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Original Research

The Effect of Varnishing and Soaking on Formability of the AW-5052-H28 Aluminium Alloy Sheets in Erichsen Cupping Test

Krzysztof Żaba *, Łukasz Kuczek, Maciej Balcerzak

Department of Metal Working and Physical Metallurgy of Non-Ferrous Metals, Faculty of Non-Ferrous Metals, AGH—University of Science and Technology, al. Adama Mickiewicza 30, 30-059 Cracow, Poland; lukasz.kuczek@agh.edu.pl (Ł. Kuczek), maciejbalcerzak1@gmail.com (M. Balcerzak)

* Correspondence: krzyzaba@agh.edu.pl

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Abstract

This article presents the results of experimental tests on the stretch-forming ability of 0.21-mm-thick AW-5052-H28 aluminium alloy sheets used in the production of pull-off cups. Erichsen test under various tribological conditions (dry friction, lubrication with graphite lubricant) was used to assess the sheet formability. Punches with a various diameter of the spherical end (8 and 20 mm) were used in the tests. The effect of soaking conditions and varnishing variants on the value of Erichsen indices IE and IE_{11} was investigated. The sheets were soaked for 13 minutes at various temperatures: 185°C, 190°C and 200°C. In test conditions without lubrication, the lowest value of the IE index = 3.3 mm was observed for sheets in as-received state and for samples after soaking. However, the highest values of the Erichsen index in tests without lubrication were measured for varnished samples and repeatedly soaked. The tests conducted under lubrication conditions with graphite grease revealed usually higher values of the IE index compared to testing conditions without the use of grease. The values of the IE_{11} index were approximately twice lower than the IE indices. Observation of the bulge surface revealed a smooth surface, which means that the material is characterised by a fine-grained microstructure.

Keywords: aluminium alloy, soaking, Erichsen test, formability, sheet metal

1. Introduction

Formability of sheet metal is a property that allows the material to be deformed without the risk of cracking. The ability of metallic materials to undergo plastic deformation is limited due to the microstructure of material depending on their chemical composition. Metals with high elongation are characterised by good formability resulting from the phenomenon of strain hardening (Sobota, 2017). The deformability of sheet metal can be assessed using various tests. Many tests have been developed to test deformability, however, the most commonly used are (Banabic et al., 2000; Reddy et al., 2020): the Swift cup test, the Olsen test, the Fukui conical cup test, the hydraulic bulging test, the hole expansion test, the limiting dome height test and the Erichsen deep-drawing test.

Owing to the requirements posed by the market, manufacturers of packaging closures must ensure the appropriate style of the closures offered (Marsh and Bugusu, 2007). The most popular form of personalisation of closures is the application of lithography to the surface of the closure. The print is done with inks that require high temperatures to dry them. The number of sheet-heating processes depends on the quality requirements and customer requirements. Ensuring adequate reliability of the production process of packaging closures made it necessary to study the input material, the effect of soaking and varnishing variants on strength and microstructural properties. Plastic working of aluminium alloys is problematic due to the presence of build-up on forming tools and galling behaviour (Devenport et al., 2023; Zheng et al., 2023). One of the methods of improving the forming process is the use of coatings on tools characterised by a low coefficient of friction (CoF) and high resistance to wear (Bang et al., 2021; Bang et al., 2022). Tool surface parameters, such as CoF, hardness or the tendency to gall are very important to ensure the proper course of the production process. In industries using aluminium alloy sheets, particular emphasis is placed on product quality. Excessive wear from punching and forming tools creates a risk of fluctuations in the stability of the production process (Fernandes et al., 2017).

Packaging closures are most often made of aluminium alloy AW-5052-H28 (AlMg2.5). This alloy belongs to the 5xxx group of Al-Mg aluminium alloys with a magnesium content of 3-5 wt.%. 5xxx series alloys are medium-strength, reaching a strength of 300 MPa (Leśniak et al., 2014). Their usefulness in the packaging industry is particularly related to high corrosion resistance. Increasing expectations regarding the strength of products made of aluminium alloys of the 5xxx series, combined with their surface treatment, require complex mechanical and tribological tests, e.g. in order to analyse the suitability of selected coating materials and adapt them to specific operating conditions (He et al., 2022; Yamamoto and Nonaka, 2022).

The most important property of sheet metal determining its suitability for forming is stretch-forming ability (Wankhede and Suresh, 2020). Aluminium alloys have been the subject of many studies focused on analyzing the impact of friction and the type of heat treatment on formability. He et al. (2022) tested 1.2-mm-thick AW-5052-H24 aluminium alloy sheet using Erichsen test. It was found that the bulging property of test sheets could be improved by choosing good lubrication conditions. Singh et al. (2017) studied the formability of AW-1200 aluminium alloy sheets and they found that the formability could be increased by controlling the soaking temperature of sheet metals. Sekhar (2019) investigated the formability of 1-mm-thick AW-5052-H32 aluminium alloy sheets by developing a forming limit diagram. Results of Erichsen test revealed that the formability has been improved by soaking. Sravanathi et al. (2015) analysed the formability of AW-5052-H32 aluminium alloy sheets under dry conditions, grease lubrication and soaked condition. The samples after soaking showed enhanced good drawability compared to other test conditions. Subramani et al. (2018) used Using Design of Experiments (DOE) to explore the formability of 1-mm-thick AW-5052 aluminium alloy sheets (temper not specified). It was observed that normal anisotropy and the strain hardening exponent were the most influencing factors in determining the sheet formability. Yamashita et al. (2021) analysed the effect of strain rate on formability of the AW-5052-H34 sheet with thickness of 0.5 mm. The forming limit strains were larger under quasi-static condition in the linear path.

To the best of the authors' knowledge, tests on the deformability of thin sheets of the AW-5052 alloy in the H28 temper condition have not been carried out so far. This article presents the results of testing this sheet using the Erichsen test. In order to enhance novelty, the tests were carried out for sheets subjected to soaking in various conditions and varnishing the sheet metal surface using various varnishes.

2. Experimental

2.1. Material

In the investigations the 0.21-mm-thick AW-5052-H28 aluminium alloy sheets were tested. These sheets are commonly used to produce pull-off caps. The chemical composition of the EN AW-5052-H28 aluminium alloy (in wt.%) is Si (0.4), Fe (0.5), Cr (0.3), Zn (0.2), Cu (0.1), Ti (0.1), Mg (1.6-2.5), Mn (0.5-1.1) and Al (balance). The basic mechanical properties of tested sheets in the as received state (Table 1) were determined on the basis of a uniaxial tensile test according to EN ISO 6892-1 (2020) standard. Zwick/Roell Z020 (Zwick/Roell Group, Ulm, Germany) testing machine was used to determine mechanical properties of the test material. Sheet metal strips were cut along three directions from sheets at an angle of 0°, 45° and 90° with respect to the rolling direction of the sheet metal. Tests were performed in three replications. The parameters presented in the Table 1 represent average values from three samples.

Sheet metal processing before the pull-off cups (Fig. 1) forming process involves heat treatment and varnishing the sheet metal surface using various varnishes. The methods of preparing the analysed sheet metals and denotation of the samples are presented in Table 2.

Table 1. Basic mechanical properties of AW-5052-H28 aluminium alloy sheets.

Sample orientation, °	$R_{p0.2}$, MPa	Ultimate tensile strength (UTS) R_m, MPa	A, %
0	279.7	315.0	5.0
45	276.0	311.0	5.7
90	283.7	319.7	5.5

Fig. 1. Geometric model of an example pull-off cup.

Table 2. Denotation of samples and parameters of surface treatment.

Sample denotation	Surface treatment
S1	No treatment (as-received state)
S2	Varnishing with adhesive varnish Salchi VI1106 and soaking at 200°C for 13 minutes
S3	Varnishing with adhesive varnish Salchi VI1106 and coating varnish Salchi ANC6001, soaking at 200°C for 13 minutes and at 190°C for 13 minutes
S4	Varnishing with adhesive varnish Salchi VI1106, coating varnish Salchi ANC6001 and overprint varnish Salchi VE2028, soaking at 200 °C for 13 minutes, at 190 °C for 13 minutes and at 185 °C for 13 minutes
S5	Soaking at 200°C for 13 minutes
S6	Soaking at 200°C for 13 minutes and at 190°C for 13 minutes
S7	Soaking at 200°C for 13 minutes, at 190°C for 13 minutes and at 185°C for 13 minutes

Only one side of the sheet is varnished. In order to better identify the sides of the sheet metal, this article assumes that the varnished surface will be referred to as ‘inner side’ and ‘outer side’ for non-varnished surface.

Mean roughness Ra and ten point height of irregularities Rz were measured on both sides of the sheet metals on a T1000 (Hommel-Etamic Jenoptik, Jena, Germany) roughness-measuring instrument. A measuring length of 4.8 mm was assumed. Surface roughness parameters were measured in three directions (0°, 45° and 90°) relative to the sheet rolling direction. Table 3 shows the average values of the Ra and Rz parameters measured on both sides of the sheets.

Table 3. Selected surface roughness parameters of the sheet metals.

Sample denotation	Ra, µm		Rz, µm	
	Inner side	Outer side	Inner side	Outer side
S1	0.24	0.22	1.49	1.38
S2	0.42	0.23	2.27	1.53
S3	0.43	0.72	2.15	4.31
S4	0.40	0.18	2.00	1.02
S5	0.26	0.25	1.63	1.53
S6	0.25	0.25	1.68	1.51
S7	0.24	0.25	1.55	1.52

2.2. Erichsen test

The Erichsen test was performed on a universal-sheet metal testing machine (Fig. 2), model 142-40 (Erichsen GmbH & Co. KG, Hemer, Germany). Tests were conducted according to the recommendations of the EN ISO 20482 (2014) standard. The research was carried out using two sets of tools differing in the distance between individual indentations (Table 4). In the case of a tool with a diameter of the spherical end of the punch of 20 mm, tests were carried out with graphite lubricant and without lubricant on the surfaces of contact between the sheet metal and the punch. The Erichsen index IE was also determined depending on the surface of the sheet metal (inner or outer) that was in contact with the punch. The tests were carried out at a constant punch speed of 10 mm/min. The average Erichsen index values for a given material were determined from three measurements.

Fig. 2. Universal-sheet metal testing machine, model 142-40.

Table 4. Geometric parameters in the Erichsen test.

Erichsen index	Diameter of the spherical end of the punch, mm	Bore diameter of the die, mm	Distance between individual indentations, mm	Dimensions of samples, mm	
				Thickness	Width
IE	20	27	90	~0.22	90
IE_{11}	8	11	40	~0.22	40

3. Results and discussion

The results of measuring the Erichsen index of the AW-5052-H28 aluminium alloy sheets depending on the friction conditions (without lubrication and with graphite grease) are shown in Fig. 3. The tests were carried out for one side of the sheet, identical to the side that is in contact with the punch during its forming. Slight differences were found between the obtained Erichsen index values. Due to smaller standard deviations (SD = 0.06-0.1 mm), it was found that the results obtained in tests carried out without lubrication were more reliable. Samples S1, S5 and S6 were characterized by the lowest value of the IE index (IE = 3.3 mm). However, the highest Erichsen index values in tests without lubrication were measured for samples S3 and S4. This means that these sheets are characterised by the highest formability among the analyzed samples.

Similar results were obtained when testing with graphite grease. The Erichsen index values in this case were usually higher than the results obtained in tests without the use of lubricant (Fig. 3), which was related to lower friction between the sheet and the punch. The exception was sample S4, which showed lower indentation depth under lubrication conditions, but a large standard deviation (SD) was obtained (SD = 0.35 mm). The values of standard deviations in tests using graphite grease were between 0.1 (sample S6) and 0.42 mm (sample S1).

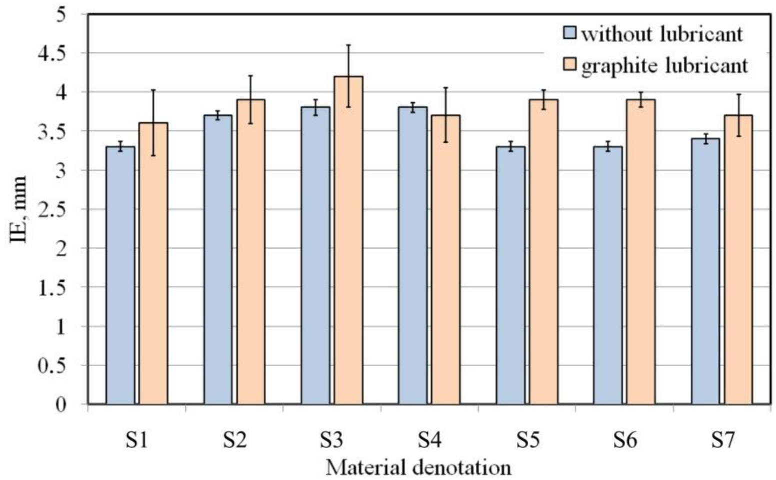

Fig. 3. Erichsen index IE values depending on the type of sample.

Based on the Erichsen test, it is possible to qualitatively determine the grain size of the sheet and the homogeneity of the material. In all cases, a smooth surface of the bulge was found, which means that the material is characterized by a fine-grained microstructure (Fig. 4). At the same time, the character of the crack differed from that of an arc, which may indicate the banded microstructure of the tested materials.

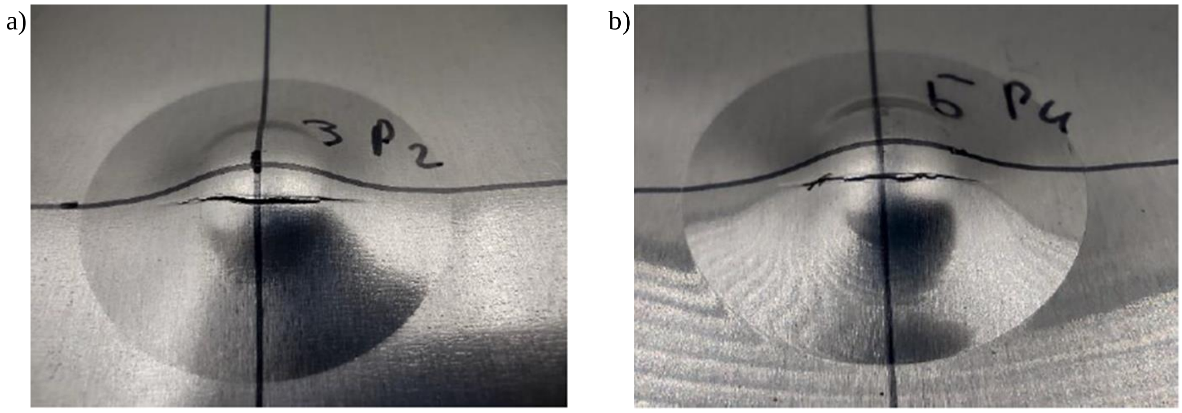

Fig. 4. View of samples deformed using punch with a diameter of the spherical end of 20 mm for samples a) S3 and b) S6.

The influence of the side of the tested sheet that was in contact with the punch during the Erichsen test was also analyzed. It was found that the values of the Erichsen index measured on both sheet sides are similar (Fig. 5). The largest discrepancies of 0.2 mm were observed for samples S1 and S5. This is a difference within the measurement error. The highest value of the IE index (3.8 mm) was found for the sample S3, and the lowest (3.3 mm) for the sample S1. Changing the side of the material in contact with the punch did not change the quality of the bulge surface or the character of the cracks. For sample S3, the value of the SD during tests on the outer side of the sheet was 0.1 mm. For the remaining samples, SD = 0.01 mm was obtained. During tests of samples at the inner side, for samples S4-S7 much larger values of SD between 0.12 mm and 0.15 mm were observed.

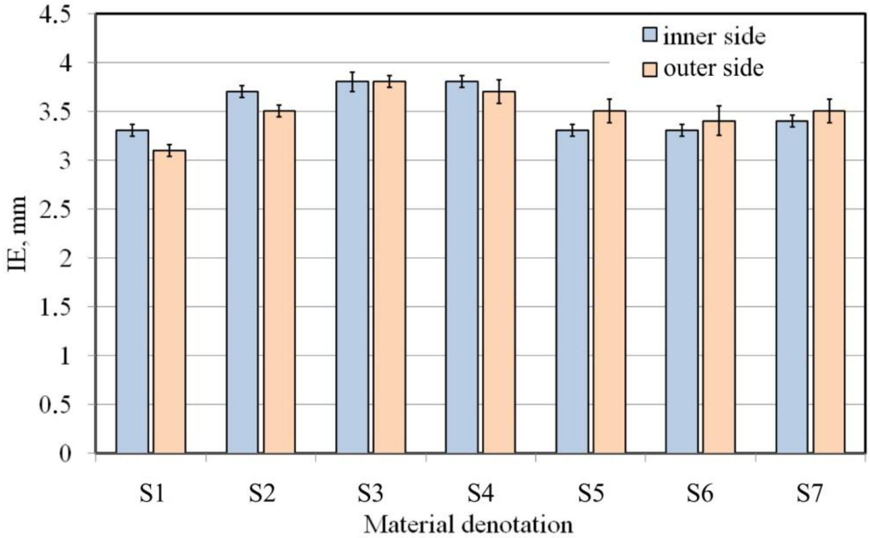

Fig. 5. Values of Erichsen index IE depending on the test side of sheet metal.

Due to the small thickness of the tested sheet metal, the Erichsen test (IE_{11}) was performed using a punch with a diameter of the spherical end of the punch of 8 mm. Under dry friction conditions, slight differences were found in the results obtained with the highest formability (IE_{11} = 0.22 mm) determined for samples S2-S4 (Fig. 6). The use of lubricant slightly changed the values of IE_{11} index obtained for non-lubricated conditions. Sample S3 exhibit the maximum formability (IE_{11} = 2.3 mm). The character of the change in the Erichsen index IE_{11} coincides well with the values obtained in the same test, but using a punch with a diameter of the spherical end equal to 20 mm (Fig. 7). The IE_{11} index values are approximately twice smaller than the IE index values. Regardless of the material analysed and the test conditions, in the test using a punch with a diameter of the spherical end equal to 8 mm (Fig. 8), the character of the cracks was similar to that obtained using a punch with a diameter of the spherical end equal to 20 mm (Fig. 4).

The effect of soaking temperature on the mechanical properties (yield stress, UTS and elongation) of the sheet metals was the subject of a previous article (Czapla et al., 2023). It was found that soaked and/or lacquered samples showed a decrease in yield stress and UTS compared to as-received sample.

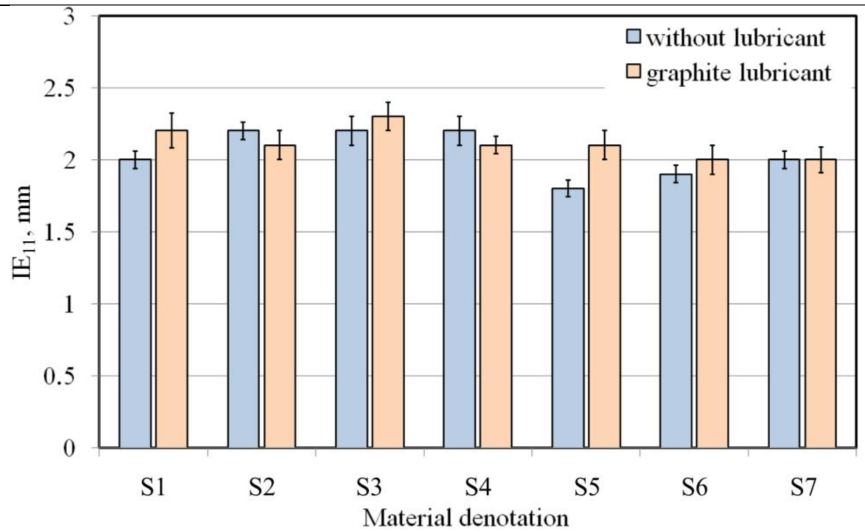

Fig. 6. Erichsen index IE_{11} values depending on the type of sample.

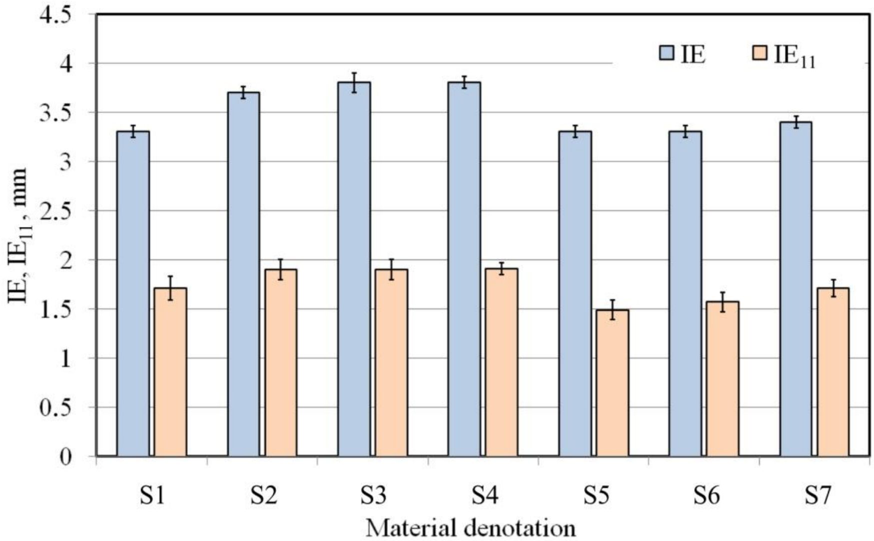

Fig. 7. Comparison of the Erichsen indices IE and IE_{11} obtained in non-lubricated conditions.

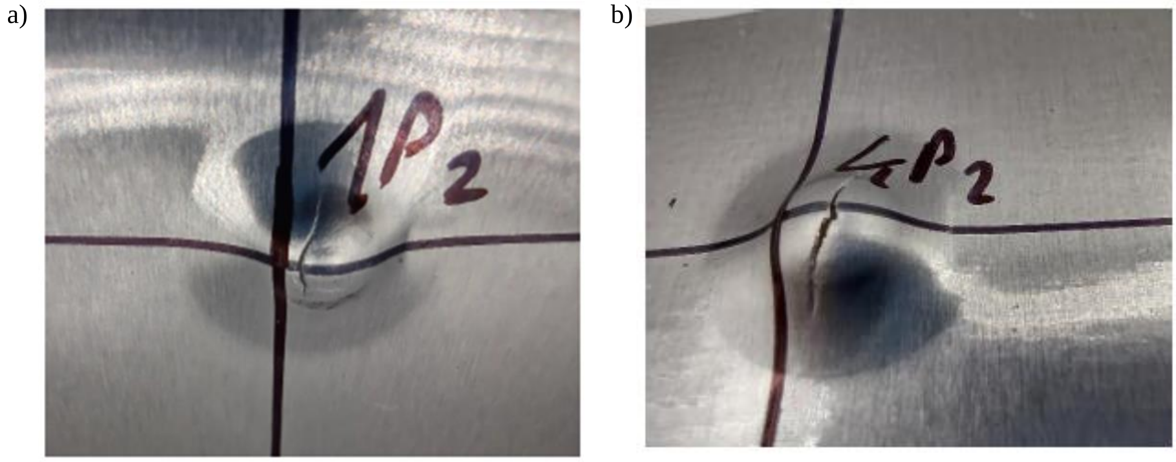

Fig. 8. View of samples deformed using punch with a diameter of the spherical end of 8 mm for samples a) S3 and b) S6.

4. Conclusions

This article presents the results of experimental tests on the stretch-forming capacity of AW-5052-H28 aluminium alloy sheets used in the production of pull-off cups. The Erichsen test was used to assess the formability of varnished and soaked sheet metals. Punches with a various diameter of the spherical end (8 and 20 mm) were considered in the investigations. The following main conclusions were obtained:

- Slight differences were found between the obtained values of Erichsen indices IE and IE_{11} during formability tests without lubricant and with graphite grease. However, smaller standard deviation values (SD = 0.06-0.1 mm) were found in tests carried out without lubrication.
- The lowest value of the IE index = 3.3 mm was observed for sheets in the as-received state and for soaked sheets (samples S5 and S6).
- In non-lubricated conditions, varnished and soaked sheets showed the greatest tendency to stretch-forming.
- Bulged specimens were characterized by a smooth surface, which confirms the fine-grained microstructure of the workpiece material.
- For specific samples, the values of the IE_{11} indices were approximately twice lower than the IE indices.
- Qualitatively similar IE indices were obtained when testing sheet metals on the inner and outer sides. Similarly, the quality of the bulge surface and the character of the cracks were similar on both sides of the sheet.
- Varnished (Salchi VI1106 + Salchi ANC6001) and soaked (200°C for 13 minutes and 190°C for 13 minutes) sample exhibit the maximum IE_{11} index of 2.3 mm.

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Wpływ Lakierowania i Wygrzewania na Odkształcalność Blach ze Stopu Aluminium AW-5052-H28 w Próbie Tłocznosci Erichsena

Streszczenie

W tym artykule przedstawiono wyniki badań eksperymentalnych odkształcalności blach ze stopu aluminium AW-5052-H28 o grubości 0.21 mm stosowanych do produkcji kapsli zawierających zawleczkę. Tłoczność blachy określono metodą Erichsena w warunkach tarcia suchego i smarowania smarem grafitowym. Wykorzystano stemple o średnicy sferycznej końcówki 8 oraz 20 mm. Badano wpływ warunków lakierowania i wygrzewania na wartość wskaźników Erichsena IE oraz IE_{11}. Wygrzewanie blach przeprowadzano w czasie 13 minut i w różnej temperaturze: 185°C, 190°C oraz 200°C. W warunkach bez smarowania najmniejszą wartością wskaźnika IE = 3,3 mm charakteryzowały się blachy w stanie dostawy oraz próbki po wygrzewaniu. Natomiast najwyższe wartości wskaźnika Erichsena w badaniach bez smarowania zmierzono dla próbek lakierowanych oraz wielokrotnie wygrzewanych. Testy przeprowadzone w warunkach smarowania smarem grafitowym ujawniły przeważnie większe wartości wskaźnika IE w porównaniu do warunków testowania bez użycia smaru. Wartości wskaźnika IE_{11} były około dwukrotnie mniejsze niż wskaźnika IE. Obserwacja powierzchni wytłoczenia pozwoliła stwierdzić gładką powierzchnię, co oznacza, że materiał charakteryzował się drobnoziarnistą mikrostrukturą.

Słowa kluczowe: stop aluminium, wygrzewanie, test Erichsena, odkształcalność, blacha