there is still lack of information about the microstructure and mechanical properties evolution of this kind of tubes.

The evolution of microstructures and related mechanical properties during tube drawing process and similar processes like wire drawing, bar drawing have very importance as the same final geometry and material with different processing history will have completely different response during loading step. Several researches have been conducted to study the effect of processing history on microstructure, effective strain, microhardness, and mechanical properties. Rumiński et al. [12] analyzed effect of die geometry on the mechanical properties and distribution of strain field in the tube sinking process. They showed strain inhomogeneity on the tube wall cross section occurs in the tube sinking process and the largest effective strain occurs at the inner surfaces of the drawn tube. Sadok et al. [13] studied effect of die geometry on the strain field in the rod drawing process. Castro et al. [14] evaluated influence of die angle on the tensile mechanical properties of round section annealed copper bars drawn using a single pass drawing process. They showed that the yield strength and ultimate tensile strength values increase and the elongation decreases with the increase of die angle.

To the author's best knowledge, the previous studies found in the literature generally focused on the effects of individual processing parameters such as die geometry, lubrication condition, area reduction, and temperature on the microstructure, strain field, and mechanical properties of final product. However, there is not any study to clarify effect of mandrel shape and initial tube

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dimensions on the microstructure and mechanical properties of product. In addition, in the processes used in the previous works, various passes are required to obtain various area reduction values. In this paper, the mechanical characteristics evolution of cold drawn AA 6063 aluminium tubes with different area reductions were studied using a single pass. The drawing process was recently developed to produce the variable wall thickness tubes. The stepped and conical mandrels were used to investigate effect of mandrel geometry on the mechanical properties of drawn tubes. Three different values of tube outer diameters were used to study effect of initial tube dimensions on the evolution of mechanical properties versus area reduction. The investigated properties are Vickers hardness, yield strength, ultimate tensile strength (UTS), strain at UTS, and tensile elongation. The evolution of mechanical properties will be explained based on the evolution of microstructure. The anisotropy in microstructure and mechanical properties will be discussed too.

2 Experimental Procedures

Three batches of AA 6063-O aluminium tubes, supplied by Alfiniti Co., were utilized in the present investigation. Tubes outer diameter and wall thickness are 53.98 mm $\times$ 2.4 mm (batch A), 63.50 mm $\times$ 2.4 mm (batch B), and 69.85 mm $\times$ 2.4 mm (batch C). Two specimens were cut from two tubes from the batch B for the chemical composition assessment. The chemical composition in weight percentage of these tubes was examined by optical emission spectrometry (OES) and is presented in Table 1. These tubes were drawn at room temperature using variable thickness tube drawing process. This process is a modification in the classical tube drawing methods which makes production of axially variable wall thickness tubes possible. During this process, the tube is pulled by constant speed while the mandrel is moved to achieve the stepped variable wall thickness tube. More details of this process are available in Ref. [7]. Three types of mandrel (stepped mandrel, and conical mandrels with two different angles $\beta = 1$ deg and $\beta = 5.02$ deg) were used (Fig. 1). The designs of the mandrels and die are presented in Fig. 2.

The final outer diameter of drawn tubes is 47.63 mm and these tubes have variable wall thickness in axial direction. The tube drawing experiment included fabrication of 3–5 different regions with 3–5 constant thicknesses along the tube with 150 mm length and 50 mm transient length between them (Fig. 3(a)). The length of 150 mm will be used as tensile test samples. The thickness of drawn tubes was measured using micrometer. The radial (ϵ_{radial}) and circumferential (ϵ_{circ}) strains were calculated by $\epsilon_{\text{radial}} = \ln(h_f/h_0)$ and $\epsilon_{\text{circ}} = \ln[(OD_f - h_f)/(OD_0 - h_0)]$, where OD_0 and OD_f are, respectively, the initial and final outer diameters of tube and h_0 and h_f are the initial and final thicknesses of tube. The axial strain (ϵ_{axial}) is calculated based on the incompressibility condition, i.e., $\epsilon_{\text{axial}} = -\epsilon_{\text{radial}} - \epsilon_{\text{circ}}$. The thickness, cross section reduction (CSR) and strains of these tube areas are presented in the Table 2. As it was mentioned in Ref. [11], the tube drawing process with variable wall thickness has generally two principal steps: tube sinking step (without mandrel contact) and wall thickness reduction step (using position controlled mandrel). Most of the times depending on the process parameters like drawing speed and lubrication condition between tools and tube, sinking step leads to augmentation of tube wall thickness. However, in the wall thickness reduction step, the mandrel will move inside the tube to reduce its wall thickness. It can be seen from Table 2

Table 1 Chemical composition of AA 6063-O alloy (wt. %)

	Al	Si	Fe	Cu	Mn	Mg	Cr	Zn
Specimen 1	base	0.47	0.17	0.01	0.03	0.45	0.003	0.004
Specimen 2	base	0.48	0.17	0.02	0.03	0.49	0.005	0.004

Fig. 1 The illustration of variable wall thickness tube drawing using (a) a position controlled stepped mandrel and (b) position controlled conical mandrel [7]

that ϵ_{radial} in some positions of tubes are positive because these positions belong to the tube sinking region.

As it is clear in Fig. 3(b), the samples for optical microscopy analysis and Vickers measurements were cut from different zones of the tube in both transverse direction-radial direction (TD-RD) and drawing direction-radial direction (DD-RD) surfaces. The samples were analyzed using an Olympus BX51M upright microscope coupled to a CLEMEX image analysis software. Before optical microscope analysis, samples were mechanically polished using an automatic Tegrastest grinding/polishing machine then electropolished using a fluoboric electropolishing acid solution from Fisher Scientific at the 30 V for 120 s. Grain boundaries of approximately 420 grains were determined manually with IMAGE TOOL software using optical microscopy images to determine the grain area (A). The grain size was calculated by the following equation: $d = \sqrt{4A/\pi}$. The Vickers hardness of the samples was measured using a micro hardness machine (Clemex, Germany) at the applied load of 10 g for 15 s. This machine includes a motorized turret and stage, all controlled by the CLEMEX CMT-HD software.

Uniaxial tensile tests were carried out at room temperature by using an electromechanical testing machine (MTS/Alliance RT100). According to ASTM standard E8 (2004) [15], three standard specimens were cut from different positions of the tubes with 12.5 mm wide gauge section (Fig. 3(c)). The gauge length of the specimen is 57 mm. The specimens were stretched up to fracture point under displacement control at constant speed of 3 mm/min. Based on the load-deformation curves, true strain-stress curve for this material were calculated.

3 Experimental Results and Discussions

3.1 Microstructure. Figures 4(a) and 4(b) show the typical microstructure of as received AA6063-O alloy tube. Grains are equiaxed in both TD-RD and DD-RD samples. Figures 4(c) and 4(d), 4(e) and 4(f), 4(g) and 4(h), 4(i) and 4(j), and 4(k) and 4(l) show the microstructure of the samples deformed at the CSR of 11.61%, 17.46%, 24.40%, 31.40%, and 35.99%, respectively. These samples were cut from different locations in tube drawn using stepped mandrel. With increasing amount of cold deformation, the microstructure of the samples changed gradually. When the material was deformed with 11.61% cross section reduction (tube sinking step) the microstructure refinement was observed in both TD-RD and DD-RD samples. Also, it was observed that the grains was uniformly equiaxed in the TD-RD sample and

Fig. 2 Photos and designs of (a) stepped mandrel; (b) conical mandrel with angle $\beta = 1$ deg; (c) conical mandrel with angle $\beta = 5.02$ deg, and (d) die with angle $\alpha = 10$ deg

elongated in the DD-RD sample. The grains in the TD-RD sample became smaller gradually and the grains in the DD-RD sample are more elongated when the CSR increased. The grain refinement in both samples and the elongation of grains in the DD-RD sample are more significant when the CSR is larger than 35.99%. It is worth to mention that the CSR = 35.99% is not the maximum val-

ues can be obtained by the tube drawing process of AA 6063 tubes. The formability limit of this kind of tubes is about 40% as reported by Bui et al. [11].

The grain size distribution of 420 grains in term of number of frequency is illustrated in Fig. 5. These grains were evaluated by the optical microscopy images in both TD-RD and DD-RD

Fig. 3 (a) Schema of variable wall thickness tube; (b) preparation of specimens for optical microscopy and Vickers measurements: TD-RD (transverse direction-radial direction) and DD-RD (radial direction- drawing direction) samples; (c) tensile test specimen

samples of the deformed specimens at various deformation states. It is observed that grain size distributions follow a log-normal statistical function:

$$P(D : S, M) = \frac{1}{D \cdot S \cdot \sqrt{2\pi}} \exp \left[-\frac{1}{2} \left(\frac{\ln(D) - M}{S} \right)^2 \right]$$

where $\int_0^\infty P(D : S, M) d(D) = 1$, D is the diameter of the grain, M and S are constant parameters describing the mean grain size and

Table 2 Thickness, CSR and strains for the different zones of tube

	Thickness (mm)	CSR (%)	ϵ_{axial}	ϵ_{radial}	ϵ_{circ}
Initial tubes	2.40	0	0	0	0
Tubes drawn from initial tube of $OD_0 = 53.98$ mm using stepped mandrel	2.44	11.61	0.121	0.017	-0.138
	2.27	17.46	0.190	-0.056	-0.134
	2.07	24.40	0.278	-0.148	-0.130
	1.87	31.40	0.375	-0.250	-0.125
	1.74	35.99	0.444	-0.322	-0.122
Tubes drawn from initial tube of $OD_0 = 53.98$ mm using conical mandrel with angle $\beta = 1$ deg	2.42	12.50	0.131	0.008	-0.139
	2.238	18.53	0.205	-0.070	-0.135
	2.04	25.41	0.293	-0.163	-0.131
	1.845	32.25	0.389	-0.263	-0.126
	1.643	39.40	0.501	-0.379	-0.122
Tubes drawn from initial tube of $OD_0 = 53.98$ mm using conical mandrel with angle $\beta = 5.02$ deg	2.33	14.22	0.167	-0.032	-0.135
	2.13	21.25	0.253	-0.122	-0.131
	1.92	28.71	0.352	-0.226	-0.126
	1.75	34.79	0.441	-0.319	-0.122
Tubes drawn from initial tube of $OD_0 = 63.50$ mm using conical mandrel with angle $\beta = 5.02$ deg	2.50	23.95	0.271	0.039	-0.310
	2.31	29.44	0.346	-0.040	-0.306
	2.09	35.72	0.439	-0.138	-0.301
	1.90	41.46	0.533	-0.236	-0.297
Tubes drawn from initial tube of $OD_0 = 69.85$ mm using conical mandrel with angle $\beta = 5.02$ deg	2.54	30.17	0.356	0.055	-0.411
	2.31	36.04	0.444	-0.038	-0.406
	2.10	41.59	0.534	-0.134	-0.401

standard deviation of the log-normal distribution. The distributions follow a log-normal statistical law where their parameters have been optimized for the best fit and given in Table 3.

Variation of grain size with respect to CSR is presented in Fig. 6(a). The trends of grain refinement are similar in the in the TD-RD and DD-RD samples: from the initial material to the deformed material by sinking process (CSR = 11.61%), the grain size dramatically decreases; from the deformed material at CSR = 11.61% to the deformed material at CSR = 35.99%, the grain size exhibits a small additional decrease. An interesting point of Fig. 6(a) is that the grain refinement rates are different in the TD-RD and DD-RD samples. The grain refinement rate of the deformed material in the TD-RD sample is faster than in the DD-RD sample. The mean grain size measured in the TD-RD sample is smaller than that measured in the DD-RD sample and the grain size difference in both samples is more considerable when CSR increases. That led to the anisotropy of microstructure and mechanical properties in the AA6063 drawn tubes. The anisotropy of microstructure and mechanical properties was also observed in the materials processed by the accumulative roll bonding process [16,17], cold rolling [18], hot rolling [19], severe plastic deformation [20], and dynamic severe plastic deformation [21,22].

Figure 6(b) shows the aspect ratios of the grain size observed in the TD-RD and DD-RD samples as function of the CSR. The average grain aspect ratio in the DD-RD sample increases quickly when the CSR increases. However, the average grain aspect ratio in the TD-RD sample remains at constant values (≈ 1.5) during the tube drawing process. Zahid et al. [20] showed that the difference of grain aspect ratio in two directions of Al alloys preformed by severe plastic deformation can be eliminated by annealing at elevated temperatures.

3.2 Mechanical Properties. Effect of cross section reduction on Vickers hardness is shown in Fig. 7. The error bars for the samples show the range of hardness values obtained for 20 measurements for each sample. The results in Fig. 6 show that the grain size and aspect ratio of grains are similar in the TD-RD and DD-RD samples for the initial materials. However, it can be observed that the hardness is significantly different between TD-RD sample

Fig. 4 Polarized optical microstructure of AA 6063 tubes: (a, b) starting material (CSR = 0%), deformed samples at (c, d) CSR = 11.61%, (e, f) CSR = 17.46%, (g, h) CSR = 24.40%, (i, j) CSR = 31.40%, (k, l) CSR = 35.99% (50X magnification); (a, c, e, g, i, k) TD-RD samples; (b, d, f, h, j, l) DD-RD samples

and DD-RD sample for the initial tube (CSR = 0). The tube material seems to be anisotropic at the initial conditions. This anisotropy is probably caused by other microstructure characteristics such as texture. It should be noted that the texture cannot be measured by optical microscopy used in this work. Bui et al. [23] measured the texture of the comparable tube material using electron backscattering diffraction (EBSD) technique. They showed that the texture found in the initial tube was composed mainly of the

Fig. 5 Grain size distribution after one pass of tube drawing: (a) starting material (CSR = 0%), deformed samples at (b) CSR = 11.61%, (c) CSR = 17.46%, (d) CSR = 24.40%, (e) CSR = 31.40%, and (f) CSR = 35.99%

(1-11)<110> orientation and weaker cube orientation (001)<100>. These texture components may lead to the difference of hardness measured in two planes of initial material. The hardness values are found to increase with cold drawing. In addition, the increase rates are different in the TD-RD and DD-RD samples. The increase rate in the DD-RD sample is faster than that in the TD-RD sample. The similar values exist in both samples of the samples drawn at 11.61% and 17.46% CSRs too. It is

Table 3 Generated log-normal statistical grain size distributions of AA6063 alloy

	CSR (%)	Measured mean grain size D (μm)				D _{min} (μm)	D _{max} (μm)	Relative dispersion $\Delta D/D$
		S	M					
TD-RD sample	0	87.19	0.42	4.38	18.00	348.00	3.78	
	11.61	59.92	0.33	4.04	18.00	176.00	2.64	
	17.46	55.02	0.33	3.95	17.00	164.00	2.67	
	24.40	51.11	0.30	3.89	17.00	141.00	2.43	
	31.40	44.55	0.38	3.72	11.00	156.00	3.25	
DD-RD sample	35.99	36.30	0.40	3.51	8.00	134.00	3.47	
	0	88.38	0.40	4.40	20.00	329.00	3.50	
	11.61	63.63	0.38	4.08	16.00	222.00	3.24	
	17.46	61.32	0.38	4.04	15.00	216.00	3.28	
	24.40	57.91	0.35	4.00	16.00	187.00	2.95	
	31.40	54.71	0.41	3.92	12.00	210.00	3.62	
	35.99	49.62	0.43	3.81	10.00	203.00	3.89	

worth to mention that these values are higher in DD-RD sample in the higher CSR samples. For example, the mean Vickers hardness values of drawn tube at 35.99% CSR in the DD-RD sample is about 51.85 Hv and larger than that in the TD-RD sample (49.8 Hv). This anisotropy in hardness is also probably caused by the differences in the grain size and grain shape in two samples as shown in Fig. 6 and by the texture evolution by Bui et al. [23]. Further, the anisotropy in mechanical properties is caused by the anisotropy in microstructure, i.e., grain size, texture, and dislocations structure as also concluded in Li et al. [24].

The specimens drawn with stepped mandrel, using initial tube outer diameter of 53.98 mm were tested under tensile tests until failure. The true stress-true strain curves of the deformed and primary samples are shown in Fig. 8. The corresponding mechanical characteristics such as the yield strength determined at 0.2% offset, the UTS, the strain at UTS, and the strain to failure (elongation) are listed in Tables 4 and 5 given in Appendix. It can be observed that the primary tube (CSR = 0%) shows lower yield strength and the ultimate tensile strength (44.4 MPa and 99.1 MPa, respectively) and large elongation (30%). The flow stress of the deformed tubes is higher and its elongation is smaller than that of the initial tube. After 35.99% cross section reduction, the sample has the highest yield strength (138.1 MPa), which is almost three times higher than the primary one. However, the elongation of this sample comes down to 7.8%. It can be observed that the necking point occurs at the UTSs of 99.1 MPa (at strain at UTS $\varepsilon = 19.7\%$), 126.5 MPa (at $\varepsilon = 15.2\%$), 123 MPa (at $\varepsilon = 7.9\%$), 131.3 MPa (at $\varepsilon = 4.3\%$), 141.2 MPa (at $\varepsilon = 3.2\%$), and 145.2 MPa (at $\varepsilon = 2.5\%$) for initial samples, deformed samples at 11.61%, 17.46%, 24.40%, 31.40%, and 35.99% CSR, respectively. Figure 9 shows the tensile properties of cold tubes drawn with stepped mandrel and two conical mandrels as a function of

Fig. 7 Effect of CSR on the Vickers hardness changes

Fig. 8 True strain-stress curves showing the room temperature tensile behavior of drawn tubes

CSR. As it was expected, the yield strength and UTS of the deformed samples increase and the corresponding strain at UTS, elongation decreases with increase of CSR. At the same value of CSR, the conical mandrel with $\beta = 5.02$ deg results in tubes with higher yield strength and UTS, but smaller elongation in comparison with the tubes drawn with stepped mandrel and with conical mandrel having $\beta = 1$ deg. However, the mandrel shape does not have effect on the strain at UTS of drawn tube. Figure 10 shows the comparison of evolution of mechanical properties versus CSR

Fig. 6 (a) Effect of CSR on the grain refinement of AA6063 tubes and (b) effect of CSR on the aspect ratio of AA6063 tubes

Fig. 9 Effect of CSR on (a) the yield strength, (b) UTS, (c) strain at UTS, and (d) elongation of the drawn tubes using stepped and conical mandrel

Fig. 10 Effect of CSR on (a) the yield strength, (b) UTS, (c) strain at UTS, and (d) elongation of the tubes drawn from three different initial tube outer diameters using conical mandrel with angle $\beta = 5.02^\circ$

for the tubes drawn from three different initial tube outer diameters using conical mandrel with $\beta = 5.02$ deg. It was found that at the same value of CSR the tubes drawn from the smaller initial tube outer diameters have higher yield strength, UTS and strain at UTS in comparison with the tubes drawn from the larger initial tube outer diameters. The experimental results showed also that the initial tube outer diameters have no effect on the elongation of drawn tubes (see Fig. 10(d)). All mechanical properties of tubes drawn with different mandrel techniques and different initial tube outer diameters were summarized in the Tables 5–9 in Appendix.

The effect of mandrel shape and tube outer diameter on the yield strength and UTS may be explained by the fact that the difference in mandrel shape and tube outer diameter results in different residual stress state in the tubes as stated by Bihanta et al. [10,25]. Consequently, the residual stress has an influence on mechanical properties of final tubes.

The work of fracture (WoF) of the AA6063 tubes was also determined from the tensile tests. This quantity gives the plastic work exerted until fracture, corresponding to the area under the stress-strain curve, and characterizes the toughness of the material as reported by Bui et al. [26]. The WoF of the deformed samples are smaller than that of initial tube samples (see Tables 4–9 given in Appendix). It also confirms that after 35.99% cross section reduction, the material losses 72% of WoF. Figure 11 presents the loss of WoF during tube drawing process using three different mandrels. Figure 12 presents the loss of WoF during tube drawing process of tube drawn from different tube outer diameters. The experimental results showed that there are not significant effects of mandrel shape and initial tube outer diameter on the loss of WoF of drawn tubes.

3.3 Discussions. As mentioned before, the conventional tube drawing process produces the tubes with constant wall thickness in which presents homogeneous microstructure and mechanical properties along the axial direction of tube. However, the tube drawing process presented in this paper produces tubes with variable wall thickness from the initial constant wall thickness. The amount of cold work, defined as cross section reduction, is different along the axial direction of drawn tube. The difference in cold work results in the inhomogeneity in microstructure and mechanical properties in the drawn tube. Moreover, it was also known that the difference in cold work leads to nonuniform distribution of stored energy by dislocation in the drawn tubes. Since, the value of stored energy determines the number of nuclei in annealing heat treatment [27], i.e., recovery and recrystallization, the microstructure of tube workpiece after annealing will be inhomogeneous too. Ivanov and Markovic [28] studied the influence of hard cold working on characteristics of copper tubes during annealing process. They showed that the amount of cold deformation before intermediate

Fig. 11 Effect of CSR on the WoF of the drawn tubes using stepped and conical mandrel

Fig. 12 Effect of CSR on the WoF of the drawn tubes using conical mandrel for three different initial outer diameters

annealing has great influence on microstructure and mechanical properties of annealed copper tubes. Nah et al. [29] investigated the effect of strain states during cold rolling on the recrystallized grain size in an aluminium alloy. They showed the great dependence of recrystallization texture and grain size on the strain path upon prior deformation. In this study, there are two possibilities of the use of drawn tubes after tube drawing process: the drawn tube can be used in other manufacturing processes (i.e., tube bending, hydroforming) or another step of drawing with or without the annealing heat treatment. In both cases, the difference degree of cold work will lead to the inhomogeneity in microstructure and mechanical properties of the final products. Therefore, it is important for the material designers to determine and predict the inhomogeneity in microstructure and mechanical properties in deformed workpiece during tube drawing processes. The present study provides a datasheet of inhomogeneity in mechanical properties and clears the effect of drawing regime and also the effect of mandrel on the inhomogeneity in mechanical properties of drawn AA 6063 tubes during the variable wall thickness tube drawing process.

As mentioned before, tubes with complex geometry can be manufactured using tube hydroforming process and the tube drawing, bending and annealing heat treatment processes are considered as intermediate (or preforming) processes to provide the initial tube for the tube hydroforming process. Kang et al. [30] mentioned that the size of start tube is one of principal factors which influence the hydroformability. Trana [31] showed that the preforming process can be performed during the closing of the hydroforming tool. Both above mentioned papers showed that hydroformability of tubes can be improved using several ways. Therefore, the drawn tube (even its low ductility) can be used directly in the next processes without annealing heat treatment to reduce time and product costs. Predicting loss of ductility of drawn tubes is useful to decide on the using or not using of annealing heat treatment.

4 Conclusion

Knowledge of evolution of mechanical properties during tube drawing process is necessary in order to obtain drawn tubes with required mechanical properties. This work helps to understand effect of mandrel geometry and initial tube dimensions on the microstructure and mechanical properties evolution of tubes drawn with variable wall thickness in a single pass. The results can be summarized as follows:

- The variable wall thickness tube drawing process produces tubes with different cross section reduction. The difference of cross section reduction leads to the inhomogeneity in microstructure, mechanical properties, and anisotropy characteristics along the axial direction of drawn tubes.
- The anisotropy in microstructure leads to anisotropy in mechanical properties of tubes. The anisotropy is more significant with increasing of cross section reduction.

- The microhardness, yield strength, ultimate tensile strength of the deformed samples increase and the corresponding strain at ultimate tensile strength, elongation decrease with the increase of cross section reduction.
- At the same value of cross section reduction, the conical mandrel with larger angle results in the tubes with higher yield strength and ultimate tensile strength, but smaller elongation in comparison with the tubes drawn with conical mandrel having smaller angle and with stepped mandrel. Also the conical mandrel having angle $\beta = 1$ deg results in the tubes with smallest ultimate tensile strength.
- At the same value of cross section reduction, the tubes drawn from the smaller initial tube outer diameters have higher yield strength, ultimate tensile strength, and strain at ultimate tensile strength in comparison with the tubes drawn from the larger initial tube outer diameters.

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Appendix

Table 4 Mechanical properties of AA 6063-O initial tube

	Yield strength (MPa)	Ultimate tensile strength (MPa)	Strain at UTS (%)	Elongation (%)	WoF (MJ/m ³)
AA 6063-O	44.4 ± 2.7	99.1 ± 0.3	19.7 ± 0.4	30 ± 1.0	28.4 ± 0.8

Table 5 Mechanical properties of AA 6063-O tubes drawn from initial tube of OD = 53.98 mm using stepped mandrel

	CSR = 11.61%	CSR = 17.46%	CSR = 24.46 %	CSR = 31.40%	CSR = 35.99%
Yield strength (MPa)	104.7 ± 0.6	112.0 ± 0.8	123.7 ± 1.1	134.3 ± 2.3	138.1 ± 0.6
UTS (MPa)	126.5 ± 1.1	123.0 ± 0.3	131.3 ± 1.1	141.2 ± 2.0	145.2 ± 1.2
Strain at UTS (%)	15.2 ± 0.6	7.9 ± 0.4	4.3 ± 0.1	3.2 ± 0.2	2.5 ± 0.1
Elongation (%)	20.5 ± 1.2	12.1 ± 0.4	8.3 ± 0.2	7.1 ± 0.7	5.9 ± 0.2
WoF (MJ/m ³)	22.2 ± 1.3	13.4 ± 0.4	10.0 ± 0.4	9.1 ± 0.8	7.8 ± 0.4

Table 6 Mechanical properties of AA 6063-O tubes drawn from initial tube of OD = 53.98 mm using conical mandrel with angle $\beta = 1$ deg

	CSR = 12.26%	CSR = 18.53%	CSR = 25.41%	CSR = 32.25%	CSR = 39.40%
Yield strength (MPa)	104.5 ± 2.3	115.4 ± 0.9	125.8 ± 0.8	134.5 ± 1.1	142.6 ± 1.4
UTS (MPa)	113.6 ± 1.0	120.9 ± 0.9	130.0 ± 0.8	138.3 ± 0.8	146.2 ± 1.4
Strain at UTS, %	13.8 ± 0.8	7.3 ± 1.1	4.1 ± 0.3	4.1 ± 0.8	3.3 ± 0.5
Elongation, %	18.0 ± 0.7	10.6 ± 1.1	7.3 ± 0.4	6.5 ± 0.8	5.3 ± 0.5
WoF (MJ/m ³)	16.9 ± 0.2	13.0 ± 1.7	9.4 ± 0.7	9.0 ± 1.1	7.6 ± 0.6

Table 7 Mechanical properties of AA 6063-O tubes drawn from initial tube of OD = 53.98 mm using conical mandrel with angle $\beta = 5.02$ deg

	CSR = 14.22%	CSR = 21.25%	CSR = 28.71%	CSR = 34.79%
Yield strength (MPa)	112.6 ± 1.1	121.9 ± 0.3	132.3 ± 0.2	138.8 ± 0.6
UTS (MPa)	131.8 ± 1.9	134.0 ± 2.1	141.9 ± 0.1	147.5 ± 0.2
Strain at UTS (%)	11.0 ± 0.7	5.5 ± 2.0	4.2 ± 0.4	3.6 ± 0.6
Elongation (%)	14.5 ± 0.7	8.6 ± 2.1	6.8 ± 0.3	5.9 ± 0.8
WoF (MJ/m ³)	17.0 ± 0.9	10.7 ± 2.6	9.0 ± 0.4	8.1 ± 1.0

Table 8 Mechanical properties of AA 6063-O tubes drawn from initial tube of OD = 63.50 mm using conical mandrel with angle $\beta = 5.02$ deg

	CSR = 23.95%	CSR = 29.44%	CSR = 35.72%	CSR = 41.46%
Yield strength (MPa)	124.3 ± 0.2	129.2 ± 0.1	136.8 ± 0.2	142.0 ± 0.8
UTS (MPa)	136.0 ± 0.7	139.2 ± 0.5	145.8 ± 0.5	150.5 ± 0.2
Strain at UTS (%)	4.6 ± 0.4	3.6 ± 0.8	3.2 ± 0.5	2.7 ± 0.5
Elongation (%)	8.4 ± 0.2	6.8 ± 0.8	6.0 ± 1.0	4.5 ± 1.2
WoF (MJ/m ³)	10.6 ± 0.3	8.9 ± 1.0	8.1 ± 0.5	6.3 ± 1.7

Table 9 Mechanical properties of AA 6063-O tubes drawn from initial tube of OD = 69.85 mm using conical mandrel with angle $\beta = 5.02$ deg

	CSR = 30.17%	CSR = 36.04%	CSR = 41.59%
Yield strength (MPa)	130.3 $\pm$ 0.3	131.7 $\pm$ 0.6	137.0 $\pm$ 0.3
UTS (MPa)	138.6 $\pm$ 0.6	139.3 $\pm$ 0.4	144.1 $\pm$ 0.4
Strain at UTS (%)	3.1 $\pm$ 0.1	2.7 $\pm$ 0.5	2.4 $\pm$ 0.5
Elongation (%)	6.6 $\pm$ 0.1	5.7 $\pm$ 0.4	4.9 $\pm$ 0.3
WoF (MJ/m ³)	8.6 $\pm$ 0.2	7.4 $\pm$ 0.5	6.6 $\pm$ 0.4

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