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A micro deep drawing of ARB processed aluminium foil AA1235

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Abstract

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Keywords

deep, drawing, micro, arb, foil, aa1235, processed, aluminium

Disciplines

Engineering | Science and Technology Studies

Publication Details

Hadi, S., Tieu, A. Kiet., Lu, C. & Zhu, H. (2013). A micro deep drawing of ARB processed aluminium foil AA1235. *International Journal of Materials and Product Technology*, 47 (1-4), 175-187.

A micro deep drawing of ARB processed aluminium foil AA1235

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Keywords: strength; grain; AA1235; foil; rolling; accumulative roll bonded; ARB; micro forming; annealing; aluminium; deep drawing.

Reference to this paper should be made as follows: Hadi, S., Tieu, A.K., Lu, C. and Zhu, H. (2013) 'A micro deep drawing of ARB processed aluminium foil AA1235', *Int. J. Materials and Product Technology*, Vol. 47, Nos. 1/2/3/4, pp.175–187.

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This paper is a revised and expanded version of a paper entitled 'Flow stress of aluminum foil AA1235/H14 in microforming' presented at the 15th International Conference on Advances in Materials and Processing Technology, AMPT2012, Wollongong, Australia, 23–26 September 2013.

1 Introduction

Aluminium (Al) is widely used in the production of micro parts and mechanical components due to its light weight, good formability, corrosion resistance and low cost. The technology of micro forming of aluminium, however, is still limited, compared to the mature technology of macro-forming. The difference between the micro drawing process and conventional drawing process is in the size of the punch diameter and sheet thickness. For a micro deep drawing process the maximum size of the punch diameter is about 9 mm and the sheet thickness between 0.001 and 0.3 mm, whereas for a conventional deep drawing the punch diameter is between 100 and 1,000 mm with the strip thickness between 0.08 and 1 mm (Hirt et al., 2003).

Unfortunately, the current macro-forming theory needs to be modified for micro forming because of a significant variation in mechanical properties when scaled down to micro size products. For this reason, it is necessary to understand the basic mechanical properties of materials, particularly in terms of strength and ductility, prior to their application in micro forming.

Micro forming can be performed on various metals such as Al foil, copper, magnesium, zinc alloy and stainless steel 304 (Gau et al., 2013). The forming flow stress

is influenced by a number of parameters such as heat treatment, specimen thickness and width as they affect the grain size and (thickness/grain size) ratio ϕ .

Goh and Shang (1982) have shown that the thickness, width and loading direction of the tensile test specimens can significantly influence the strength coefficient (K) and strain hardening coefficient (n) in the Hollomon equation $\sigma = K\epsilon^n$ for rolled copper.

The flow stress is reduced with a smaller specimen size (Zhou et al., 2007) and a lower ratio ϕ (Raulea et al., 2001; Diehl et al., 2006; Peng et al., 2007; Yun et al., 2010; Chan et al., 2011). Formability is determined by the limiting drawing ratio (LDR) (Oluwole et al., 2010). An LDR of 1.7 for demagnetised mild steel was achieved with a blank thickness of 25 μm and a punch diameter of 1 mm (Vollertsen et al., 2006). The formability of micro parts worsens as ϕ ratio falls less than 1 (Gau et al., 2007). The formability of Mg alloy was successfully drawn when the punch radius was increased from 4 to 7 mm and the profile radius increased from 0.5 to 2 mm (Watiti and Labeas, 2010).

The accumulated roll bonding (ARB) process is one of the severe plastic deformation processes used to achieve the ultra-fine grains and increase the strength of the material but with a reduced ductility. In this process the thickness of the sheet is reduced by 50%, and then cut into two equal halves. The interface of the two pieces are then brushed and cleaned, stacked, preheated and then rolled with the same reduction. This is repeated for a few cycles and then annealed to improve the ductility (Kwan et al., 2008).

A reduction of 50% the thickness of the sheet is generally applied in the ARB process (Rezaei et al., 2011). However, it has been found that it is difficult to provide an effective bond between thin sheets, and a higher reduction well above 50% is required to achieve a satisfactory bonding.

If the ARB process is carried out at a temperature below the recrystallisation temperature, the rolled material will not be quite ductile and the bond strength will not be sufficiently strong (Saito et al., 1999). Preparatory treatment at the interface of materials of ARB can be done by brushing on both plates to improve the bond strength (Saito et al., 1999). The bonded Al/Al strips by cold rolling were annealed before each ARB test to eliminate the effect of work hardening (Alawode and Adeyemi, 2005; Jamaati and Toroghinejad, 2010; Rezaei et al., 2011). Annealing or aging after an ARB process can improve the ductility which is suitable for further bulk processing.

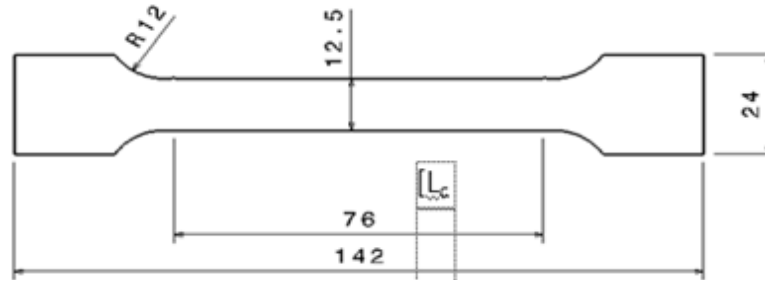
In this paper, the flow stress of Al 1235 foil is determined in terms of thickness and grain size. The materials are then processed by the ARB process for four cycles to produce 72 layers, annealed and then drawn to the cup. The purpose of micro forming through the ARB process is to investigate the relationship between the fine grain size (higher strength) and formability. The effect of heat treatment after the ARB process on formability has also been studied.

2 Experimental details

Two sets of tensile tests were performed in accordance with the Australian Standard (AS1391, 2010) on AA1235/H14 materials with a width of 12.5 mm and five thicknesses of 16, 41, 70, 130, and 300 μm . The effect of specimen width of 1, 3 and 6 mm on the flow stress was also determined for 41 and 70 mm thicknesses. The chemical composition of AA1235 provided by the manufacturer (Ruimin, 2010) is as following: Al = 99.350%, Fe = 0.420%, Si = 0.100%, Ti = 0.020%, Zn = 0.012%, Ni = 0.003%,

Mn = 0.002%, Cu = 0.001% and other = 0.030%. Each as-received specimen was annealed at 450°C for 4 hours before the tensile testing. The tensile test specimen dimensions are shown in Figure 1. The test specimens were tested on the Shimadzu tensile testing machine with a speed of 10 mm/minute.

Figure 1 Size of the tensile test specimens for material of AA1235



Type	Width (<i>b</i>)	Original gauge length (<i>L_o</i>)	Minimum parallel length (<i>L_c</i>)	Minimum transition radius (<i>R</i>)
1	3 ± 0.2	12	18	3
2	6 ± 0.3	24	36	6
3	12.5 ± 1	50	75	12

The interface between the layers were brushed with stainless steel wire, cleaned with acetone, then both brushed surfaces were stacked and welded at the front end before ARB rolling. The samples were heated at 200°C for 10 minutes before undergoing an ARB rolling process, unlubricated on the Hille 100 rolling mill. The ARB samples were originally consisted of nine layers of individual strips, 210 mm length × 120 mm width, and then rolled with a reduction of 65% to achieve a strong bond between the layers that form a thickness of 0.3 mm after the first cycle. After the second, third and fourth cycles, the number of layers were 18, 36 and 72 layers, respectively.

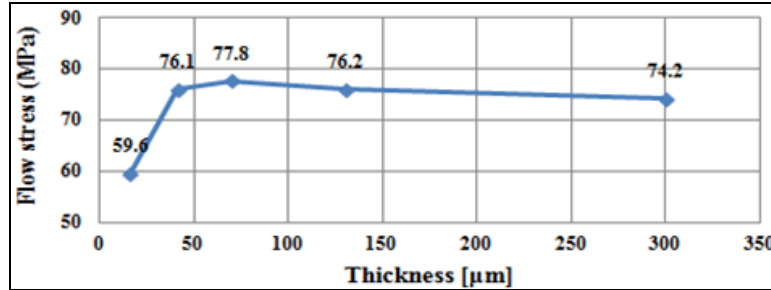
ARB processed samples of 0.3 mm thickness were stress relieved at 200°C for 8 hours and then drawn by a pair of punch (diameter 7.49 mm) and die (diameter 8.21 mm). The grain size (*d*) of the ARB material were determined by the scanning electron backscattered diffraction (EBSD). The material was then subjected to a cup drawing process on an Instron 5566 testing machine.

3 Results and discussions

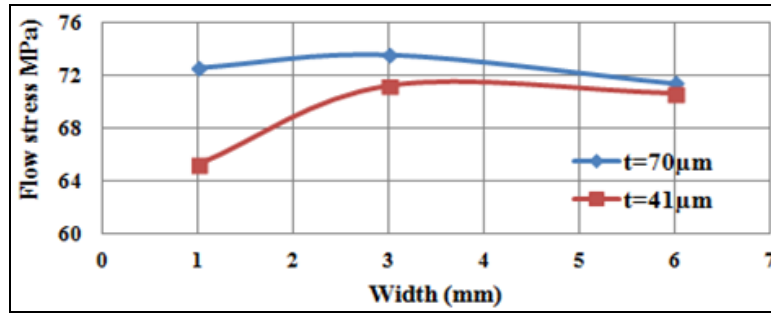
3.1 Flow stress

Tensile tests were carried out on annealed AA1235/H14 samples, width of 12.5 mm and thickness of 16, 41, 70, 130, and 300 μm. In the other tests, two thicknesses 41 and 70 μm with three different widths 1, 3 and 6 mm were also considered. In the annealing process the material is heated above the recrystallisation temperature which allows the grain to obtain a uniform grain. The results of tensile tests are close to each other which indicate that the tensile tests are repeatable. Tensile test results for AA1235 of thicknesses 16, 41 and 70 μm have not been reported previously anywhere.

Figure 2 (a) Flow stress (MPa) versus thickness for width = 12.5 mm and (b) flow stress (MPa) versus width for thicknesses 41 μm and 70 μm of AA1235 annealed at 450°C for 4 hours (see online version for colours)



(a)



(b)

Figure 2(a) shows the flow stress on the specimen width of 12.5 mm and thicknesses of 16, 41, 70, 130 and 300 μm . The flow stress is reduced with a decrease in thickness from 70 to 16 μm . The results are similar to the findings by Peng et al. (2007) who observed a tensile stress reduction when the thickness decreased from 2,000 to 170 μm .

To determine the effect of specimen width, tensile tests were performed on AA1235 with specimen thicknesses 41 and 70 μm . Figure 2(b) shows that the flow stress is reduced by 1.93% as the width widens from 3 to 6 mm and increased by 8.6% when the width increases to 12.5 mm. It is similar to the results obtained by Zhou et al. (2007) with 3003 Al foils of 0.1 mm thickness.

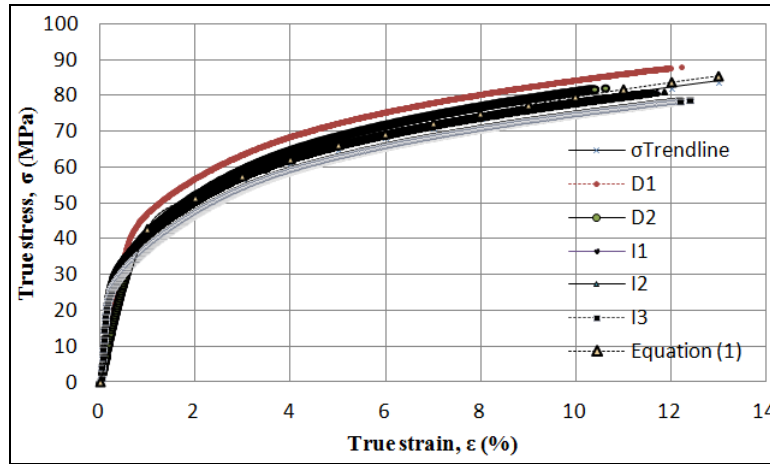
For specimen widths of 1, 3 and 6 mm and thicknesses 41 and 70 μm , Figure 2(b) shows that the average flow stress changed little. With the thickness of 41 μm there was a marked decrease in the flow stress for the width between 1 and 3 mm. The flow stress equations of the as-received AA1235 (constant width 12.5 mm) for a thickness of 16, 41, 70, 130 and 300 μm respectively are $\sigma = 28.19\epsilon^{0.53}$, $\sigma = 42.66\epsilon^{0.26}$, $\sigma = 41.69\epsilon^{0.27}$, $\sigma = 38.02\epsilon^{0.30}$, $\sigma = 39.81\epsilon^{0.27}$. From a series of multiple regressions, a generalised flow stress equation for AA1235 in terms of strain and thickness can be described by equation (1).

$$\sigma = (254.1t^2 - 9.826t + 46.39)\epsilon^{(-1.703t^2 + 0.578t + 0.249)} \quad (1)$$

where σ is the flow stress, t the specimen thickness in μm , width 12.5 mm and ϵ the true strain.

Flow stress curves from the first and second tensile tests for the thickness of 41 μm are shown in Figure 3 for a width of 12.5 mm.

Figure 3 Flow stresses of the first (D1, D2) and the second (I1, I2, I3) tensile test of $t = 41 \mu\text{m}$ (see online version for colours)

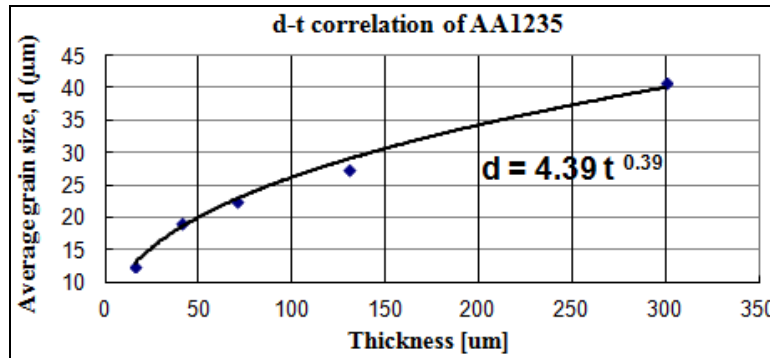


The Hall-Patch equation can be written as shown by equation (2),

$$\sigma = \sigma_{0(\varepsilon)} + k_{hp(\varepsilon)} / \sqrt{d} \quad (2)$$

where the constants at a specific strain (ε) are $\sigma_{0(\varepsilon)}$ and $k_{hp(\varepsilon)}$, and d is average grain size.

Figure 4 Correlation between grain size (d) and thickness (t) of AA1235 (see online version for colours)



Equation (3) relates the grain size (d) and thickness (t) of the AA1235 Al specimens as shown in Figure 4.

$$d = 4.39t^{0.39} \quad (3)$$

Combining equations (3) and (1), the flow stress of AA1235 in terms of grain size (d) and thickness (t) can be determined according to equation (4),

$$\sigma = (13.1d^{5.17} - 22.26d^{2.58} + 46.39)\varepsilon^{(-1.703t^2 + 0.578t + 0.249)} \quad (4)$$

The average grain size (d) of AA1235 for specimen thicknesses of 16, 41, 70, 130 and 300 μm were determined from EBSD results and classified according to the Australian Standard AS1391 (2010). The grain size values of 12.7, 19.2, 22.8, 27.7 and 40.9 μm correspond to the standard grain size number G of 9, 8, 7.5, 7 and 6, respectively.

The correlation between the specimen thickness and grain size number (G) of AA1235 are shown in Table 1. For the thinnest specimen of 16 μm , the ϕ ratio of 1.26 corresponds to the lowest tensile strength of 59.6 MPa. This is 23.7% lower than the highest value of 78.1 MPa ($\phi = 3.07$) for the thickness of 70 μm . It was found by Peng et al. (2007) that for Al99.5% 2S, the yield strength increased with (thickness/grain size) ratio ϕ .

Table 1 Correlation between the thickness and G (AS1733, 1976) of Al foil of AA1235

t (μm)	d (μm)	ϕ	Grain size number (G)	TS (MPa)	YS (MPa)
16	12.7	1.26	9	59.6	42
41	19.2	2.13	8	71.2	32
70	22.8	3.07	7.5	78.1	37
130	27.7	4.70	7	73.6	31.5
300	40.9	7.34	6	74.2	38

A correlation between ϕ and the strength of AA1235 is shown in Figure 5. The tensile strength increases for ϕ between 1.26 and 3.07, but stabilises at higher ϕ values.

Figure 5 Correlation between ϕ and strength of AA1235 (see online version for colours)

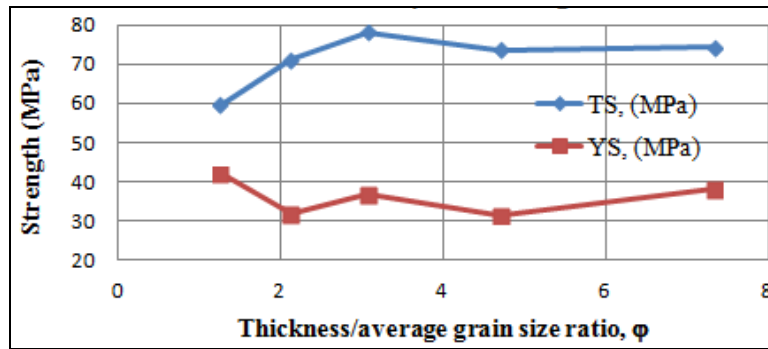
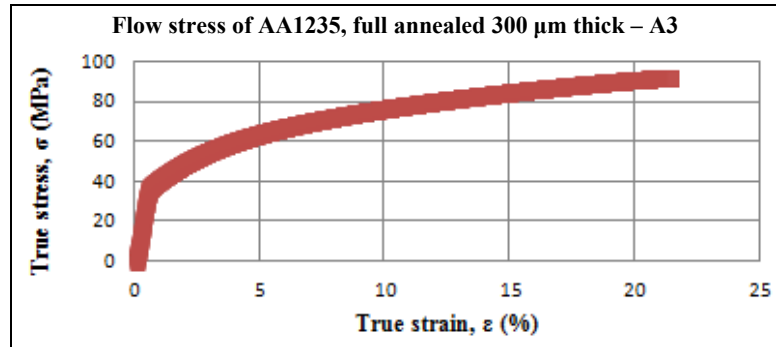
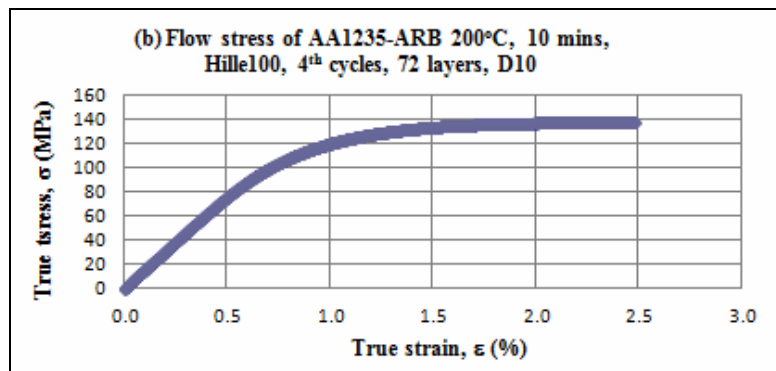


Figure 6(a) shows that for full annealed AA1235 materials the elastic limit stress is 34.77 MPa, the corresponding strain 0.49% and the modulus of elasticity 70.74 MPa. For the ARB processed materials after four cycles, the elastic limit stress of 75.08 MPa with a strain of 0.48% and the modulus of elasticity 153.35 MPa as shown in Figure 6(b). The ARB processed samples and then subsequently stress relieved as in Figure 6(c) show that the elastic limit is 76.75 MPa, the strain 0.64% and the modulus of elasticity 119.92 MPa. A shallower cup was obtained with only ARB processed material compared with the full annealed condition or with the combined ARB process and subsequent stress relief.

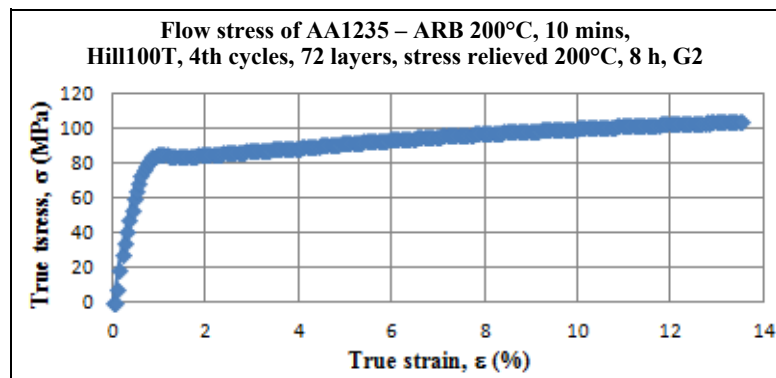
Figure 6 Flow stress (a) full annealed, (b) ARB processed and (c) ARB processed subsequently stress relieved (see online version for colours)



(a)



(b)



(c)

Results of flow stress of AA1235 material from the three heat treatment conditions on the full annealed process, ARB process and the subsequent stress relieved ARB process are shown in Figure 6. The flow stress of AA1235 material from full annealed condition in Figure 6(a) shows that the maximum elongation is 22% with the corresponding stress of 90 MPa. In Figure 6(b), the flow stress of ARB processed material shows the smallest

elongation of 2.5% with the maximum stress of 140 MPa. For the material that has undergone an ARB process and subsequently stress relieved, seen in Figure 6(c), the elongation is approximately 12.8% and the true stress about 104 MPa. From the three curves, the subsequent stress relief after the ARB process has reduced the true stress by 25% from 140 to 104 MPa, but the elongation has been increased from 3% to 12.8%, an increase of 326%. The increase in elongation indicates that the combination of an ARB process and stress relief has a better formability than the ARB process alone. This is the reason why the cup can be drawn deeper without any tear or wrinkles. This result is similar to the findings in Su et al. (2013) who annealed at 200°C AA1050 and AA6061 to improve ductility.

3.2 Micro deep drawing

The aim of micro forming of metal in this study is to gain a deeper cup for one-step process with a minimal damage. The damage in a drawing process can be a tear in the corner of the cup, wavy edge (earing) and wrinkles on the cup wall.

In this paper, the cup drawing is carried out with a punch diameter of 7.49 mm and a die diameter of 8.21 mm. The blank size used is 0.300 mm thick with a diameter of 14 and 15 mm. The blank material from the full annealed AA1235 was drawn to a cup with a LDR value of 1.87. The LDR achieved by conventional deep drawing seldom exceeds 2 (Kadkhodayan and Pourhasan, 2010). To improve the LDR value, the blank material is stress relieved at 200°C for 8 hours prior to the cup drawing process in order to reduce the possibility of tearing caused by residual stresses generated during the ARB process.

The original sheet thickness is 0.3 mm and after the ARB process, the final thickness of the sheet material with 72 layers after the fourth cycle is about 0.30 mm with an individual layer thickness of 4.7 μm thick. The average grain size of AA1235 full annealed material is 40.9 μm as shown in Figure 7(a), while the average grain size of the ARB processed sample in Figure 7(b) is 2.15 μm . The ratio between the thickness of the layer (4.7 μm) and the size of the average grain diameter (2.15 μm) (ϕ) is 2.18.

Figure 7 SEM image for AA1235 (a) full annealed condition and (b) ARB processed and subsequently stress relieved (see online version for colours)

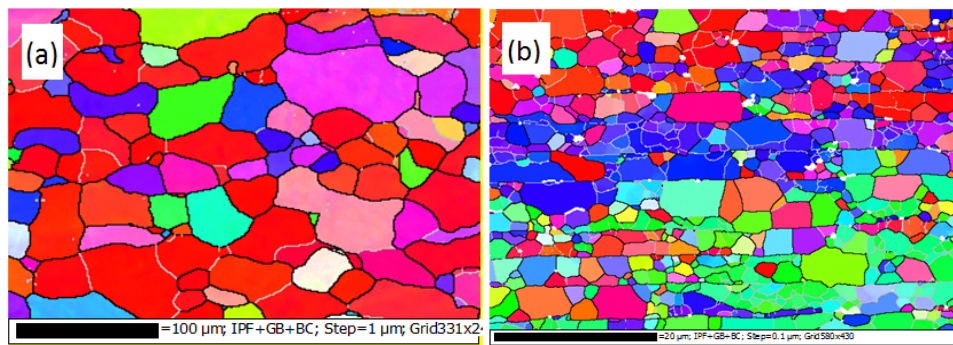
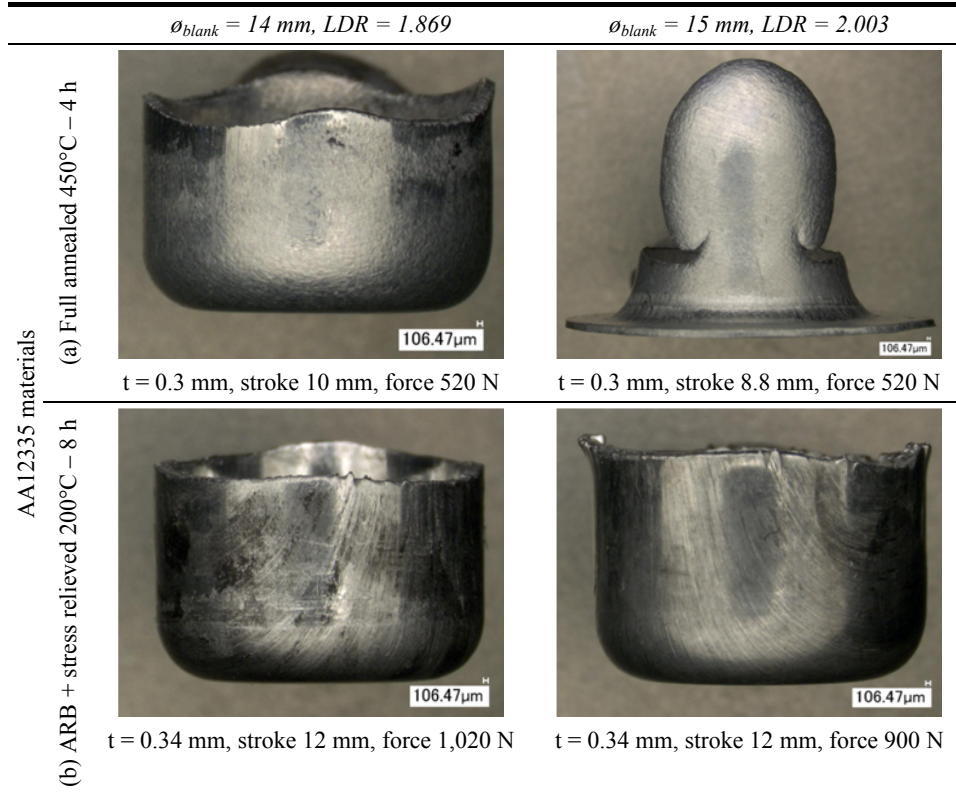


Figure 8(a) shows a premature failure of the cup when formed from the blank diameter 15 mm with the fully annealed AA1235 material. It was successfully formed with the blank diameter of 14 mm although with large earings. The materials after processed by ARB and then stress relieved at 200°C for 8 hours were successfully drawn for both

14 mm and 15 mm blank diameter with much reduced earings as shown in Figure 8(b). The LDR of 2.003 is higher when compared with the LDR of 1.869 for annealed material only. This has never been achieved for AA1235 material.

Figure 8 Cup drawing results from full annealed and ARB processed subsequent stress relieved for (a) $\phi_{\text{blank}} = 14$ mm and (b) $\phi_{\text{blank}} = 15$ mm



The earing of the cup is caused by the planar anisotropy (ΔR) of the sheet which is related to the average plastic strain ratio (R_{avg}) according to equation (5). R is the ratio of the strain respectively in the direction of the width and thickness of the specimen ($R = \epsilon_w / \epsilon_t$). The three R values apply along the direction at angle 0, 45, and 90° to the direction of rolling. ΔR is calculated from equation (6) (Kalpakjian and Schmid, 2009; Tajally and Emadoddin, 2011).

$$R_{\text{avg}} = (R_0 + R_{90} + 2R_{45})/4 \quad (5)$$

$$\Delta R = (R_0 + R_{90} - 2R_{45})/2 \quad (6)$$

Earing is caused by material anisotropy. The average material anisotropy is expressed in terms of the normal anisotropy (R_{avg}) and planar anisotropy (ΔR). If ΔR is equal to zero, there is no earing. A high value of R_{avg} varies with LDR, so the higher the value of R_{avg} the higher the drawability. The R_{avg} values for a variety of treatments, including full-annealed, ARB cycles, and combined ARB cycles and subsequently stress relieved are 0.639, 0.595, and 0.651 respectively as shown in Table 2.

Table 2 Anisotropy parameters of AA1235

Process	R_{avg}	ΔR	Grain size (μm)
Full annealed 450°C – 4 h	0.639	0.556	40.9
ARB 4th cycles	0.594	0.278	1.75
ARB + stress relieved 200°C – 8 h	0.651	–0.022	2.15

After the four cycles of the ARB process, the respective values of ΔR and R_{avg} are 0.278 and 0.594 compared with 0.556 and 0.639 of the full annealed material. The anisotropic behaviour of AA7075 sheet annealed at 270 to 450°C produces ΔR values between 0.240 to 0.285 and 0.64 to 0.90 for R_{avg} (Tajally and Emadoddin, 2011). Both aluminium sheets with different series and different annealing temperature have comparable values for ΔR and R_{avg} .

The R_{avg} value of the ARB process and subsequent stress relieved AA1235 material is 0.651, which is associated with the highest LDR and the successful drawing of a cup without tearing. With the planar anisotropy ΔR of –0.022, the earing is much reduced when compared with the full-annealed material condition.

The R_{avg} value of full annealed AA1235 material is 0.639 compared to 0.651 of the combined ARB process and a subsequent stress relief. The latter has a higher drawability which is associated with a higher R_{avg} value.

Results showed that the cup formation of full annealed blanks can be formed into a cup with an LDR of 1.87. With a blank diameter of 14 mm and punch diameter 7.49 mm, the cup of ARB processed material had torn at the corner radius between the bottom and wall of the cup at 2.8 mm stroke instead of 6 mm full stroke. When a stress relieving process was applied after the four ARB cycle, a larger LDR value of 2.003 was obtained. The larger LDR value indicates the higher ability to form a material.

4 Conclusions

The tensile strength of full annealed AA1235 increases with the specimen thickness from 16 to 70 μm and decreases with a specimen thickness from 70 to 300 μm . Equations of flow stress of AA1235 related to grain size and thickness have been obtained. The effect of width is not significant. For the first time, the ARB processed AA1235 materials with 72 layers have been successfully drawn in micro deep drawing process. The combined process of ARB process and a subsequent stress relief not only improves the formability through a higher normal anisotropy, but the process can also reduce the planar anisotropy of the sample which can reduce the earings.

Acknowledgements

The authors would like to thank the Director of Human Resources, Directorate General for Higher Education (DIKTI), Ministry of Education and Culture of Indonesian Government for funding the PhD scholarship for S. Hadi.

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