INVESTIGATION ON EARING BEHAVIOR OF AA 2024-T4 AND AA 5754-O ALUMINUM ALLOYS

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ABSTRACT

Aluminum and aluminum alloys are widely used in engineering design mainly because of advantages of their light weight, high strength-to-weight ratio, corrosion resistance and relatively low cost. Deep drawn parts usually have different wall heights because of earing behaviour. This behaviour is due to the planar anisotropy (Δr) of sheet metals. A measure of the variation of normal anisotropy with the angel to the rolling direction in sheet plane is known as planar anisotropy. If the magnitude of the planar anisotropy is relatively large as absolute value, the earing behaviour becomes more effective so larger ears occur. Furthermore, the orientation of the sheet with respect to the die or the part to be formed will be important. In addition, cutting of scraps in the parts which have ears leads to material waste.

The scope of this study is to determine the planar anisotropy of AA 5754-O and AA 2024-T4 aluminum alloys and to investigate the earing behaviour by the way of deep drawing of cylindrical cups.

KEYWORDS: (Earing behavior, Planar anisotropy, Aluminum Alloys, Deep drawing)

1. INTRODUCTION

Nowadays, the need to materials which meets demands of light and high mechanical properties increase more and more that. Aluminum is the most widely consumed non-ferrous metal in the world. Aluminum and aluminum alloys are widely used in engineering design mainly because of advantages of their light weight, high strength-to-weight ratio, corrosion resistance and relatively low cost [1,2]. Aluminum sheet forming is making rapid advances in technology [3]. It has become increasingly important in automobile, food, aerospace, electricity, building and machine tools industry [1]. As demand for new products, use of aluminum and aluminum alloys will greatly expanded around the world due to its many advantages.

For structural applications, the alloy must have some properties such as ductility, strength, corrosion resistance, toughness, etc. Pure aluminum has a low tensile strength of approximately 90 MPa and cannot be easily used in applications where rupture is essential and resistance to deformation. For this reason, small amounts of alloying elements such as manganese, copper, silicon, magnesium and zinc are added to aluminum primarily to enhance strength. In addition, aluminum can be strengthened by heat treatment or strain hardening or cold working. Further strength is obtained by heat treatment. Thus its strength could reach up to approximately 700 MPa [1,2]. Wrought alloys are categorized as non-heat-treatable and heat-treatable alloys. While non-heat-treatable alloys are strengthened by strain hardening or cold working, heat-treatable alloys are strengthened by solution heat-treatment and aging [1].

The most efficient way of reducing frame weight of plane and automobile and improving performance is reducing material density [4]. The aim of reduce vehicle weight and improve corrosion resistance of materials, new materials have been developed. Especially in automobile industry, for the use of aluminum alloys sheets instead of stainless steel, great effort is spending. The main concerns in the automotive industry are primary safety and environmental issues and weight reductions. Decrease of the body weight of automobile provides significant fuel saving. Therefore, aluminum alloy sheets are used for various body panels such as the engine hood to achieve lighter vehicles [5]. Aluminum is one of the most widely used metals in aircraft construction [6]. It is very important material for the aviation industry because of high strength-to-weight ratio and its comparative ease of production. Although use of aluminum in aircraft decreases owing to use of composite materials, high strength aluminum alloys are, and will remain, important airframe materials [4].

The 5XXX series alloys are widely used in automotive industry due to advantages of high strength, good corrosion resistance and relatively excellent formability. These alloys are strengthened by strain hardening. The most important alloy of these series is AA 5754 alloy in which magnesium is the principal alloying element [1,6]. The AA 5754 alloy sheet is usually employed in an annealed (O) [6]. The 2XXX series alloys are traditionally used aerospace industry and has high fracture toughness and high resistance to fatigue crack propagation. In addition the 2XXX alloys has used in damage tolerance applications, such as the lower wing skins and fuselage structure of commercial aircraft [1]. 2XXX series alloys are particularly well suited for parts and structures requiring high strength-to-weight ratios and are commonly used to make truck and aircraft wheels, truck suspension parts, aircraft fuselage and wing skins, and structural parts [6]. These alloys are hardened by heat treatment and so high strength can be obtained. AA 2024 has been the most widely used alloy in the 2XXX series [4]. AA 2024 alloy is the primary alloys used in airframe structural applications.

Conventional sheet forming is widely used, particularly, in automotive and aircraft industry. The forming operations such as deep drawing, bending and stretching are employed especially in forming of outer body panels. The advances in automotive and aircraft industries in the last decade have led to an increasing need of sheet metal forming technology. Because safety issues, fulfilling customer satisfactions and increasing market competition increase, the need of stronger and more economic products increases more and more [7]. Sheet metal forming is the process of converting a flat sheet metal into a part of desired shape without fracture, wrinkling and excessive localized thinning. The process may be simple operation such as bending or a sequence of very complex operations such as stamping. In most of the sheet metal forming processes, after sheet metal is clamped between the die and blank-holder, it is formed into a shape over the punch. The movement of the sheet metal down the die cavity is controlled by the force of the blank holder. Stretching and deep drawing processes are generally preferred and used in sheet forming operations.

Deep drawing is the process of shaping a flat sheet metal into a cup. Deep drawing operation causes a sheet metal to elongate along a direction and to narrow along perpendicular to that direction. The simplest example of this is drawing of a plane cylindrical cup. In this process, a circular plate is kept between two dies and pressed at the center with a flat bottomed die. In this way, the sheet becomes drawn inside. The tensile forces formed by the punch stretch the sheet radially and as the sheet metal diameter decreases, the sheet is pressed circumferentially [8]. Because deep drawing is a complex process, during the process, various forming defects, such as earing, fracture, wrinkling, flanging and undesired surface texture result from material feature or die geometry, may be occur. If one or a combination of these defects affects a sheet metal, then it makes that sheet metal useless. These forming defects may be result from mechanical and metallurgical properties of the sheet materials as well as dies, friction or geometric parameters [9].

Mechanical properties of sheet metals are the most important factors that affect sheet metal formability. Chemical composition of the material, production methods and various treatments applied to the material during production are among the main factors that create differences in mechanical properties of sheet metals. Basic mechanical properties of a material are determined by tensile tests. Higher value of strain is the most marked indication of the increase in the formability of the material. Ductility is generally inversely proportional to strength and hardness. Beside strength and strain, strain-hardening exponent (n), normal anisotropy (r) and strain rate sensitivity exponent (m) are other factors that affect mechanical characteristics of sheet formability [10]. Normal anisotropy is an indication of resistance against to thinning of material. It is defined as the ratio of strain in the thickness to the strain in the width of a material. Materials with high values of normal anisotropy can be drawn better than those with low values. In deep drawing process, the material at a flange is stretched radially into a certain direction and pressed circumferentially perpendicular to this direction [11]. While normal anisotropy has great effect in deep drawing, it has relatively low effect in stretching [9,11,12]. The most important mechanical property that affects performance of deep drawing is the coefficient of normal anisotropy r and so materials with higher r have better formability. This coefficient depends on the crystallographic structure and crystallographic direction of a material [13].

Materials whose properties do not change with direction are known as isotropic materials. However, most sheet metals used in industry may exhibit different properties on RD; rolling direction, TD; traverse direction and DD; diagonal direction (45 degrees to rolling direction) due to crystallography and rolling. These differences are known as planar anisotropy Δr . Planar anisotropy is an indication of change of normal anisotropy with respect to the directions. Due to this feature which depends on the directions, a feature known as earing is usually seen on upper edges of the cups formed in deep drawing. In other words, the upper edges of the cup takes a wavy shape instead of smooth edges [9,14]. Earing occurs due to the fact that the drawing ratios are different at different directions in deep drawing. In other words, earing is an anisotropic structure resulting from formation of texture in a material structure. Direction and amount of the texture formed in a material affects the degree of anisotropy and hence the amount of earing. It is extreme importance that location of a sheet metal with respect to a die in forming of materials exhibit earing behavior. Moreover; cutting or smoothing the ears of the parts leads to material loss and increases the number of processes. Therefore, it is necessary that the earing formation is kept under control. For optimum drawability, it is required that normal anisotropy (r) of a material is high and planar anisotropy Δr of a material is low [8]. When the r value is high, deeper cups can be drawn and when the Δr value is low, earing is not developed or reduced. Deep drawability of aluminum alloys is good for $0,6<r_m<0,85$ and bad for $r_m < 0,6$ [15,16].

Besides the properties of sheet metals can show changes according to the directions on the sheet plane, there can also be differences between average properties on the sheet plane and the average properties along the thickness direction. When the material with same properties on all directions (sheet plane and thickness direction) is subjected tensile test, it is expected that width and thickness strains are equal. Namely, if the rate of strain along the thickness to strain along the width of material is equal, it is called as isotropic material. If the material's unit strain along the width is different from the unit strain along the thickness, then it means that there is a normal anisotropy in the material [11].

Accordingly, the planar anisotropy in sheet materials must be investigated in detail to develop aluminum alloy sheets with excellent deep drawability [5]. In this study, anisotropy values of AA 5754-O and AA 2024-T4 aluminum alloy sheets were determined and their earing behaviors were investigated by deep drawing cylindrical parts of the alloys.

2. DEFINITION OF ANISOTROPY

2.1 Plastic Anisotropy

The plastic anisotropy, *r* value, or plastic strain ratio is considered is a direct measure of drawability of sheet metal and is useful for evaluating deep drawing process [12]. It is defined as the ratio of the true width strain to the true thickness strain in uniform elongation region (beyond material elastic limit) of tensile test and is expressed by

$$r = \frac{\varepsilon_w}{\varepsilon_t} \tag{1}$$

where ε_w is true width strain and ε_t is true thickness strain. The longitudinal strain is defined as ε_l. The true strains values are formulized as the following equations.

$$\varepsilon_w = \ln\left(\frac{w}{w_0}\right) \tag{2}$$

$$\varepsilon_t = \ln\left(\frac{t}{t_0}\right) \tag{3}$$

$$\varepsilon_l = \ln\left(\frac{l}{l_0}\right) \tag{4}$$

where w_o, t_o and l_o are initial width, thickness and length respectively. *w*, *t* and *l* are final width, thickness and length respectively. The thickness strain can be measured directly but the thickness strain of a thin sheet cannot be measured accurately. So it is difficult task and its error rate is higher [11,17]. *r* value is much more sensitive to errors in width measurement and thickness than errors in length measurement [18].

Therefore it may be calculated also from the length and width measurements using the following constant volume assumption.

$$\varepsilon_w + \varepsilon_t + \varepsilon_l = 0 \tag{5}$$

It can be expressed by the following equation for ε_t.

$$r = -\frac{\varepsilon_w}{\varepsilon_l + \varepsilon_w} \tag{6}$$

r value can be continuously determined by measuring changes in with and length [11]. Measurements usually are performed at 10, 15 and 20 % engineering strain [18,19]. Determining the plastic strain ratio is governed by ASTM E517 Standard Test Method for Plastic Strain Ratio r for Sheet Metal [19].

For optimum drawability, it is wished that r value of material is high, [11]. If the r value differs from unity, this shows a difference between average in-plane and through thickness properties which is usually characterized by the anisotropy [12]. The r value frequently changes with direction in the sheet. It is more useful that normal anisotropy r_m value is determined. The normal anisotropy;

$$r_m = \frac{(r_0 + 2r_{45} + r_{90})}{4} \tag{7}$$

as defined. Where the subscripts are the angle between the tensile specimen axis and the rolling direction [11,17]. As r_m value increase, drawability of sheet metal increase [10-12]. Cold rolled aluminum alloys have r_m values ranging from 0.6 to 0.8 [10,11].

2.2 Planar Anisotropy

This phenomenon is known as earing. There may be two, four, or six ears, but four ears are most common. Earing results from planar anisotropy, and ear height and angular position correlate well with the angular variation of r. For two or four ears, earing is described by the parameter. In deep drawing, the upper edges of the cup formed may be having usually a wavy shape known as earing due to anisotropy [9,14,17]. In other words the height of the walls of drawn cups usually has peaks and valleys [19] as shown in Fig. 1. It is therefore common to measure the planar anisotropy.

These appeared ears in deep drawing process may be number of two, four, or six ears. But four ears are most common [10,17]. The r_m value determines the average wall height of the deepest draw possible. The Δr value determines the extent of earing. For optimal drawability, it is necessary to a combination of a high r_m value and a low Δr value [11].

Planar anisotropy causes earing [9,14,17] and height and angular position of the ears completely relates to angular changing of r value. The earing is defined with Δr value and is a measure of changing normal anisotropy value with direction [11]. The Δr value is formulated by;

$$\Delta r = \frac{(r_0 - 2r_{45} + r_{90})}{2} \tag{8}$$

When $\Delta r = 0$, the earing does not emerge. While Δr is bigger than zero, the earing occurs at 0° and 90° and if Δr is smaller than zero, it occurs at 45°. This variation is shown in Fig. 2.

Fig. 1 Two deep drawn cup which shows earing behavior [20]

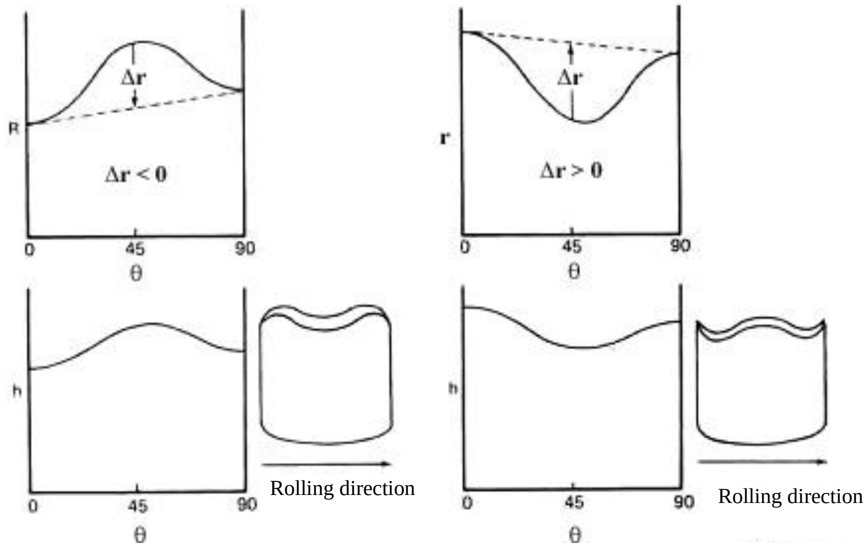


Fig. 2 The relation between angular changing of normal anisotropy and the earing behavior [19]

After a cylindrical cup is deep drawn, the earing tendency Z is calculated by

$$Z = \frac{(h_{max} - h_{min})}{0.5\,(h_{max} + h_{min})} 100$$

formula. h_{max} ; average of heights of earings, h_{min} ; average of heights of valleys.

3. MATERIAL AND METHOD

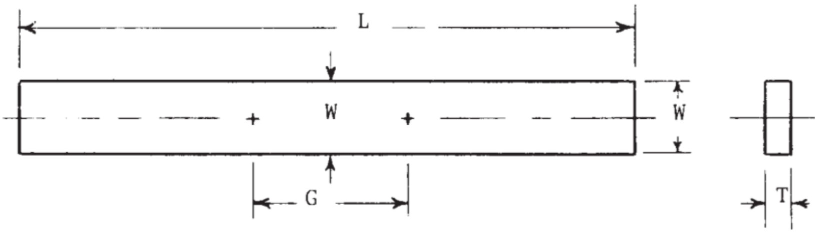
3.1 Determination of Plastic Anisotropy

The chemical composition of the AA 5754 and AA 2024 aluminum alloy sheets used in experiments has given in Table 1. AA 5754 and AA 2024 materials having 1 mm thickness were prepared at the directions of RD, DD and TD with using water jet according to ASTM E 517 (Fig. 3). AA 5754 was annealed at 380°C during 4 hours and it becomes O-temper. Then AA 2024 was solution heat treated at 493°C during 30 minutes, after quenching it has natural aged at room temperature during one week. So it becomes T4 temper. In order to measure the deformations of formed specimens, one surface of specimens were gridded with 2.5 mm square grid using serigraphy or silk-screening method.

Table 1: Chemical composition of AA 5754 and AA 2024 aluminum alloy sheets

Material	Cu	Mn	Fe	Si	Zn	Mg	Cr	Ti
AA 5754	0.10	0.5	0.4	0.4	0.20	3.35	0.3	0.15
AA 2024	4.61	0.55	0.22	0.09	0.14	1.35	0.01	0.02

While the specimens were elongated until 10 % strain value at the speed of 10 mm/min using tensile test equipment, the photographs of the specimens were taken at various strains and 10 % strain (Fig. 4). Then longitudinal and width strains (ε_l and ε_w) were measured on the photographs by the ASAME automated strain analysis system. In order to validate ASAME measurements, ε_l and ε_w values were also measured for AA 5754-O with optical comparator



L : Length 200 mm
W : Width 20 ± 0.13 mm
G : Gage length 50 ± 0.25 mm
T : Material thickness

Fig. 3 The specimen used for measuring anisotropy [19]

whose precision is 0.001 mm. Before and after the specimens were elongated, the dimensions of grid on the each specimen were measured and ε_l and ε_w were calculated. The thickness strain ε_t was calculated from the constant volume assumption and the plastic anisotropy values at each direction were obtained from Equation 1. In addition, mechanical properties of the materials were determined with tensile test. All of the tests were performed three times.

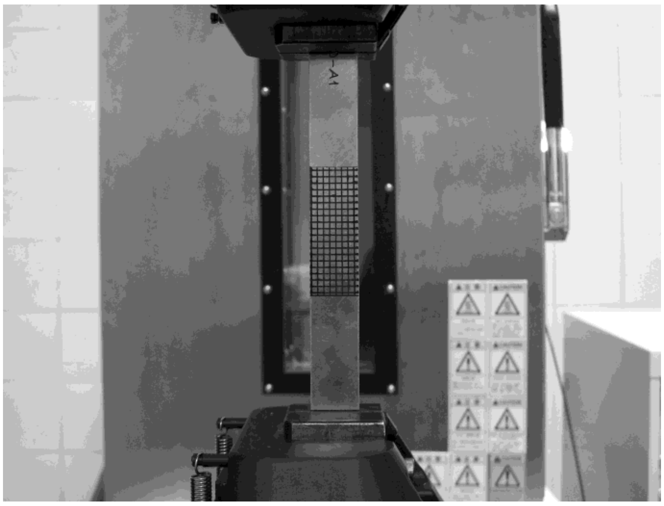
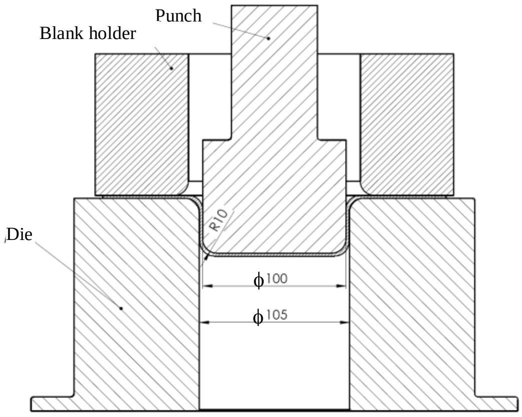


Fig. 4 An example of the photograph of the anisotropy specimen during the test

3.1 Determination of Effect of Earing Behavior

The effect of anisotropy value of AA 5754-O and AA 2024-T4 aluminum alloy sheets to their earing behavior was investigated by deep drawing of a cylindrical cup. The initial diameters deep drawing specimens were 200 mm for AA 5754-O and 170 mm for AA 2024-T4. Then they were deep drawn by using MTS Press having a 100 mm diameter punch. The experimental set up used in the deep drawing test is shown in Fig. 5. The test speed was 25 mm/min and blank holder force was applied as 30 kN.

After forming, the heights, numbers and positions of ears were determined. The specimens were fixed by a divisor and the earing heights of cups were measured. The comparator was adjusted to zero at rolling direction and all peaks and valleys of cup were measured. The earing tendency Z was calculated from heights of maximum and minimum cup walls. All of the tests were performed three times.



a) b)

Fig. 5 a) The experimental set up used in the deep drawing test, b) Schematic diagram of tool set up

4. RESULT AND DISCUSSION

4.1 Mechanical Properties and Anisotropy Coefficients of Materials

Mechanical properties and anisotropy coefficients of the materials were given in Table 2 and in Table 3 respectively. In Table 2, *n* is strain hardening exponent and *K* is strain hardening coefficient. According to the results, shown in Table 3, measuring with ASAME is fairly reliable.

The planar anisotropy of AA 5754-O sheet is very small. It can be expected that all of the mechanical properties are close to the each other. But the total elongations at different directions are different. When the planar anisotropy of AA 2024-T4 is examined, it can be seen that the value is notably high compared to AA 5754-O. Mechanical properties of AA 2024-T4 are nearly same at RD and TD but they are different at DD. Therefore AA 5754-O can be assumed nearly isotropic but AA 2024-T4 cannot be.

Table 2: Mechanical properties of AA 5754-O and AA 2024-T4 materials

	Angle with rolling direction	σ_Y (MPa)	σ_U (MPa)	$e_{Tot.}$ (%)	n	K (MPa)
AA 5754-O	RD	90	212	22,06	0,33	470
	DD	92	209	27,04	0,33	448
	TD	92	208	25,34	0,34	456
AA 2024-T4	RD	272	424	17.54	0.21	726
	DD	263	417	17.82	0.21	699
	TD	272	426	16.63	0.207	725

Table 3: Anisotropy values of AA 5754-O and AA 2024-T4 materials

Method	Material	r_0	r_{45}	r_{90}	r_m	Δr
ASAME	AA 2024-T4	0.67	1.21	0.85	0.98	-0.47
	AA 5754-O	0.72	0.67	0.85	0.72	0.11
Optical comparator	AA 2024-T4	0.54	1.1	0.74	0.87	-0.46
	AA 5754-O	0.76	0.67	0.75	0.71	0.087

4.2 Earing behaviors of Materials

Because the center of the blank was not aligned properly with the centers of the die and the punch during processing, some of the specimens were inclined as shown in Fig 6. When the wall heights were measured, a graph was obtained as shown in Fig. 7 that actual earing behavior is not observed. In order to obtain the actual earing heights, the inclination heights must be subtracted from heights of peaks and valleys. So the slope of the inclination line was set to zero. Thus, the obtained actual earing behavior is shown in Fig. 8 for two materials.

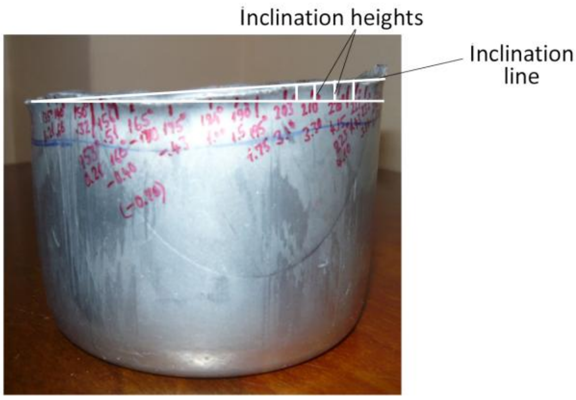


Fig. 6 A sample of the inclined specimen

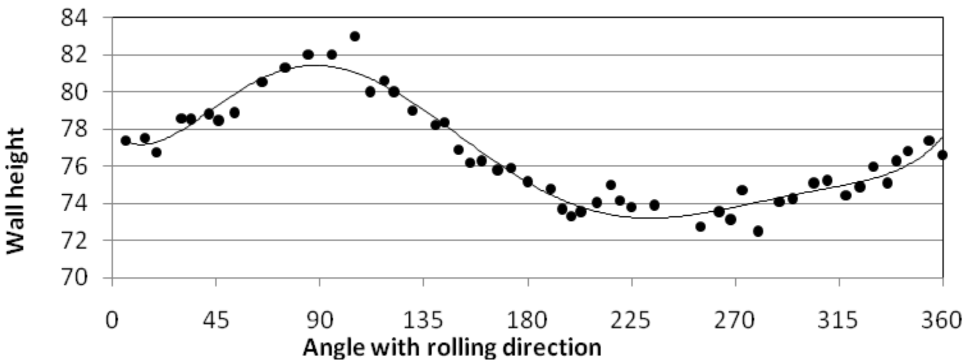
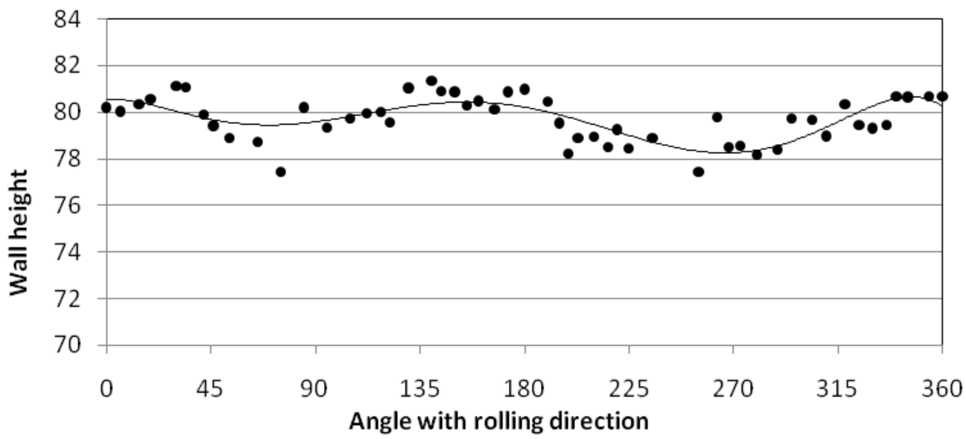
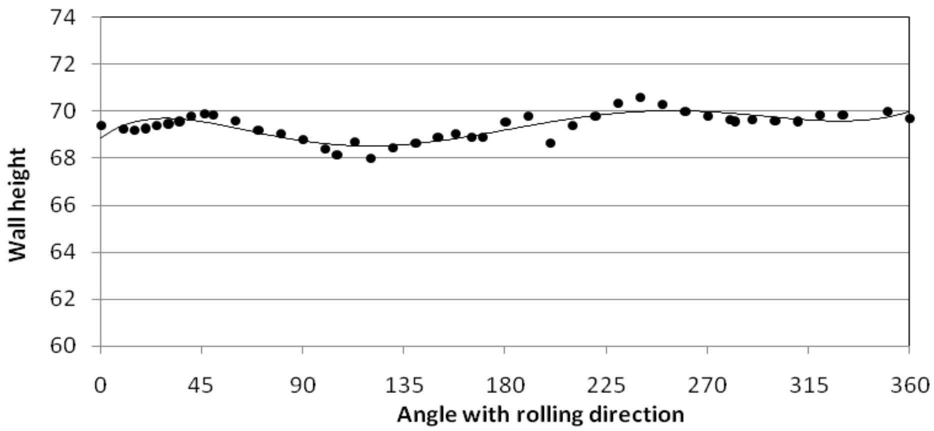


Fig. 7 If there is an inclination, actual earing behavior is not directly observed

Two ears were observed for the materials. Because the Δr of AA 5754-O is bigger than zero and Δr of AA 2024-T4 is smaller than zero, the ears occur at 0° and 180°, at 45° and 225° respectively. The earing tendencies Z were calculated by using Equation 9 as 1.45 % and 2 % respectively. Because the planar anisotropy of AA 5754-O is very small compared to AA 2024-T4, the earing behavior of AA 5754-O is smaller than AA 2024-T4.



a)



b)

Fig. 8 The real earing profiles of a) AA 5754-O, b) AA 2024-T4 cups

5. CONCLUSIONS

- According to the obtained anisotropy results from optical comparator and ASAME, measuring with ASAME is fairly reliable.
- The planar anisotropy of AA 2024-T4 is notably high compared to AA 5754-O. Therefore AA 5754-O can be assumed nearly isotropic but AA 2024-T4 cannot be.
- Two ears were observed at 0° and 180° for AA 5754-O and at 45° and 225° for AA 2024-T4. The earing behavior of AA 5754-O is small compared to AA 2024-T4.
- The earing tendencies were 1.45 % and 2 %. These values aren't so much important in manufacturing processes.
- Although the planar anisotropies of the materials is fairly different from each other, there is not reasonable difference between earing tendencies.

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6. REFERENCES

[1] George E. Totten and D. Scott MacKenzie, Handbook of Aluminum, Physical Metallurgy and Processes, *Marcel Dekker Inc.*, New York (2003).

[2] US Army Materials and Mechanics Research Center, Military Standardization Handbook, Aluminum and Aluminum Alloys (1966).

[3] J. M. Story et al., Issues and Trends in Automotive Aluminum Sheet Forming, *International* Congress *and Exposition*, Detroit, Michigan, March 1-5 (1993).

[4] F.C. Campbell, Manufacturing Technology for Aerospace Structural Materials, UK (2006).

[5] B. Cantor et al., Automotive Engineering Lightweight, Functional, and Novel Materials, Taylor *& Francis Group*, USA (2008).

[6] ASM Handbook, Properties and Selection: Nonferrous Alloys and Special-Purpose Materials, Vol. 2, USA (1990).

[7] Engl, B. and Schneider, Ch., ULSAB-The Ultra Light Steel Auto Body, *Proc. of the* SheMet298, Enschede/Holland, April 6-8, (1998), 3-11.

[8] B. Taylor, Formability Testing of Sheet Metals, *ASM Handbook, Forming and forging*, Vol. 14 (1993), 1930-1985.

[9] Banabic D., et al., Formability of Metallic Materials, *Springer-Verlag*, Germany (2000).

[10] George E. Dieter, Mechanical Metallurgy, *McGraw-Hill Book Company*, UK (1988).

[11] B. Taylor, Metal Handbook, *American Society of Metals* (1988).

[12] Marciniak Z., Hu S.J., Duncan J.L., Mechanics of Sheet Metal Forming. *Butterworth-Heinemann*, London (2002).

[13] Raghavan K.S., A Simple Technique to Generate In-Plane Forming Limit Curves and Selected Applications, *Metallurgical and Materials Transactions 26A*, (1995), 2075-2084.

[14] Khaleel, M.A., Johnson, K.I., Smith, M.T., On the Thinning Profiles in Super Plastic Forming of a Modified 5083 Aluminum Alloy, *Materials Science Forum*, Vol. 243-245 (1997), 739-744.

[15] Cimenoglu, H., Kayali, E.S., Factors of Formability of Aluminum Alloys, *11Th International Aluminum Symposium* (1984), Seydisehir.

[16] Delikücük Y., Effects of Annealing Parameters of Al-Mn Alloys on Deep Drawability, Selcuk University, *Applied Science Institute* (1989), Konya.

[17] Hosford W. F., Duncan J. L. Sheet Metal Forming: A Review, *JOM* (1999).

[18] Richard Gedney, Sheet Metal Formability, *Advanced Materials & Processes*, 2002, 33-36.

[19] ASTM E 517, Standard Test Method for Plastic Strain Ratio *r* for Sheet Metal, United States.

[20] www.aluminium.matter.org.uk