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Optimization of heat treatment in cold-drawn 6063 aluminium tubes

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ABSTRACT

The effect of heat treatment condition on mechanical properties and bendability of 6063 aluminium cold-drawn tubes was investigated. The standardized heat treatment presently used in manufacturing of cold-drawn tubes increases the cost and time of the process which ultimately reduces plant productivity. The effects of time, temperature, and furnace heating rate were studied in order to identify an optimized heat treatment for tubes with different cold work levels. Drawn from the as-extruded state, tubes were heat treated to under-aged, peak-aged, and over-aged conditions with time and temperature ranging from 1 min to 24 h and 130–200 °C, respectively. Mechanical properties were determined with full section tensile tests whereas tube bendability was evaluated on an industrial draw bending machine. These characteristics were evaluated in each condition in order to identify the heat treatment which allows conforming to 6063-T832 temper requirements and gives sufficient bendability. Moreover, bendability was successfully correlated to fracture strain measured during a uniaxial tensile test and a threshold value over which problem-free bending operation was determined.

1. Introduction

The current market for aluminium tubes such as sport articles, demands good mechanical properties, surface finish, and precise dimensions. The tube drawing process can provide extruded tubes with these required characteristics. The 6063 aluminium alloy is often used because it is easily extruded. Tube drawing is a process in which a tube is pulled through a steel conical die and a mandrel, reducing both diameter and tube thickness. This can be done in a single pass or in multiple passes. Cold working of the aluminium upon drawing decreases ductility, and as-drawn tubes are likely to fracture during bending. Using the cold drawing process alone, the mechanical properties required for the 6063-T832 temper certification can not be reached. Green (1963) mentioned that, in practice, a heat treatment (HT) of 75 min at 160 °C must be performed between the drawing and bending operations. Although this heat treatment increases strength and bendability of the tubes, cost of the process is also increased. Long periods required to heat the tubes in a furnace have an adverse effect on productivity and energy efficiency. In fact, plant productivity would be improved if the heat treatment time was shortened and the alloy strengthening response was faster.

Designers of aluminium snowshoes are looking for 6063-T832 alloy as the highest temper recognized in ASTM Standard B483M (2005) for the 6063 alloy. This temper designation specifies the minimum mechanical properties which are obtained by cold work subsequent to solution heat treatment and prior to precipitation treatment. These properties are presented in Table 1. Tubes shall also have sufficient bendability to make the different models of snowshoe frames illustrated in Fig. 1.

The heat treatment effects on mechanical properties of the 6000 series aluminium alloys were investigated many times in the past. Dutkiewicz and Litynska (2002) studied the strengthening behaviour following deformation and subsequent aging. They showed that maximum hardness is obtained with 60% deformation and 2 h aging at 165 °C. Gao et al. (2002) showed that specimens of higher strength resulted from a longer exposition to natural pre-aging at room temperature followed by a given subsequent artificial aging. Gavgali et al. (2003) demonstrated that an artificially aged improved wear property compared to as-cast alloy. Jiang and Hong (1991) studied the effects of aging conditions on the microstructure. Peak strength was achieved with a 64 h–160 °C aging compared to 2.5 h–250 °C. Munitz et al. (2000) showed that ultimate yield strength increases with annealing at the beginning of the aging process where a peak is reached; a longer aging time then decreases the strength. Siddiqui et al. (2000) revealed that time and temperature play a very important role in the precipitation hardening process of Al-alloy. Deschamps et al. (1998) showed that a slow heating

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Table 1
Mechanical properties of the 6063-T832 temper.

ASTM temper	Tube wall thickness (mm)	Yield strength (MPa)	Ultimate tensile strength (MPa)	Elongation min. in 50 mm (full section) (%)
6063-	0.64–1.24	248.2	282.7	8
T832	1.27–6.58	241.3	275.8	8

rate favours a fine and homogenously distribution of the η′ phase while a fast heating rate resulted in large precipitate gradient in the material.

Artificial aging is usually performed between 100 and 190 °C (Polmear, 1995). As mentioned by many authors, magnesium and silicon additions to aluminium as alloying elements allow the formation of Mg_2Si precipitates in a complex sequence and alloy hardening. Dutkiewicz and Litynska (2002) concluded that the density of precipitate increases with the level of deformation. Ismail (1995) showed that precipitate growth is accelerated by introducing deformation prior to aging. Quainoo and Yannacopoulos (2004) studied the effect of cold work on the precipitation kinetics. They report that heat treatment following an increasing degree of cold work increases the density of dislocation tangles and the activation energy for dissolution of Guinier Preston zones of the first kind (GP-1). Siddiqui et al. (2000) showed that the higher strength obtained at peak-aging conditions was due to a finer grain distribution causing more obstacles in the movement of dislocation.

The majority of these works used fully solutionised alloys followed by a water quench. However, few authors worked on heat treatment of prestrained aluminium alloys. Deschamps et al. (1998) compared the microstructure evolution of a non-deformed alloy to a 10% predeformation. Quainoo and Yannacopoulos (2004) worked with deformation level of 2 and 5% prior to aging. Rack (1977) reported that warm deformation, compared to equal cold deformation has not a great influence on mechanical properties after subsequent aging. He also reported that prior strain increased the precipitation response of 6061 alloy. Rack and Krenzer (1977) studied the effects on microstructure of thermomechanical treatment with different levels of deformation. The effects of combined deformation and aging on the subsequent mechanical response of high purity 6061 aluminum have been examined and they shown that the yield strength can be increased by an appropriate choice of thermomechanical treatment.

Actually, tube strain after the cold drawing process can be as high as 65% and such a high degree of cold work may affect alloy behaviour during the precipitation heat treatment. Ismail (1995) reported a 33% increase in strength with a 15% deformation. Quainoo and Yannacopoulos (2004) showed that deformation levels of 2 and 5% prior to aging were both increasing the tensile strength.

Fig. 1. Aluminium snowshoe frame models.

Table 2
Chemical composition of the tubes.

6063 (wt%)	Si	Mg	Fe	Cu	Mn	Cr	Ti
Max.	0.6	0.9	0.35	0.1	0.1	0.1	0.05
Min.	0.2	0.45	–	–	–	–	–
Batch 1	0.45	0.47	0.13	0.002	0.023	0.002	0.009
Batch 2	0.39	0.48	0.14	0.003	0.032	0.001	0.009

The increase in hardness following cold deformation has also been demonstrated. Dutkiewicz and Litynska (2002) compared the effect on hardness of 30, 60 and 90% strain prior to aging and reported an increase with a 90% deformation. Rack (1977) also reported an increase in hardness with a 50% deformation followed by different aging temperatures.

It was observed that this type of thermomechanical treatment induces beneficial effects on other properties such as fatigue strength and stress corrosion resistance. Moreover, prestrain might accelerate the aging response compared to conventional artificial aging. Quainoo and Yannacopoulos (2004) found that increasing in the activation energy of dissolution of GP-1 zones is observed with increase of cold work. Yassar et al. (2005) studied the effect of dislocation structures on precipitation behaviour after cold deformation of 15 and 30% and proposed a sequence explaining the improvement of mechanical properties.

Ismail (1995) states that, in the case of heat treatment performed after rolling at room temperature on 6111 alloy, there is only a combination of prestrain quantity and heating parameter values in which the maximum strength of the alloy is reached.

Although most of these works used hardness measurements to characterize the evolution of mechanical properties, these are not appropriate for ASTM certification. Thus, in order to fill this deficiency and get specific data for this alloy, the effects of time, temperature, and heating rate were investigated in this paper to identity the heat treatment which is the most applicable for the manufacturing of snowshoes with aluminium tubes. The effect of prestrain was also studied to establish the optimal combination of cold-work and heating to produce the best strengthening response without adverse effects on ductility of the tubes. Mechanical properties were determined using tensile tests and confirmed by bending tests with an industrial bending machine.

2. Experimental procedure

Two batches of extruded 6063 aluminium alloy tubes were supplied in forced-air-cooled condition (F temper). Tube diameter and wall thickness were 29.5 mm × 1.4 mm and 22.2 mm × 2.1 mm. The tubes were extruded at about 500 °C according to ASTM Standard B807 (2006). The chemical composition of the tubes is shown in Table 2. No solution heat treatment was done after extrusion and the tubes were stored for more than a month in the plant at ambient temperature before being drawn. Fifteen extruded tubes were randomly chosen from each batch. A specimen was cut from each tube for a tensile test to determine the mechanical properties of the raw material and to evaluate consistency. The tubes of the first batch had undergone 50% deformation through cold drawing at room temperature in two passes. The tubes of the second batch were deformed by 40, 50, and 60% with the same process. All the tubes were cut

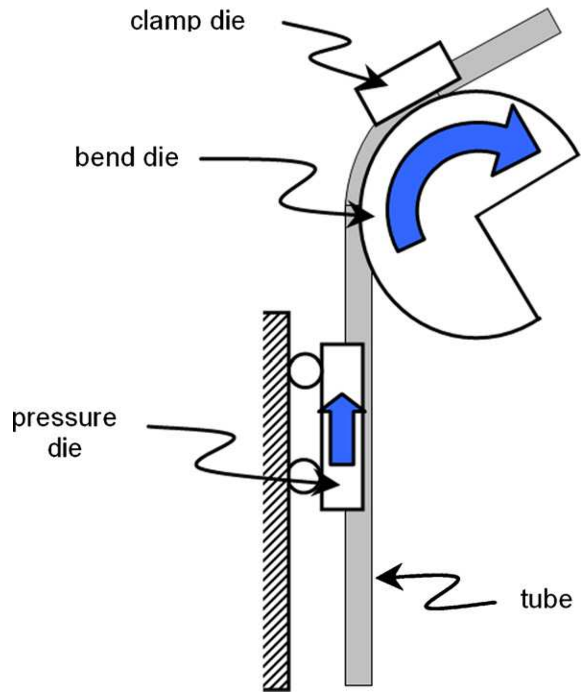

Fig. 2. Diagram of rotary bending machine.

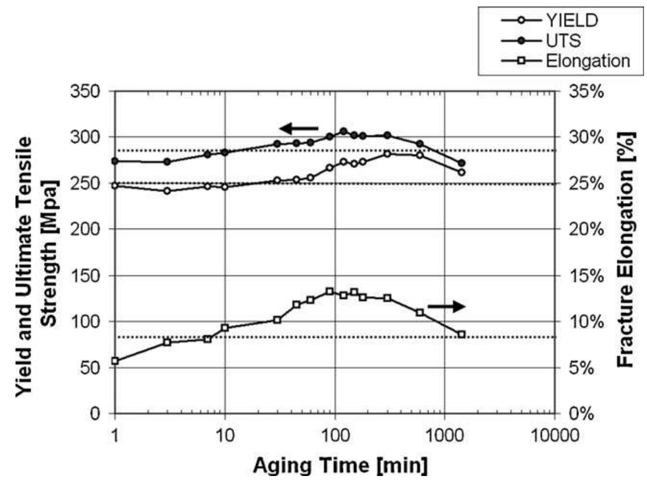

Fig. 3. Mechanical properties of Al-6063 tubes aged at 160 °C.

to 305 mm length. Heat treatments were performed, less than 24 h after drawing, in a small furnace by exposing cold-drawn tubes for time and temperature ranging from 1 min to 24 h and 130–200 °C, respectively, followed by air cooling. Immediately after cooling, tensile testing was performed on full section tubing using machined steel plugs according to ASTM Standard B557 (2002) with a 100 kN tensile machine at a constant crosshead speed of 10 mm/min. A 50 mm gage extensometer was placed at the middle of the specimen to measure elongation. Elongation values were disregarded when fracture occurred outside the extensometer and five tubes were tested for each heat treatment condition.

Three heating rates were tested by producing heat treatments preceded by a ramp. From 25 °C, the temperature was increased continuously up to 160 °C during a period of 60 and 90 min. The soaking periods started at the end of the ramp and range from 0 to 180 min. Mechanical properties of these tubes were compared to the baseline treatment, which included placing the specimens in the preheated furnace for about 10 min to reach the treatment temperature once again.

The bendability was evaluated only on the first batch of tubes using a rotary-draw bending machine as illustrated in Fig. 2. Heat treated specimens were bent over a 57 mm die radius to an angle of 150° as in the production sequence, i.e. without mandrel and without lubrication. For each heat treatment condition, nine specimens were bent. Each bend was visually inspected for defects like failures, cracks, or poor surface finish and was compared to others to identify the heat treatment providing the best bending performance. Some bends were sectioned, mounted, and polished to examine their microstructure and crack propagation. Etching was done with a solution of 1% hydrofluoric acid at room temperature for 4.5 min.

3. Results and discussion

3.1. Mechanical properties

Fig. 3 shows yield strength, ultimate tensile strength and fracture elongation for tubes with a 50% reduction treated at 160 °C from 1 min to 24 h. In all charts, the dotted lines indicate the minimum values for the 6063-T832 temper. As shown in Fig. 3, the yield and ultimate tensile strengths increase at the beginning of aging, reach a maximum of 282 and 306 MPa respectively, and decrease for extended times due to overaging. This is similar to the behaviour of heat treatable aluminium alloys without prestrain as observed many times in the past. In their study of the aging parameters of 6063 aluminum alloy, Siddiqui et al. (2000) identified the best combination of time and temperature increasing the properties in strength and hardness; some parameters improved the fatigue behaviour. Munitz et al. (2000) worked the same alloy and reported an increase of ultimate yield strength with aging time to reach a peak before decreasing with longer aging time. This is also mentioned by Jiang and Hong (1991) who report a peak in hardness obtained by aging the 6063 alloy for a longer time at lower temperature compared to shorter time and higher temperature. Gao et al. (2002) found that a long period of natural pre-aging at room temperature will result into higher strength after subsequent artificial aging.

As mentioned in other studies, during the artificial aging of undeformed alloys, elongation normally undergoes a continuous reduction. This is reported in by Munitz et al. (2000), who mention a decrease in elongation with a longer aging process. Siddiqui et al. (2000) also report a constant reduction in the percentage of elongation from an increase both in time and temperature. Over aged specimen showed a 6% ductility following 14 h at 498 K. However in the present work, the fracture elongation increased at the beginning of the treatment up to 13.2% after 90 min and then decreased for extended aging times. Actually, cold work from drawing increases the dislocation density in the metal which reduces ductility. Hence, during the heat treatment applied in the present work, a partial recovery took place with an age hardening phenomena which increased both the strength and the ductility of the tubes and conformed to the 6063-T832 requirements after 45 min. This treatment is significantly faster then the 8-h treatment at 175 °C currently used in production to reach the T6 condition in 6063 without prestrain (Parson and Yiu, 1988). It also allows reaching higher strength than the T6 temper which requires minimum yield strength of 208 MPa and ultimate tensile strength of 239 MPa. Munitz et al. (2000) also reached higher yield and ultimate strengths with longer aging time of 16, 20 and 24 h at 175 °C. According to Dutkiewicz and Litynska (2002), recovery phenomena was observed without recrystallisation during aging of 6113 alloy at 165 °C. This conclusion was based on the observation of the misorientation of a rotational Moiré pattern in subgrains with a transmission electronic microscope. Thus, recovery can be activated even if metal temperature is fairly low. It appears that large amounts of cold work done on tubes

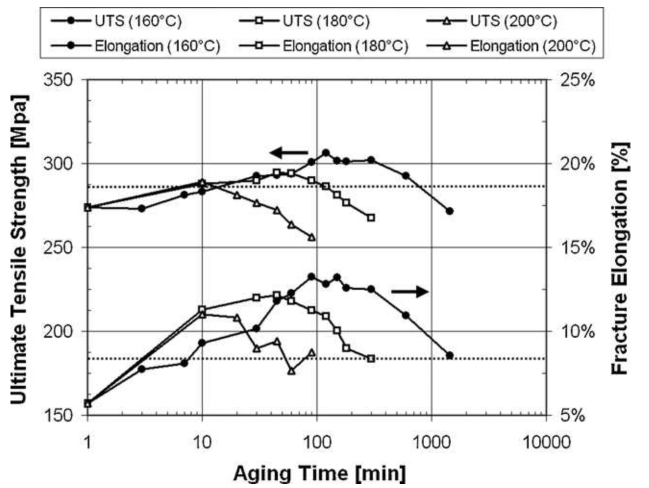

Fig. 4. Mechanical properties of Al-6063 tubes aged at 160, 180, and 200 °C.

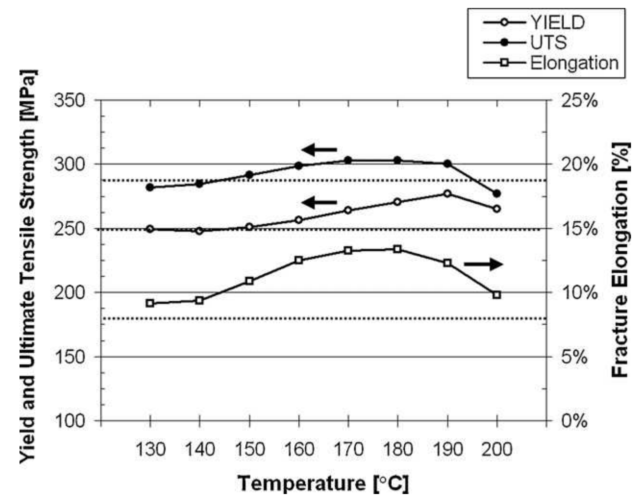

Fig. 5. Mechanical properties of Al-6063 tubes aged for 30 min at different temperature.

before the heat treatment in some conditions improves mechanical properties and can increase the overall productivity of the manufacturing process.

Fig. 4 presents the same experimental data performed at 180 and 200 °C compared to the 160 °C data. As the temperature was increased, peaks were reached faster but were lower. The same behaviour is characteristic of heat-treatable aluminium alloys and was observed in many studies on unprestrained alloys (Gao et al., 2002; Munitz et al., 2000; Siddiqui et al., 2000). Gao et al. (2002) mentions that for material having the same pre-aging conditions, the higher the aging temperature, the lower the peak strength and the time to reach peak strength. Munitz et al. (2000) report a similar behaviour where the yield stress and the ultimate tensile strength increase with time at the beginning of the process to reach a maximum (T6 condition) and then decrease if the aging process is continued for longer time. Moreover, Siddiqui et al. (2000) state that in over-aging the alloy, the size of the individual precipitated particle increases, but the number of particles decreases. This causes few obstacles to the movement of dislocations; therefore, the mechanical properties decrease.

From a production approach, increasing temperature appears to be beneficial in order to reduce treatment time. However, as shown in Fig. 4, aging at 200 °C can spoil aluminium tubes because properties start to degrade after only 10 min. The decrease is also much faster than for aging at 160 °C. For instance, according to Fig. 4, the fracture elongation reduction between 10 and 30 min at 200 °C would require more than 20 h at 160 °C to be equivalent. Hence, a higher operating temperature reduces the operating window and requires a better temperature control and uniformity in the furnace. Fig. 5 shows the effect of temperature on the mechanical properties of tubes in the range of 130–200 °C for a 30-min period, which is a more reasonable time for production. According to Fig. 5, each property reaches its maximum and then decreases as temperature increases. As mentioned by Munitz et al. (2000), the mechanical property behaviour for aging at a certain temperature for different durations is generally similar to the behaviour under heating for a constant time at different temperatures. This was also observed in the present study.

The time to reach heat treatment temperature in a large furnace can be considerable. In fact, for this specific application, preheating time is longer than the heat treatment period itself. Thus, it was investigated if preheating time can significantly modify mechanical properties and be considered as part of the heat treatment. Preheating periods of 10, 60, and 90 min were tested. Fig. 6 shows yield strength and fracture elongation data for these three cases. Difference in strength is negligible between immersion in a preheated furnace (10 min) and heating the furnace from 25 to 160 °C in 60 min or less. Elongation is slightly higher with slow heating rate for a soaking time of 60 min or less. The same holds true for a 90-min preheating time. Mechanical properties are slightly higher for aging of 60 min or less preceded by a 90-min preheating compared to the baseline. Elongation is the parameter which is the most affected, but with over 60 min of aging, the difference in elongation is negligible. Finally, no clear tendency can be expressed concerning the effect of preheating time on strength for soaking times longer than 60 min.

These conclusions are similar to those reported by Deschamps et al. (1998) who found that, for Al–Zn–Mg alloy, the influence of heating rate shows a very small influence on the strength. However, the effect of heating rate is less in the present work. According to Deschamps et al. (1998), a low heating rate preserves GP zones in the matrix. GP zones are fine and homogenously distributed precipitates which help to increase alloy strength during aging. A faster heating makes nucleation of precipitates difficult because of GP zone reversion, and the resulting precipitates are coarser. Precipitate observation and identification were not done in the present study because the work was focused on industrial recommenda-

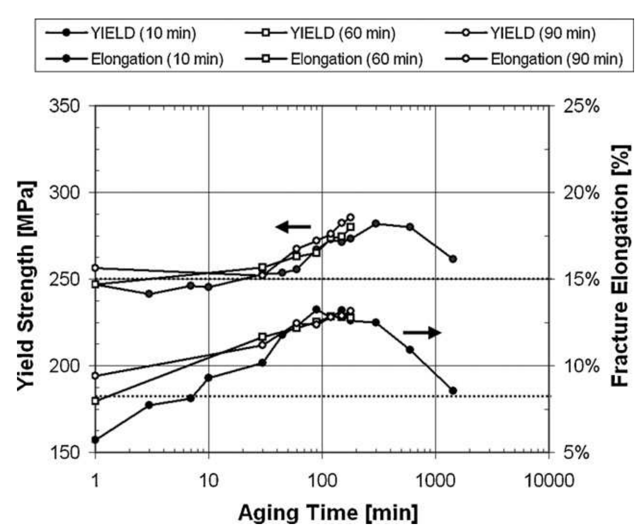

Fig. 6. Mechanical properties of Al-6063 tubes aged at 160 °C with different heating rates.

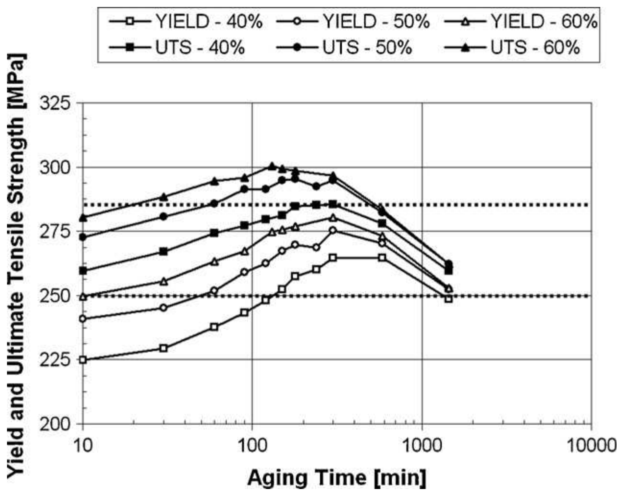

Fig. 7. Variation of yield and ultimate tensile strength with aging time at 160 °C different level of cold work.

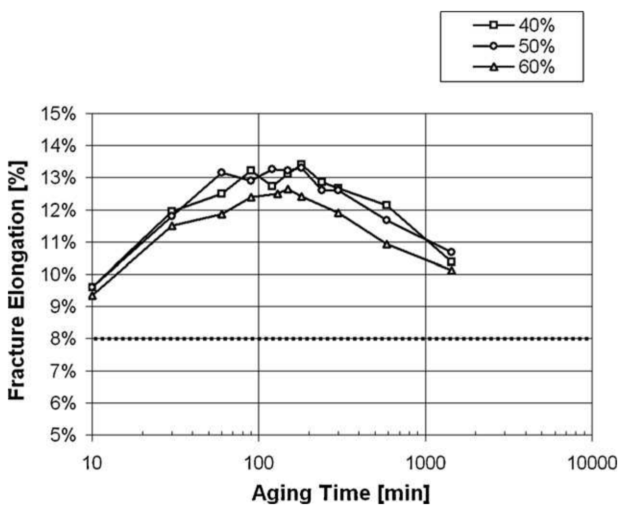

Fig. 8. Variation of elongation to fracture with aging time at 160 °C different level of cold work.

tions instead of fundamental observations. Thus, the explanations presented in Deschamps et al. (1998) cannot be verified for the prestrain 6063 alloy. From a production stand point, time for furnace warm up could be considered as part of the heat treatment if it turns out to be sufficiently long. In fact, its impact on strength should remain marginal especially if soaking duration is less than 60 min. Preheating duration is influenced by thermal load, target temperature, and furnace operation conditions. These parameters change from one batch to the next, and thus, it is impractical to take into account preheating time in mass production.

Fig. 7 shows variations of yield and ultimate tensile strengths as function of aging time at 160 °C for cold work levels of 40, 50, and 60% done by drawing before the heat treatment. Fig. 8 presents fracture elongation obtained for these samples. Table 3 shows that when the prior strain increased before the heat treatment, yield and

Table 3
Yield and ultimate strengths prior to heat treatment.

Prestrain levels (%)	Yield strength (MPa)	Ultimate strength (MPa)	Elongation (%)
40	224.0	228.5	5.7
50	241.0	246.2	5.0
60	244.9	249.8	4.5

Table 4
Time limits for good bending performance.

	HT parameters		
	Temperature (°C)	Time (min)	
		min.	max.
6063-F	160	30	300
	180	10	90
	200	–	10

ultimate strengths increase due to strain hardening phenomenon. Moreover, Fig. 7 shows that for a given aging time, higher prior strain results in an increase of strength. This overall increase of strength is a consequence of strain hardening and precipitation hardening. For yield and ultimate strength, it appears that the difference between initial and peak values are equivalent for the three prestrain levels tested. Actually, at peak, the increase is about 50 MPa for ultimate tensile strength and 35 MPa for yield strength in each case. Thus for a given aging time, when prior strain is increased, the strength improvement seems to be caused by a higher dislocation density in the alloy rather than by a greater precipitation concentration after aging. Comparable conclusions were exposed by Russell and Aaronson (1975) and Poole and Shercliff (1996).

The time to reach the ultimate peak strength changes as a function of prestrain level. The peaks are reached after 240, 180, and 130 min for tubes deformed by 40, 50, and 60%, respectively. However, yield strength is reached after 300 min in all cases. According to Quainoo and Yannacopoulos (2004), for prestrain levels ranging from 0 to 10%, time to reach ultimate peak strength is always the same after aging at 180 °C. Observations made during this investigation contradict this statement. But, as mentioned by Rack (1977), prior strain effect is sensitive to HT temperature. Furthermore, conclusions relative to prior strain levels of 40–60% are not necessarily transposable to alloy aging in the presence of low or very high prestrain.

Elongation peaks shown in Fig. 8 vary between 12.6 and 13.4% depending on the percentage of strain. Considering the analysis presented in the second part of this work, tubes deformed 60% or less by cold drawing and heat treated in optimal conditions should have enough ductility to be bent without problem.

3.2. Bendability

Based on present results, there are many heat treatments for obtaining the 6063-T832 temper. However, in production, some batches were found to have unacceptable bendability even if ASTM requirements were satisfied. In fact, treating tubes at higher temperature is less time consuming, but has a tendency to cause fracture during bending. Hence, another parameter must be identified to select the appropriate heat treatment.

Table 4 summarizes heat treatment time limits for each temperature investigated where bent specimens were acceptable. When aging was done at 160 °C, tubes could be bent after treatment times ranging from 30 to 300 min. However, defects were observable only after 10 min of exposure at 200 °C. These were not acceptable based on quality requirements and are shown in Fig. 9. Tubes treated for extended times at 200 °C show evidence of severe elliptical necking zones leading ultimately to crack initiation and fracture which spreads up to intrados. Sarkar et al. (2004) showed that these grooves were developed in conjunction with shear bands that propagated from the tensile surface into the wall during bending. In the same order of idea, Friedman and Luckey (2002) mentioned that a similar type of surface roughening appears to be occurring at the outer surface when strain increases during bending. For 6000 series alloys, this roughened texture creates valleys between grains on the

Fig. 9. Necking zones on a bent specimen heated at 200 °C for 90 min.

surface, and cracks are initiated in the cups and propagated along grain boundaries.

Fig. 10a and b shows micrographs of the longitudinal cross-section in the necking region a bent tube presented in Fig. 9 before and after etching. Many second phase particles were observed in this specimen and their maximum length was 6 µm. These particles were determined as Al–Fe–Si by EDX analysis. However, grain boundaries did not appear clearly after etching and interaction between grain boundaries and cracks initiation cannot be concluded as in Sarkar et al. (2004). Fig. 10c shows a micrograph of a crack formed near the boundary of a necking zone on a bent specimen. As shown in Fig. 10d, some second phase particles are located in voids formed before crack propagation. It was concluded that crack initiation did not occur from the decohesion of a second phase particle near the outer bent surface, but was the result of shear bands accumulation. In 6111 continuously cast aluminium alloy, Sarkar et al. (2004) showed that this kind of particle promotes crack initiation during bending of thin sheets. Furthermore, according to Broek (1991), small particles (≤1 µm) can act as crack initiators and have an adverse effect on toughness. But in this case, cracks seem to be caused by the stress concentrations and shear band accumulation at boundaries of the necking region.

The correlation between bendability and mechanical properties for 6000 series aluminium alloys in order to evaluate bendability from tensile testing was investigated in the past. For design purposes, tube bending performance is evaluated by total elongation at the extrados. According to Krajewski and Carsley (2003), a tensile test can be used to predict the bending performance of aluminium sheets after a retrogression heat treatment at 350 °C as a function of treatment time. Other indicators such as hardness, ultimate strength, elongation (Krajewski and Carsley, 2003), and reduction of area (Datsko and Yang, 1960) were successfully correlated with bendability. In those works, sheets were bendable if the indicator was over a predetermined threshold.

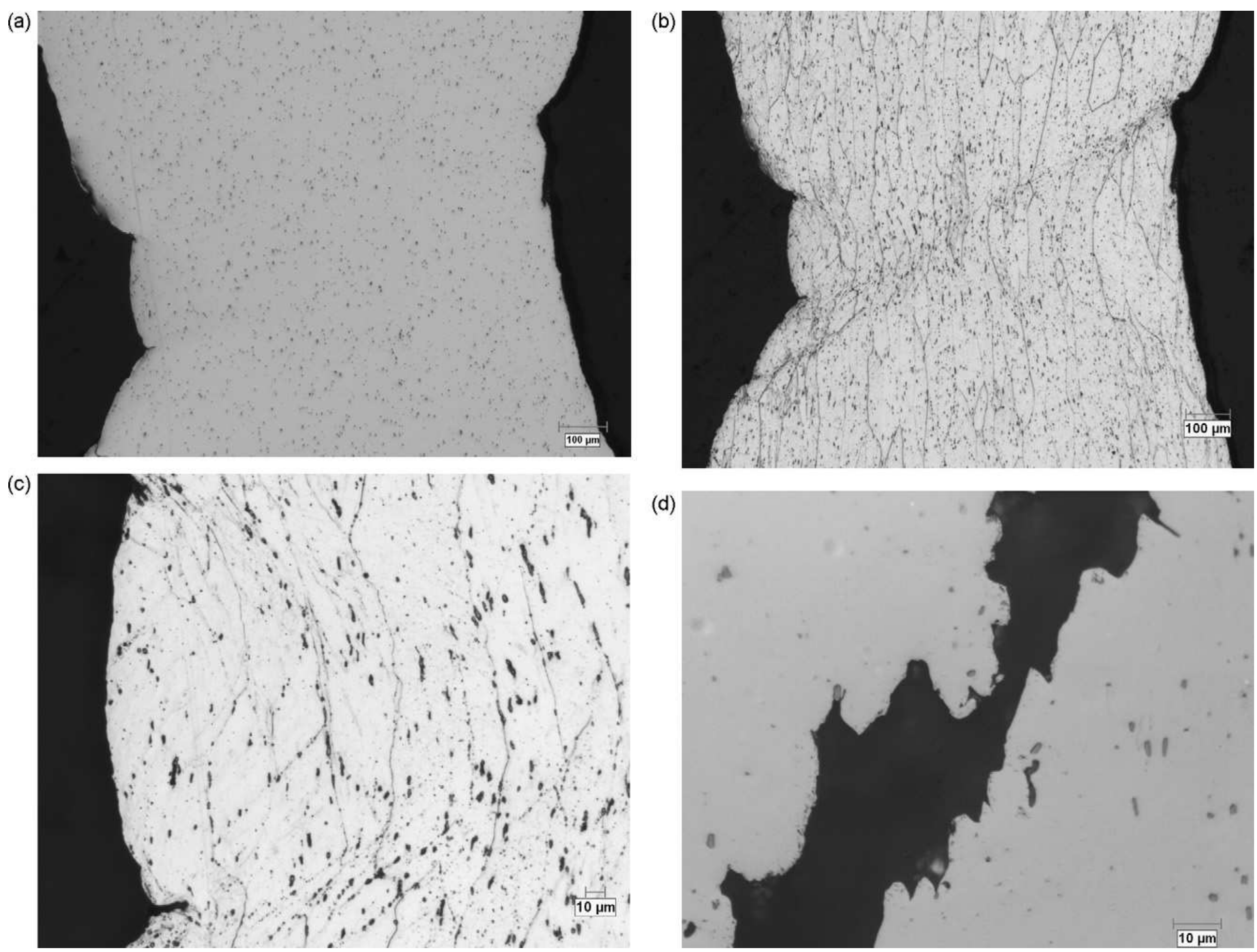

Fig. 10. Optical images of the longitudinal cross-section of a tube wall in the necking region (a) polished; (b) polished and etched; (c) detail of crack initiation for the same specimen; (d) crack propagation through the tube wall with evidence of second phase particles in voids (on other specimen).

Table 5
Results from bendability correlation analysis.

Parameters	Correlation score	Threshold value
Fracture elongation	97%	11%
Uniform elongation	94%	6.5%
Yeild/ultimate strength ratio	81%	1.06
Ultimate tensile strength	55%	250 MPa

To maintain that a HT is appropriate for snowshoe manufacturing based on data from one single tensile test, an indicator that correlates tube bendability and tensile performance must be identified. In the present work, ultimate tensile strength, yield strength/ultimate tensile strength ratio, uniform elongation and fracture elongation were investigated. Bendability was evaluated only qualitatively, i.e. tube in different heat treatment conditions either can be or cannot be bent.

The correlation between bendability and the parameter is true (= 1) if tubes aged with the same HT were bent successfully and the parameter value was higher than the threshold value. The correlation is also true (= 1) if bends had defects and the parameter value was below the threshold value. This verification was done for all HTs tested at 160, 180 and 200 °C. The proportion of validated cases relative to the total number of cases was then calculated. The same procedure was followed with different threshold values until a maximal proportion had been found.

Table 5 shows the optimal threshold value obtained and the proportion of cases for which the correlation was validated. Using a uniform elongation threshold value of 6, 94% of specimens conformed to the correlation. Fracture elongation has the best correlation with 97%. Hence, when tubes come from a lot with an average tensile fracture elongation equal to or higher than 11%, it is very probable that the majority of tubes of the lot will bend correctly in this specific application following a homogenous HT. Moreover, fracture elongation compared to uniform elongation is a simple parameter to measure and easily applicable during material testing procedures.

4. Conclusions

Heat treatment parameters of 6063 cold-drawn aluminium tubes were investigated in this work. It was shown that during aging, yield strength, ultimate tensile strength, and fracture elongation increase, reach a maximum, and decrease due to overaging. As temperature is increased, the peak strength and elongation are reached faster but are lower. Consideration of the furnace preheating period as part of the treatment was shown to have only marginal effects on mechanical properties. As the level of cold-work imposed during cold drawing is increased, the yield and ultimate strength is increased for a given heat treatment time and ductility is decreased slightly. Moreover, the peak ultimate tensile strength is reached earlier for tubes with higher level of prestrain. Bendability is influenced by heat treatment applied to the tubes and treatment time limits were determined for different temperatures in order to get problem-free bending. Moreover, fracture elongation measured in a uniaxial tensile testing was determined to have strong correlation with tube bendability. A fracture elongation over the threshold value of 11% guaranties good bending performance for this application. Thus, heat treatment parameters should be chosen to minimize heat treatment time while conforming to the ASTM 6063-T832 standard and getting a fracture elongation higher than 11%.

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