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EFFECT OF SHEET THICKNESS ON THE ANISOTROPY AND THICKNESS DISTRIBUTION FOR AA2024-T4

VPLIV DEBELINE PLOČEVINE NA ANIZOTROPIJO IN RAZPOREDITEV DEBELINE PRI AA2024-T4

Murat Dilmec[1], Huseyin Selcuk Halkaci[2], Fahrettin Ozturk[3,4], Mevlut Turkoz[2]

[1]Department of Mechanical Engineering, Necmettin Erbakan University, Konya, Turkey
[2]Department of Mechanical Engineering, Selcuk University, Konya, Turkey
[3]Department of Mechanical Engineering, Nigde University, Nigde, Turkey
[4]Department of Mechanical Engineering, The Petroleum Institute, Abu Dhabi, United Arab Emirates
muratdilmec@konya.edu.tr

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In this study, the effect of sheet thickness on the anisotropy and thickness distribution at room temperature (RT) was investigated for AA2024-T4 sheets. The anisotropy was determined using automated strain measurement with a grid analysis and profile-projector methods. The results indicate that the effects of the thicknesses of 0.8 mm, 1 mm, and 2 mm on the anisotropy were insignificant. In addition to the anisotropy measurement, the thickness variation of the specimens was also monitored. Besides the anisotropy values, no significant differences were observed between various thicknesses and directions.

Keywords: planar anisotropy, automated strain-measurement method, sheet thickness, AA2024

V tem delu je bil preiskovan vpliv debeline pločevine AA2024-T4 na anizotropijo in razporeditev debeline pri sobni temperaturi (RT). Anizotropija je bila ugotovljena z avtomatskim merjenjem raztezka z analizo mreže in metodo projiciranja profila. Rezultati kažejo, da je vpliv debeline 0,8 mm, 1 mm in 2 mm na anizotropijo zanemarljiv. Dodatno z meritvami anizotropije je bilo tudi spremljano spreminjanje debeline vzorcev. V primerjavi z vrednostmi anizotropije ni bilo opažene pomembne razlike pri različnih debelinah in smereh.

Ključne besede: ravninska anizotropija, avtomatizirana metoda merjenja deformacije, debelina pločevine, AA2024

1 INTRODUCTION

Normal anisotropy r is an indication of resistance to the thinning of a material and is defined as the ratio of transverse strain to thickness strain at the uniform elongation region. In sheet materials, material properties usually change with rolling directions.[1] If the r value is equal to 1, the material is considered to be isotropic otherwise it is anisotropic. Planar anisotropy Δr is an indication of a variation in the r value depending on the direction. Mechanical properties of sheet materials become very different depending on the crystallography and rolling process.[1,2] In a sheet-forming operation, the orientation of a sheet is quite important in order to produce the desired shape with a high accuracy. It is well known that an earing is usually seen on the upper edges of the cups formed with deep drawing. In other words, the upper edge of a cup takes a wavy shape instead of being smooth.[3] Earing behavior occurs due to the fact that the drawing ratios are different at different directions in deep drawing. In this case, the orientation of a sheet helps produce the desired geometry.[4]

Mechanical properties of sheet metals are the most important factors that affect sheet-metal formability. The chemical composition of a material, production methods and various treatments applied to the material during the production are among the main factors that change the mechanical properties of sheet metals.[5] Beside strength and strain, the strain-hardening exponent n, normal anisotropy r, and strain-rate sensitivity exponent m are the other factors that affect the mechanical characteristics of sheet formability.[6,7]

Hospers[8] and Banabic et al.[9] stated that the r and n values affect the formability significantly. Raghavan[10] specifies that the r value has a great influence on deep drawing, increasing the drawability. However, it has a relatively low effect on the stretching process. For an optimum drawability, it is desired that the materials have a high r value and a low Δr value.[8] If the r value is high, deeper cups can be drawn and if the Δr value is low, the earing behavior is suppressed. Deep drawability of aluminum alloys is good when $0.6 \leq r \leq 0.85$ and not adequate when $r \leq 0.6$.

Hatipoglu[11] looked at the effect of the rolling direction on the flow curve for AA2024-T3. The planar anisotropy of a 1 mm sheet was determined as –0.13. Therefore, he assumed the material was isotropic.

As described in the above studies, the effect of sheet thickness on the anisotropy is not studied for AA2024-T4. However, it is necessary to study this area when dealing with an alloy important for the aerospace industry.

In this study, the effect of sheet thickness on the anisotropy of AA2024-T4 was thoroughly investigated. The study was performed at RT for the rolling (0°), diagonal (45°) and transverse (90°) directions. Two different measurement methods were used to measure the anisotropy. These methods are the automated strain-measurement method with grid marking and the measurement with a profile projector. The thickness changes in the 0.8 and 2 mm Nakajima test specimens were also monitored.

2 EXPERIMENTAL PROCEDURE

In this research, AA2024-T4 with the thicknesses of 0.8 mm, 1 and 2 mm was studied. The chemical composition of the alloy is given in **Table 1**. First, the tensile and anisotropy test specimens were cut in the directions of 0°, 45°, and 90° according to the ASTM E 8M-04 and ASTM E 517[12] standards, respectively, for all the thicknesses. Then they were solution heat treated or solutionized at 493 °C for 30 min, quenched in cold water and allowed to age naturally at RT for at least 7 d. The mechanical properties of the materials changed within 7 d. After 7 d, a substantially stable condition, which is the T4 temper, is achieved. In order to see the variations in the mechanical properties of AA2024 with respect to time, tensile tests were conducted for the 1st h, 4th, 5th, 10th, and 30th d of the aging of the material with the thickness of 1 mm. The edges of the specimens were ground to eliminate the notch effect.

2.1 Determination of mechanical properties

The tensile-stress and strain curves were obtained by conducting the tensile tests according to the ASTM E 8M-04 standard for all the thicknesses and the directions of 0°, 45°, and 90°. The tensile tests were conducted using a Shimadzu AG-IS testing machine with a capability of 100 kN. Since the yield point was not clearly detected for any of the samples due to the brittle nature of AA2024-T4, this value was determined with the 0.2 % strain offset method.

2.2 Determination of anisotropy

The ASTM E-517 standard was used to determine anisotropy for all the thicknesses. A 2.5 mm × 2.5 mm grid pattern was applied to a specimen surface with the serigraphy method shown in **Figure 1**. The size of the pattern was applied after the heat treatment, being 50 mm long, along the overall width. This method is one of the most convenient and easy applications for grid marking.[13] The details of the serigraphy method were explained in the authors' earlier study.[14] The grid patterns have high accuracies and resolutions. The patterns were resistant to deformation and operating processes such as friction and lubrication. In their earlier study, the authors found, with the serigraphy method and the Automated Strain Analysis and Measurement Environment (ASAME) software, that the total accuracy and repeatability of the grid pattern were 0.011 and 0.0062, respectively, in the range of 95 % confidence.[14] It is a reasonable assumption that this method may be adequate for the measurements.

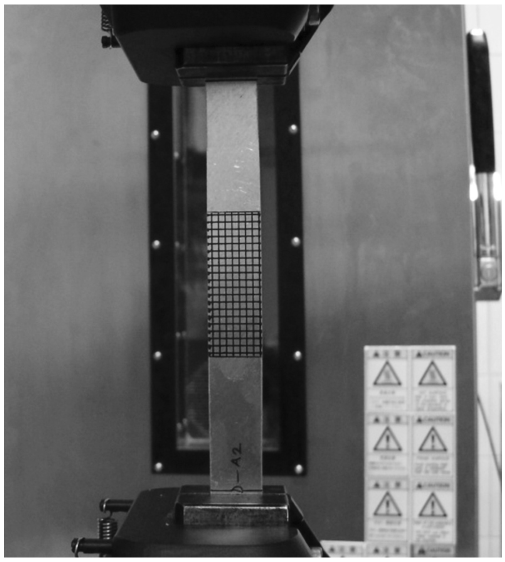

Figure 1: Photograph of an anisotropy specimen during the tensile test
Slika 1: Posnetek vzorca za anizotropijo med nateznim preizkusom

The patterned specimens were elongated or pulled by up to 10 % of the strain value at the speed of 25 mm/min using a tensile testing machine. The automated strain measurement with a grid analysis and the profile projector method were used to determine the anisotropy coefficients.

2.2.1 Automated strain-measurement method

The grid-analysis method is a method which requires a long time to determine the strain values of a specimen. The measurements can be performed manually or with a computer. In this study, the strain measurements were made using the ASAME software. The grid marking is an extremely important process for accurate measurements.

For many materials, the anisotropy value generally remains constant until the ultimate tensile strength is reached. For this reason, the measurements are usually

Table 1: Chemical composition of AA2024 sheets with various thicknesses (*w*/%)
Tabela 1: Kemijska sestava pločevine AA2024 z različno debelino (*w*/%)

Sheet thickness (mm)	Cu	Mg	Mn	Fe	Si	Zn	Ti	Other	Al
0.8–2	4.34–4.44	1.23–1.34	0.62–0.63	0.12–0.17	0.058–0.068	0.077–0.092	0.024–0.029	0.035–0.070	93.29–93.39
ASTM B 209M-07	3.8–4.9	1.2–1.8	0.3–0.9	0.5	0.5	0.25	0.15	0.15	90.85–93

performed at the 10 % strain to determine the r value. When the anisotropy data is provided, it must be specified which elongation r value is obtained.

In the automated strain-analysis method the photographs of the grid pattern were taken before the deformation and used as reference. Then the photographs of the grid patterns of the specimens were taken at the 10 % strain during the tensile test. Moreover, the photographs were also taken for (5, 6, 7 and 9) % elongation values during the process in order to see whether the anisotropy values of the materials with various thicknesses change with different elongation values. A professional Single Lens Reflex camera with a 12 MP resolution was used to record the deformed grids. Then the longitudinal strain ε_l and width strain ε_w were calculated from the measured data on the photographs by the ASAME system. The thickness strain ε_t can be measured directly, but it is a difficult task and its error rate is high. Therefore, ε_t cannot be measured accurately for a thin sheet.[15] In this research, the strain in the thickness direction was calculated using the assumption of a constant volume as follows:

$$\varepsilon_l + \varepsilon_w + \varepsilon_t = 0 \quad (1)$$

Using equation (1), ε_t was calculated and then the anisotropy coefficient was calculated using equation (2):

$$r = \varepsilon_w/\varepsilon_t \quad (2)$$

2.2.2 Profile-projector method

In order to validate the ASAME measurements, the ε_l and ε_w values were also calculated using the profile-projector data with a 0.001 mm precision. Although the dimensions of the grids are 2.5 mm × 2.5 mm having a high precision, the dimensions of at least 6 and 15 grids were measured for length on each specimen. The initial gage length l_0 and width w_0 were determined. After the specimens were elongated up to the 10 % strain value, the final gage length l and width w were measured using the profile projector and the strain values were calculated with equations (3) and (4). Then ε_t was calculated from equation (1). The plastic anisotropy values for each direction were obtained from equation (2):

$$\varepsilon_w = \ln\left(\frac{w}{w_0}\right) \quad (3)$$

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

These measurements were conducted for three different regions in order to increase the accuracy and the obtained values were averaged. So the r values were determined for the 0°, 45°, and 90° directions using both methods.

The average of the obtained values is called the normal anisotropy r_m and it was calculated with the following equation:

$$r = \frac{r_0 + 2r_{45} + r_{90}}{4} \quad (5)$$

where r_0, r_{45}, and r_{90} are the anisotropy values for the 0°, 45°, and 90° directions, respectively. The planar-anisotropy values were calculated with equation (6):[2,16]

$$\Delta r = \frac{r_0 - 2r_{45} + r_{90}}{2} \quad (6)$$

All the tests were repeated at least three times in order to check the repeatability. The results were obtained with a 99 % confidence.

2.3 Monitoring the thickness distribution

The thickness distributions on the deformed Nakajima specimens with a width of 100 mm (**Figure 2**) for the thicknesses of 0.8 mm and 2 mm in the directions of 0°, 45°, and 90° were measured in order to verify whether the obtained anisotropy values change with respect to the sheet thickness for AA2024-T4. Initially, the specimens were cut using a fret saw, making the shape in the most critical section, from at the apex of the dome perpendicularly to the fracture; then the thickness distributions were measured with a profile projector at the intervals of 1 mm with a 0.002 mm accuracy and a 20X scale factor.

All the tests in this study were also conducted at least three times in order to check the repeatability.

3 RESULTS AND DISCUSSION

3.1 Mechanical properties of the materials

The yield curves obtained on different days of the natural aging are given in **Figure 3** for AA2024 with a 1 mm thickness. As shown in the figure, the mechanical properties became stable after the 5th d. For this reason, the experiments were conducted after 7 d.

The measured mechanical properties for the materials with various thicknesses are given in **Table 2**. The mechanical properties obtained are compatible with those in the literature.[11,17–19] The variations in the flow curves according to the rolling directions for the 0.8 mm and 2 mm thicknesses are given in **Figure 4**.

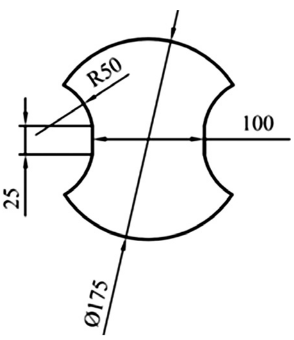

Figure 2: Nakajima specimen with the width of 100 mm
Slika 2: Vzorec Nakajima s širino 100 mm

Table 2: Mechanical properties of AA2024-T4 with various thicknesses
Tabela 2: Mehanske lastnosti pločevine AA2024-T4 z različno debelino

Sheet thickness (mm)	Direction	True yield strength σ_a/MPa	True tensile strength σ_u/MPa	Total true strain ε	Strain hardening coefficient n	Strength coefficient K/MPa
0.8	0°	263 ± 5	497 ± 4	0.1685 ± 0.007	0.20 ± 0.004	762 ± 3
	45°	249 ± 4	473 ± 5	0.1815 ± 0.027	0.20 ± 0.004	738 ± 2
	90°	264 ± 3	502 ± 6	0.1713 ± 0.020	0.21 ± 0.004	719 ± 3
1	0°	271 ± 4	499 ± 4	0.1640 ± 0.008	0.21 ± 0.006	724 ± 6
	45°	263 ± 5	500 ± 8	0.1797 ± 0.027	0.22 ± 0.012	686 ± 6
	90°	270 ± 2	495 ± 5	0.1745 ± 0.007	0.21 ± 0.004	714 ±10
1.2	0°	270 ± 1	512 ± 4	0.1773 ± 0.015	0.22 ± 0.003	764 ± 3
	45°	266 ± 1	536 ± 2	0.1741 ± 0.017	0.21 ± 0.005	749 ± 5
	90°	263 ± 2	518 ± 3	0.1721 ± 0.006	0.22 ± 0.004	751 ± 7
2	0°	308 ± 3	546 ±10	0.1796 ± 0.007	0.22 ± 0.027	753 ± 7
	45°	262 ± 4	537 ± 5	0.1823 ± 0.019	0.23 ± 0.001	718 ± 5
	90°	271 ± 5	499 ± 6	0.1803 ± 0.006	0.23 ± 0.010	730 ± 8
ASTM B 209M-07 (0.5–1.6 mm)	–	Min. 245	Min. 400	0.15	0.17–0.22	676–690

3.2 Anisotropy coefficient

A sample strain distribution on a deformed specimen measured by using the grid-analysis method is given in **Figure 5**. Uniform strain distributions were obtained for all the tests as shown in the figure.

The obtained anisotropy values are given in **Table 3** for the (5, 6, 7 and 9) % elongation values during the process. The variation in the anisotropy values depending on the percent elongation are visually displayed in **Figure 6** averaging the results of three repeats for each percent elongation. It is seen that the anisotropy values do not significantly change depending on the elongation in the specified range for each direction. The obtained anisotropy values at 10 % for AA2024-T4 and AA5754-O with a 1 mm thickness by using the automated strain-measurement and profile-projector methods are given in **Table 4**. Since the results are close to each other with the maximum 15 % error, the reliability of the automated strain-measurement method is presented. Therefore, the anisotropy values for the other thicknesses

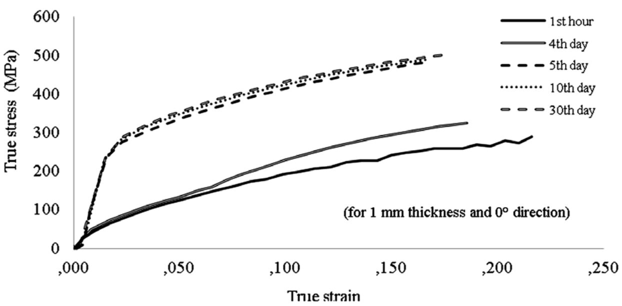

Figure 3: Mechanical properties of AA2024-T4 for various natural-aging times
Slika 3: Mehanske lastnosti AA2024-T4 pri različnih časih naravnega staranja

Table 3: Anisotropy values for various percent elongations for a 1 mm thickness, $r = \varepsilon_w/\varepsilon_t$
Tabela 3: Vrednosti anizotropije pri različnih deležih raztezka pri debelini 1 mm, $r = \varepsilon_w/\varepsilon_t$

Direction	Repeat	5 %	6 %	7 %	8 %	9 %	10 %	Mean
0°	1.	0.73	0.75	0.75	0.74	0.70	0.74	0.74
	2.	0.64	0.66	0.64	0.65	0.63	0.69	0.69
	3.	0.71	0.70	0.74	0.78	0.77	0.77	0.76
45°	1.	0.92	0.93	0.96	0.91	0.92	0.91	0.92
	2.	0.89	0.96	0.95	0.95	0.98	1.02	0.96
	3.	0.85	0.87	0.96	0.93	0.95	0.97	0.96
90°	1.	0.85	0.87	0.84	0.86	0.81	0.80	0.84
	2.	0.84	0.86	0.83	0.81	0.81	0.81	0.83
	3.	0.72	0.75	0.77	0.77	0.81	0.82	0.78

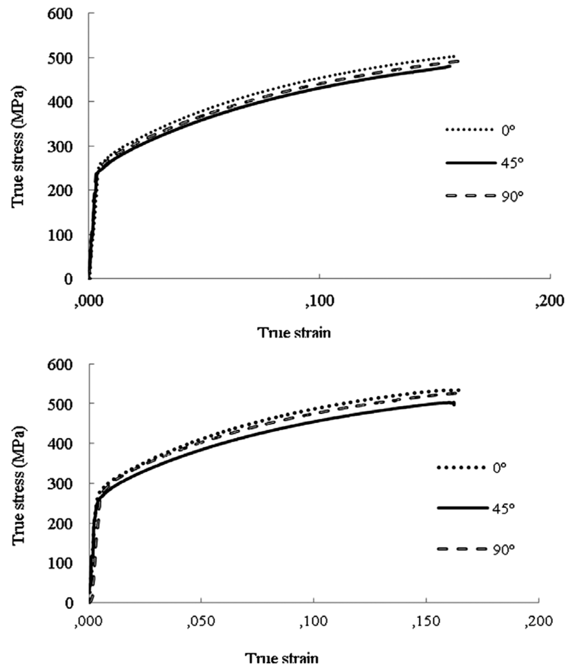

Figure 4: Variations in the flow curves with respect to the rolling directions for: a) 0.8 mm and b) 2 mm thicknesses
Slika 4: Spreminjanje krivulj tečenja glede na smeri valjanja za debeline: a) 0,8 mm in b) 2 mm

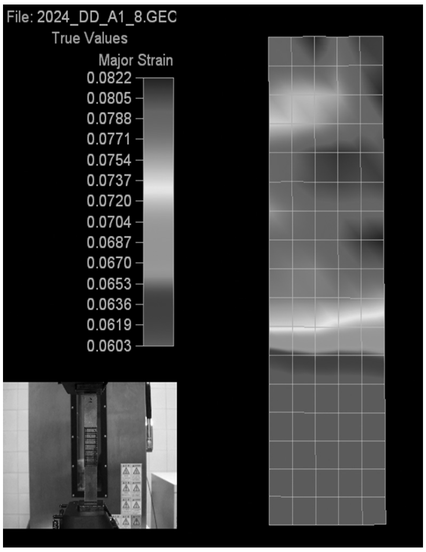

Figure 5: Uniform strain distribution on the deformed anisotropy sample

Slika 5: Enakomerna razporeditev raztezka na deformiranem anizotropijskem vzorcu

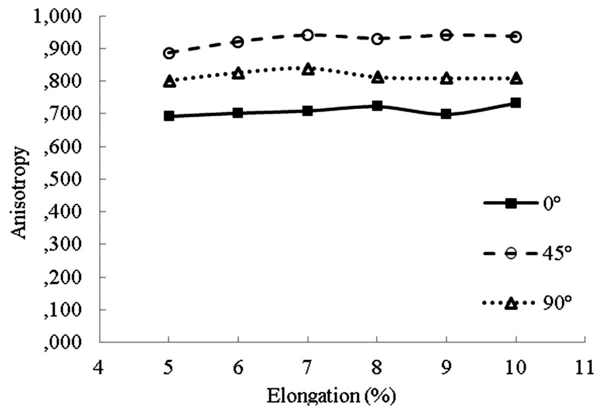

Figure 6: Variations in the anisotropy values for various percent elongations

Slika 6: Spreminjanje vrednosti anizotropije pri različnih deležih raztezkov

of AA2024 were determined by ASAME. The obtained normal and planar anisotropy values at 10 % for the (0.8, 1 and 2) mm thicknesses calculated by ASAME are given in **Table 5**.

Table 5: Anisotropy values for various percent elongations for different thicknesses, $r = \varepsilon_w/\varepsilon_t$

Tabela 5: Vrednosti anizotropije pri različnih deležih raztezka pri različnih debelinah, $r = \varepsilon_w/\varepsilon_t$

Sheet thickness (mm)	Direction	r	r_m	Δr
0.8	0°	0.79 $^{\pm 0.06}$	0.75	–0.14
	45°	0.82 $^{\pm 0.02}$		
	90°	0.57 $^{\pm 0.05}$		
1	0°	0.72 $^{\pm 0.04}$	0.88	–0.22
	45°	0.99 $^{\pm 0.02}$		
	90°	0.82 $^{\pm 0.03}$		
2	0°	0.75 $^{\pm 0.01}$	0.83	–0.17
	45°	0.90 $^{\pm 0.07}$		
	90°	0.75 $^{\pm 0.04}$		
Hursman[17] for 0.8 mm				–0.11

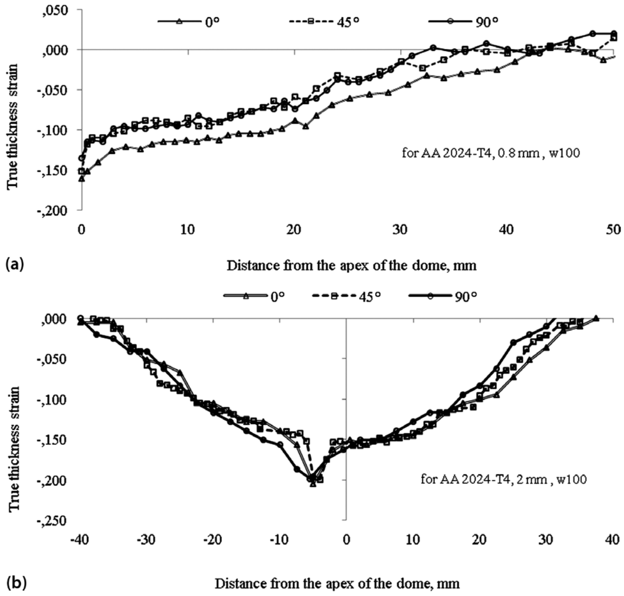

Figure 7: Variations in the thickness-strain distributions with respect to the rolling directions

Slika 7: Spreminjanje razporeditve debeline pri deformaciji glede na smer valjanja

Table 4: Anisotropy values obtained with the automated strain-measurement and profile-projector methods for the 10 % elongation for AA2024 and AA5754

Tabela 4: Vrednosti anizotropije, dobljene z avtomatizirano metodo merjenja deformacije in z metodo projiciranja profila pri raztezku 10 % za AA2024 in AA5754

Material		Profile projector			Automated strain measurement		
	Direction	r	r_m	Δr	r	r_m	Δr
AA2024-T4	0°	0.72 $^{\pm 0.03}$	0.87	-0.20	0.71 $^{\pm 0.04}$	0.88	–0.22
	45°	0.96 $^{\pm 0.03}$			0.99 $^{\pm 0.02}$		
	90°	0.82 $^{\pm 0.03}$			0.82 $^{\pm 0.03}$		
AA5754-O	0°	0.76 $^{\pm 0.02}$	0.71	0.087	0.72 $^{\pm 0.02}$	0.72	0.11
	45°	0.67 $^{\pm 0.04}$			0.67 $^{\pm 0.03}$		
	90°	0.75 $^{\pm 0.03}$			0.85 $^{\pm 0.04}$		

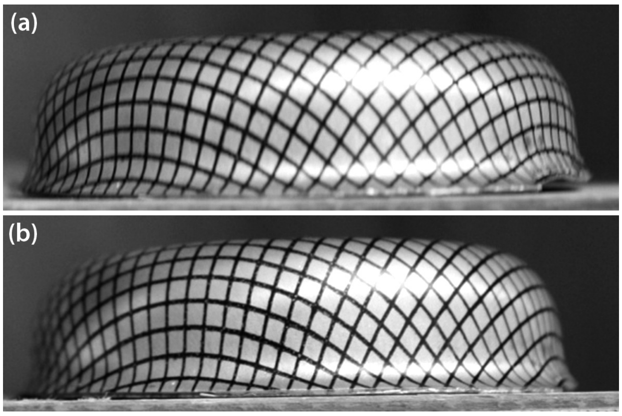

Figure 8: Earing tendency for deep-drawn parts from AA2024-T4 with: a) 1 mm and b) 2 mm thicknesses
Slika 8: Nagnjenost k ušesenju pri delih za globoki vlek iz AA2024-T4 z debelino: a) 1 mm in b) 2 mm

Hursman[17] obtained the planar anisotropy value of AA2024-T3 as -0.11. For this reason it is said that the obtained results in the current study are in accord with the literature. The Δr values for all the thicknesses of AA2024-T4 and AA5754-O with a 1 mm thickness can be acceptably small so that they do not generate the earing behavior. Thus, the materials with different thicknesses may be assumed as isotropic for AA2024-T4.

The variations in the thickness-strain distributions of the Nakajima specimens depending on the rolling direction are given in **Figure 7** for a width of 100 mm and for the 0.8 mm and 2 mm thicknesses. The figure reveals that the thickness distributions do not change considerably with respect to the rolling directions for the formed specimens with the 0.8 mm and 2 mm thicknesses in the directions of 0°, 45°, and 90°. The earing tendency was not observed for the deep-drawn parts of AA2024-T4 as shown in **Figure 8**. So it is verified that the obtained anisotropy values for various thicknesses are consistent with the measured thickness distributions.

4 CONCLUSIONS

In this study, the effect of sheet thickness on the anisotropy and the thickness distribution was investigated at RT for AA2024-T4 sheets. For the anisotropy measurements, automated strain-measurement and profile-projector methods were used and compared. The following results were obtained:

The maximum error range between the automated strain-measurement method and the profile projector is about 15 %. These results indicate that the automated strain-measurement method can be easily used for the anisotropy measurement.

The values of anisotropy were not significantly changed with respect to elongation up to the 10 % strain range for AA2024-T4.

No significant change was found with respect to the rolling directions for AA2024-T4 and AA5754-O. The planar anisotropy values are small and do not change significantly with respect to the sheet thickness of AA2024-T4. Therefore, the effect of the planar anisotropy may be ignored for AA2024-T4 with various thicknesses.

The thickness distributions do not change considerably with respect to the rolling directions.

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