EXPERIMENTAL DETERMINATION OF SPRINGBACK CHARACTERISTICS IN A THREE-POINT BENDING TEST OF THE ALUMINIUM ALLOY SHEET WITH ALUMINIUM CLADDING

Stanisław KUT*, Grzegorz PASOWICZ, Feliks STACHOWICZ***

*Faculty of Mechanical Engineering and Aeronautics, Rzeszow University of Technology,
al. Powstańców Warszawy 8, 35-959 Rzeszów, Poland
**Doctoral School of the Rzeszow University of Technology, al. Powstańców Warszawy 12 35-959 Rzeszów, Poland

stan_kut@prz.edu.pl, grzegorz.j.pasowicz@lmco.com, stafel@prz.edu.pl

received 07 April 2023, revised 24 October 2023, accepted 3 November 2023

Abstract: The springback phenomenon that occurs during cold forming is the main problem that affects the dimensional accuracy of bent products. This article presents the results of the analysis of the springback phenomenon occurring during a three-point air bending of 0.5 mm, 0.8 mm, 1.0 mm and 2.0 mm thick AW-2024 aluminium alloy sheet, AW-1050A aluminium clad. For sheets with a thickness of 1.0 mm and 2.0 mm, the influence of heat treatment and natural ageing time of sheets on the value of the springback coefficient was also tested. The springback characteristics were determined by defining the dependence of the springback coefficient on the bending deflection of the band. The experimental results obtained indicate a linear dependence of the value of the springback coefficient on the relative deflection w/fg index (w – distance between supports, fg – deflection under load), both in the case of the influence of the sheet thickness and the ageing time of the sheets.

Key words: AW-2024 sheet, three-point bending, springback, clad sheet metal, natural ageing

1. INTRODUCTION

One of the main criteria in the selection of material for the production of parts, especially in aviation and automotive production, is the index determining the ratio of its density to the strength limit [1]. Therefore, aluminium alloys, due to their properties and the well-developed ability to produce them, are widely used in aviation and other areas of the transport industry [2, 3]. Currently, apart from composite materials, their percentage share is the largest in aircraft production.

In the aerospace industry, the materials used to make aircraft skins are mainly high-strength aluminium alloys; however, the disadvantage of these materials is usually their low resistance to corrosion. Corrosion damage arising during operation is a serious threat, especially for many years of operation of aluminium aircraft structures [4, 5]. To improve the corrosion resistance of the case of high-strength sheets made of aluminium alloys, technically pure aluminium is used as the coating material, applied on both sides in the rolling process to the parent material [6].

An example of an alloy widely used in aviation production is the AW-2024 aluminium alloy, whose precipitation hardening ability is very often used to obtain the required mechanical properties [7]. After thermal treatment (heat treatment and ageing), it obtains relatively high strength and good fracture toughness [8–10]. The ageing process can be carried out naturally or accelerated (artificial ageing) [11]. Natural ageing generally gives better results in the form of increasing the strength of the material than accelerated ageing, but it takes a long time, even 4–5 days, while the use of higher temperatures during artificial ageing shortens the time of this process [12, 13].

Stampings made of aluminium sheets capable of precipitation hardening are most often shaped from the sheet in the delivery condition, i.e. after soft annealing, and then subjected to heat treatment and ageing. In engineering practice, due to a number of advantages, heat-treated sheets are also subjected to shaping in the initial stage of natural ageing [14]. For this reason, when designing processes for the forming of drawpieces from these sheets, it is important to know the value of the springback coefficient K, both for the sheets as delivered and after the heat treatment during the forming operation. It should be emphasised that shaping operations should be performed as soon as possible after heat treatment due to the deteriorating technological properties of the sheet during natural ageing.

The shaping of various types of parts and sheet metal coatings is carried out by bending processes. In the bending process, three basic stages can be distinguished in this process, i.e. elastic bending, plastic bending and springing. The distribution of longitudinal strains and stresses on the cross-section of the bent strip (Fig. 1) shows that during loading, the outer and inner layers of the material are plastically deformed, while the material in the middle layer remains under the influence of elastic stresses. As a result, after removing the load, the phenomenon of return elastic deformation is observed, i.e. the curvature of the bend decreases. The decisive coefficient for the quality of bent elements is their dimensional and shape accuracy; therefore, during the analysis and design of this process, it is very important to determine the springback effect after removing the bending load.

Quantitative assessment of the springback is carried out by means of experimental research, analytical calculations, numerical modelling and others. The amount of springback is most often determined by the dimensionless springback coefficient K. This coefficient is calculated from formula (1) as the quotient of the bending radius under load ρg and the bending radius after unloading ρs or as the quotient of the bending angle after unloading γs and the bending angle under load γg (Fig. 2).

$$K = \frac{\gamma_s}{\gamma_g} = \frac{\rho_g}{\rho_s} \quad (1)$$

where γ_g, γ_s – band deflection angle under load and after springback, respectively, ρ_g, ρ_s – band radius under load and after springback, respectively.

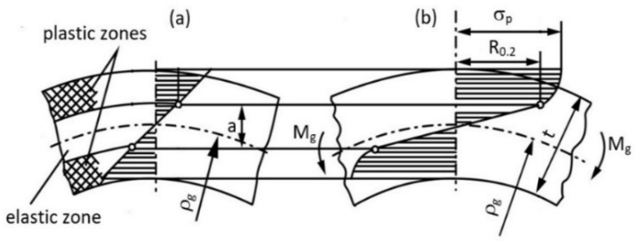

Fig. 1. Distribution of longitudinal strains (a) and stresses (b) on the cross-section of the bent strip

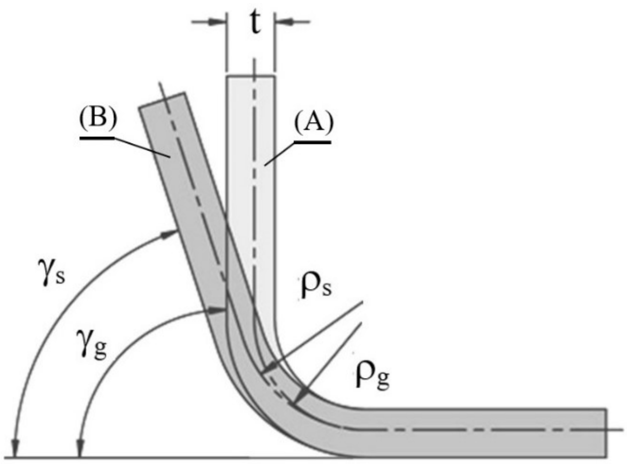

Fig. 2. The shape of a bent sample: (A) under load and (B) after unloading [15]

When designing the technological process and the bending tools, it is necessary to determine to what angle (radius) the input material should be bent to obtain the final product required after springing. Knowing the value of the springback coefficient for specific cases of bending, we can determine the radius or angle that should be used during bending in order to obtain a product with the desired shape after bending. This gives an opportunity to minimise the effects of springing after bending in the design stage of technological processes and technological devices.

In engineering practise, the correction of the shape of the prototype bending tools specified in the design is often done by trial and error. The number of these tests can be significantly reduced by increasing the accuracy of calculations that consider a wide range of coefficients affecting the amount of springback. Therefore, it is important to take into account as many coefficients as possible that influence the parameters of the analysed process when determining the value of the springback coefficient.

Various research works have been devoted to the analysis and study of the springback phenomenon of sheets after bending and for various materials, using various approaches to solving the issues under consideration – analytical [16-18], numerical [19-21] as well as the use of neural networks [22]. However, there is a lack of knowledge on the impact of cladding layers on forecasting springback of clad aluminium alloy sheets; only studies on bending aluminium-clad steel sheets can be found [23].

Knowledge about the amount of springback of materials after bending is practically useful. The lack of data from the literature on the influence of thickness, as well as the influence of heat treatment and natural ageing time of the clad sheets made of the AW-2024 alloy on the value of the springback coefficient K as a function of relative deflection (w/f_g) was the motivation to undertake this research. The prepared characteristics of the springback coefficient of the tested sheets, in addition to cognitive aspects, have practical application in the analysis of the bending process and in the design of equipment for bending these sheets, both in the delivered condition and after heat treatment and during natural ageing.

The paper presents the results of experimental investigations of the three-point air bending process of AW-2024 aluminium alloy, with rolled AW-1050A cladding for anti-corrosion protection, which, among others, are used to make the outer plating of aircraft structures. The tests were carried out for four sheet thicknesses under delivery conditions, i.e. after soft annealing, for which the dependence on the value of the springback coefficient K as a function of sheet thickness t and relative band deflection (w/f_g) was determined. In addition, for two thicknesses of the tested sheets, the effect of the natural ageing time after heat treatment on the value of the springback coefficient as a function of relative band deflection (w/f_g) was determined.

2. MATERIAL AND EXPERIMENTAL PROCEDURE

The tests were carried out using AW-2024 aluminium alloy sheets with thicknesses of 0.5 mm, 0.8 mm, 1.0 mm and 2.0 mm – and the thickness of the AW_1050A clad layers (Fig. 3) applied on both sides was 12.1%, 10.4%, 10.0% and 5.5% of the sheet thickness, respectively. Observations of the microstructure in the cross-section of the sheets (Fig. 3) showed good cohesion of the clad material with the base material. During the bending tests, no loss of cohesion was observed. The microstructure shown corresponds to the softened state of the material, with coagulation of precipitates present, without a granular structure. No significant differences in structure were observed depending on the direction of sample collection. Experimental studies, both determining the mechanical parameters of the sheet material and bending tests, were carried out for two variants:

– all sheets are tested for material as supplied, i.e. for annealed materials,
– for sheets with a thickness of 1.0 mm and 2.0 mm, heat treatment was carried out.

In the heat-treatment process, the samples were successively heated in the furnace to a temperature of 493°C and kept at this temperature for 40 min and 45 min for thicknesses of 1 mm and 2 mm, respectively [24], and then rapidly cooled in cold water. Uniaxial tensile and bending tests were carried out using sheet samples of material delivered as delivered, immediately after heat treatment and after natural ageing for 20 min, 45 min, 90 min and 120 min. The ageing time range covered by the tests was determined based on an analysis of the assortment of produced stamps and engineering practise, taking into account the AMS2770 standard [24].

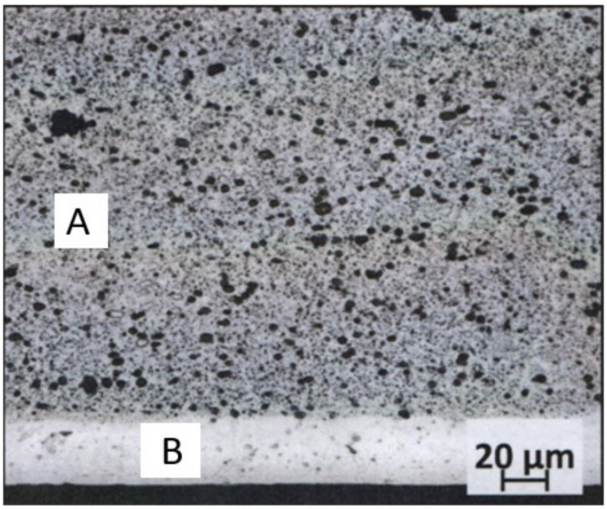

Fig. 3. An exemplary microstructure of a clad sheet in delivery condition: A – base material, B – cladding layer

From the supplied sheets, samples were taken for uniaxial stretching in the 0°, 45° and 90° according to the rolling direction of the sheets. The shape and dimensions of the samples for testing according to ISO 6892-1 are shown in Fig. 4. Static uniaxial tensile tests of individual samples were carried out on the Zwick/Roell Z030 test machine. The tensile speed of the samples was 30 mm/min. During the tensile test, the values of selected material parameters were determined:

- yield stress $R_{0.2}$,
- ultimate strength R_m,
- parameters of the strain hardening curve according to Hollomon $\sigma = C{\cdot}\varepsilon^n$, where C and n are the hardening coefficient and the hardening curve exponent, respectively.

Bending samples that were 40 mm wide and 100 mm long were taken in parallel with the rolling direction. Experimental bending tests were carried out on the Zwick/Roell Z030 testing machine in a three-point tool system with the same radii r = 5 mm (Fig. 5). For samples of each of the sheets tested, the deflection under load was set in eight cycles, successively with the value of 2 mm, 4 mm, 6 mm, 8 mm, 11 mm, 14 mm, 17 mm and 20 mm. The samples were then unloaded and the value of deflection springback was measured.

Then, on the basis of the experimental data, the numerical values of the sample deflection arrow after unloading in subsequent bending cycles were determined. The bending angle and springback angle values were calculated in subsequent cycles, together with the numerical values of the springback coefficient corresponding to these cycles. Based on the measured deflection values, the values of the deflection angles under load γg and after unloading γs were calculated.

As observed above [15], the position of the contact point of the sample with the surface of the shaping tools changes with the increase of the deflection arrow, which has a decisive impact on the value of the calculated bending angle. Therefore, to calculate the angle of bend, formula (2) was used, considering the observed phenomenon and also considering the effect of the band thickness:

$$\gamma = \mathrm{arctg}\left(\frac{2\mathrm{f}}{w-\mathrm{Af}}\right) \quad (2)$$

where f – band deflection arrow, w – distance between the outer bending rollers, A – dimensionless coefficient depending on the thinness coefficient t/r, and the size of the distance between the outer bending rolls w, determined on the basis of geometrical relationships, using the least squares method with the use of the Logger Pro programme.

The author's Eq. (2) was presented in detail together with the method of determining the coefficient A in the work [15].

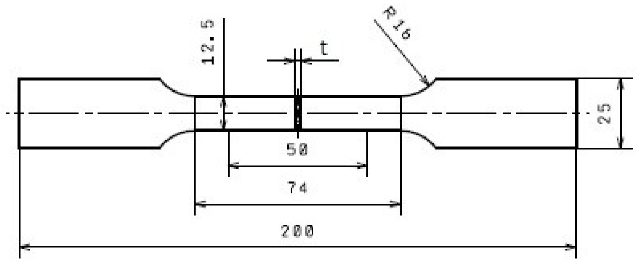

Fig. 4. Dimensions of the samples for the uniaxial tensile test in mm [15]

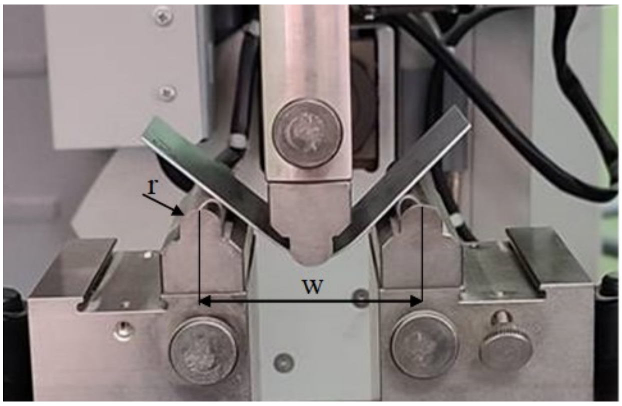

Fig. 5. A photograph of a bent sample [15]

3. RESULTS AND DISCUSSION

Based on the results of the tensile test, it can be seen that both the yield stress values and the strength limit for all thicknesses of the sheets tested under delivery conditions are more than two times higher than the values of these parameters for the clad material (Tab. 1). Heat treatment of the sheet material resulted in a very significant increase in the value of both the yield point (respectively by 110% for 1.0 mm thick sheet and 86% for 2.0 mm thick sheet), the strength limit (respectively by 99% for 1.0 mm thick sheet and 93% for 2.0 mm thick sheet) as well as for the value of the strain hardening exponent (respectively by 24% for 1.0 mm thick sheet and 44% for 2.0 mm thick sheet). With increasing ageing time, further increases in the values of both the yield point and the strength limit were observed. The values of the strain hardening exponent decrease with increasing ageing time (Tab. 2). Therefore, the observation arises that taking into account the course and effect of forming the stamps, as well as the mechanical parameters of the finished product, the conditions of heat treatment of the sheet material should be taken into account.

Tab. 1. Selected mechanical parameters of the tested sheet material under delivery condition

Sheet thickness	**Mean values of the three orientations relative to the rolling direction (0°, 45° and 90°)**			
t mm	$R_{0.2}$ MPa	R_m MPa	C MPa	n
0.5	73.33	171.66	337.42	0.260
0.8	70.25	166.45	319.67	0.256
1.0	64.62	166.43	325.78	0.268
2.0	73.01	178.05	352.99	0.256
Cladding	30.07	74.50	114.60	0.225

Tab. 2. Selected mechanical parameters of the sheet material after heat treatment and ageing

Sheet thick-ness	**Aging time**	**Mean values of the three orientations relative to the rolling direction (0°, 45° and 90°)**			
t mm	Min	$R_{0.2}$ MPa	R_m MPa	*C* MPa	*n*
1.0	0	135.994	331.806	669.104	0.3169
	20	143.779	336.116	663.629	0.3046
	45	155.888	343.384	659.387	0.2872
	90	175.573	356.754	661.054	0.2658
	120	189.493	366.459	665.233	0.2498
2.0	0	135.853	344.660	710.125	0.3236
	20	144.999	350.551	706.208	0.3143
	45	157.429	360.241	705.092	0.2994
	90	179.438	377.486	710.667	0.2720
	120	194.363	389.288	715.725	0.2587

The springback characteristics were presented as a dependence of the springback coefficient on the value of the w/fg index because, as shown earlier [15], it allows one to obtain a linear relationship between these parameters described by a linear equation of the form:

$$K = -A\left(\frac{w}{f_g}\right) + B \tag{3}$$

where A and B – material coefficients determined experimentally.

This is confirmed by the results of the experimental investigations presented in this study, as evidenced by the high values of the correlation coefficients R2 (Fig. 6). The data presented in the graph (Fig. 6) show that the springback coefficient K also depends on the thickness of the sheet t; so, in this case, it is a function of two variables:

$$K = f\left(\frac{w}{f_g}, t\right) \tag{4}$$

In order to take into account the influence of the second variable, i.e. the thickness of the sheet t, the values of coefficients A and B in Eq. (3) should be determined as a function of the thickness of the sheet. Taking into account the determined values of these coefficients for the thicknesses tested (see equations in Fig. 6), the approximation method determined the relationship between the sheet thickness and the value of coefficients A and B, which is presented in the graph (Fig. 7). After substituting the coefficients A and B determined as functions of thickness into formula (3), we obtain the relationship:

$$K = -(0{,}086\mathrm{t}^2 - 0{,}0283\mathrm{t} + 0{,}0314)\left(\frac{w}{\mathrm{f_g}}\right) + (0{,}8178 + 0{,}153\mathrm{t} - 0{,}0442\mathrm{t}^2) \tag{5}$$

allowing us to calculate the numerical value of the spring coefficient *K* as a function of the w/f_g index and the thickness of the sheet *t* in the range of thickness *t* = (0.5-2.0) mm and the quotient (w/f_g) = (2.5–25).

The above equation can be used for quick and estimated selection of the shape of the bending tools in order to obtain the required geometry of the final stamps.

As expected, the value of the springback coefficient clearly depends on the thickness of the sheet. For the sheet with a thickness of 0.5 mm, the values of the springback coefficient are clearly lower than for the other sheets (Fig. 6). This is due to the fact that for the curvatures used in bending tests, for the thinnest sheet, the share of the elastic stress layer a (Fig. 1) is the largest. In addition, for this sheet, the percentage share of the clad thickness in relation to the sheet thickness is the highest; therefore, the more easily deformable material in the outer layers of the sheets results in a greater value of springback after removing the bending load.

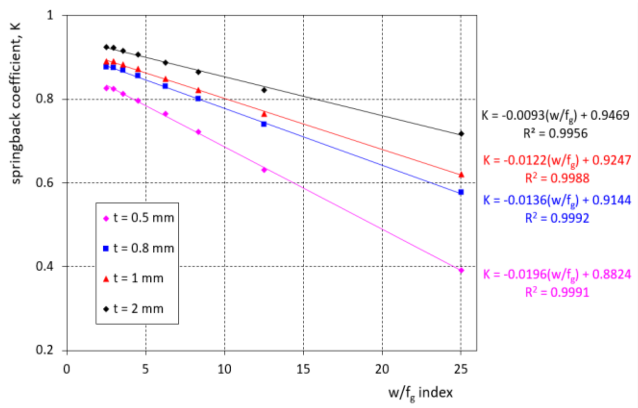

Fig. 6. Dependence of the springback coefficient on the value of the w/f_g index for sheets of different thickness

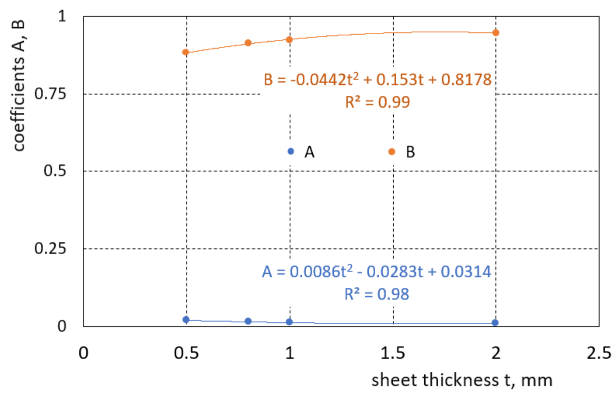

Fig. 7. The influence of sheet thickness on the value of coefficients *A* and *B* in Eq. (3)

The heat treatment of the material also resulted in a significant increase in the springback susceptibility of the sheets, especially for small bending curvatures (high values of the w/fg ratio) (Figs. 8 and 9). The values of the springback coefficient for the material delivered, especially for sheets 1.0 mm thick, are clearly higher than the values of the K coefficient for sheets after heat treatment. The values of the K coefficient decrease (increase springback) as the annealing time increases. Taking into account the practical use of these relationships, it is recommended to shape products in bending processes using sheets in the delivered condition, and then heat treat the finished parts in order to increase the mechanical parameters of the material [14].

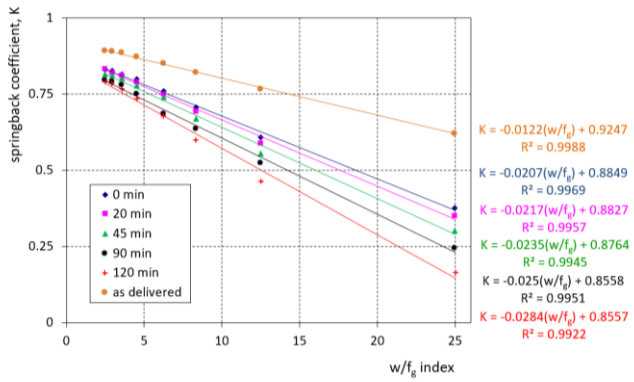

Fig. 8. Dependence of the springback coefficient on the value of the w/f_g index for sheets for different ageing times for 1.0 mm thick sheets (compared to the springback characteristics for sheet with mechanical parameters as delivered)

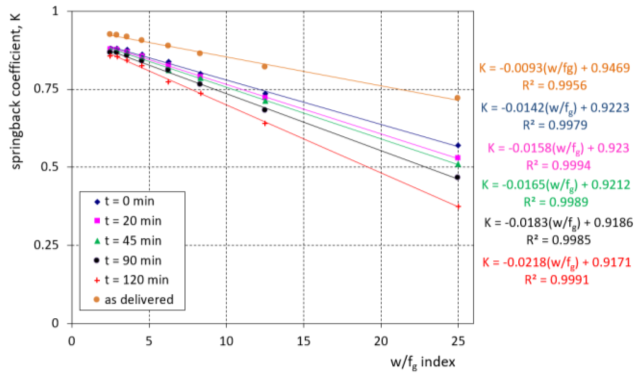

Fig. 9. Dependence of the springback coefficient on the value of the w/f_g index for sheets for different ageing times for 2.0 mm thick sheets (compared to the springback characteristics for sheet with mechanical parameters as delivered)

The value of the springback coefficient of sheets 1.0 mm and 2.0 mm thick after different ageing times showed a dependence on the tendency of the material to strain hardening (Figs. 10 and 11). An increase in the value of the strain hardening exponent results in an increase in the value of the springback coefficient. This relationship is more pronounced as the bending curvature (greater deflection of the samples).

During natural ageing of the tested sheets in the time range of 0–120 min, an increase of almost 40% and 43% in yield stress was observed for sheets with a thickness of 1.0 mm and 2.0 mm, respectively. At the same time, a much less intense increase in ultimate strength was recorded, which was 10% and 13% for sheets with a thickness of 1.0 mm and 2.0 mm, respectively (Tab. 2). The influence of these parameters, specifically the ratio $R_{0.2}/R_m$, on the springback coefficient for three values of w/f_g, is shown in Figs. 12 and 13 for sheet metal with a thickness of 1.0 mm and 2.0 mm, respectively. Both in the case of a 1.0 mm thick sheet (Fig. 12) and a 2.0 mm thick sheet (Fig. 13), the value of the springback coefficient K decreases with the increase in the $R_{0.2}/R_m$ ratio. The intensity of the decrease in the value of the springback coefficient K with an increase in the $R_{0.2}/R_m$ ratio depends on the relative deflection w/f_g and is greater with the lower value of w/f_g. In other words, the smaller the radius of the bending curvature, the greater the springback after the bending. The amount of this springback increases additionally with the increase in the $R_{0.2}/R_m$ ratio, and this increase is more intense with a smaller bending radius.

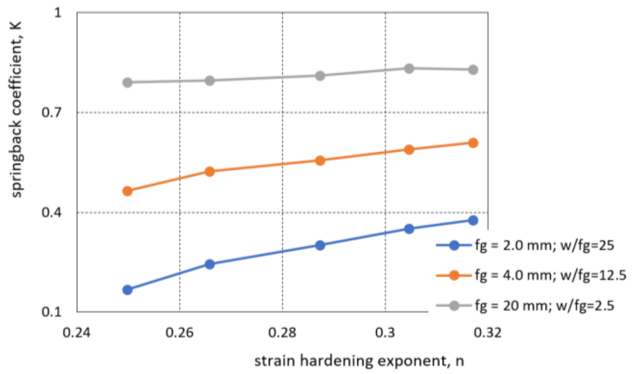

Fig. 10. Dependence of the springback coefficient on the value of the strain hardening exponent for sheets for different deflection for sheets 1.0 mm thick

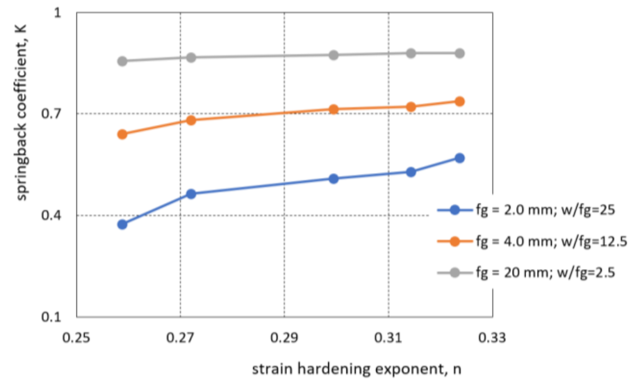

Fig. 11. Dependence of the springback coefficient on the value of the strain hardening exponent for sheets for different deflection for 2.0 mm thick sheets

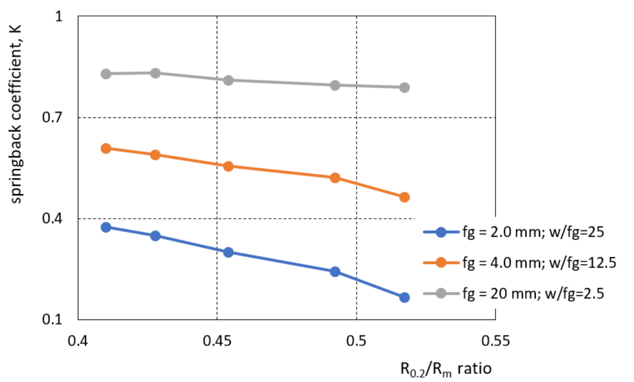

Fig. 12. Dependence of the springback coefficient on the value of the $R_{0.2}/R_m$ ratio for sheets for different deflection for 1.0 mm thick sheets

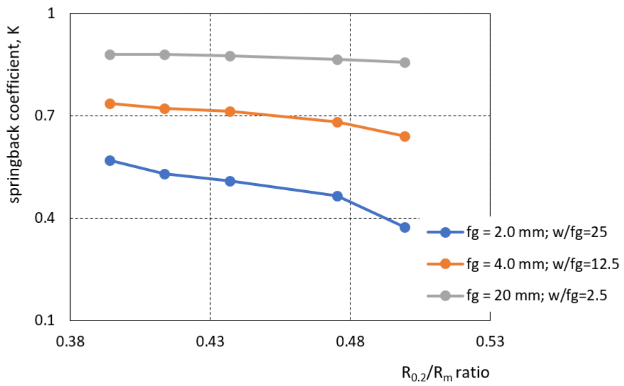

Fig. 13. Dependence of the springback coefficient on the value of the $R_{0.2}/R_m$ ratio for sheets for different deflection for 2.0 mm thick sheets

4. CONCLUSIONS

This work presents the results of the analysis of the springback phenomenon observed during elastic–plastic cold bending of 0.5 mm, 0.8 mm, 1.0 mm and 2.0 mm thick of the AW-2024 aluminium alloy with AW-1050A aluminium clad. For the sheet material in the delivery condition and after heat treatment and various ageing times, the value of the selected mechanical parameters and the springback characteristics were determined. The main conclusions of this work can be summarised as follows:

– Heat treatment of the material in the as-deliver resulted in an average approximately two-fold increase in the values of both the yield stress and the ultimate strength, and an approximately 20% increase in the hardening deformation exponent. Compared to the parameters of the heat-treated material, the increase in the yield stress and the ultimate strength after an ageing time of 120 min was on average approximately 40% and 11%, respectively. In the tested ageing time range, the strain hardening exponent values decrease with increasing ageing time, up to a value close to the value of this parameter for the material in the delivery condition.
– For all the tested sheets, a linear dependence of the value of the springback coefficient on the value on the relative deflection w/fg index was observed – with increasing bending curvature (decreasing w/fg index), the value of the springback coefficient increases. In the entire tested w/fg range, for example, for the sheet as delivered with a thickness of 2 mm, this increase was 1.28 times, while for the same sheet immediately after heat treatment, it was 1.54 times and 2.21 times after 120 min of natural ageing. It was observed that, regardless of heat treatment and ageing time, this increase was greater with the smaller the thickness of the tested sheet.
– The values of the springback coefficient for the material in the delivery state are clearly higher than the value of this index for sheets after heat treatment. Extending the ageing time of the material results in a decrease in the value of the springback coefficient.
– For heat-treated sheets, an increase in the Re/Rm ratio was observed with the increase in natural ageing time. In the tested ageing time range of up to 120 min, the value of the springback coefficient decreases as the Re/Rm ratio increases. The intensity of this decrease increases with the deflection of the sample.
– An increase in the value of the strain hardening exponent results in an increase in the value of the springback coefficient.

REFERENCES

1. Himagireesh Ch, Ramji K, Durga Prasad KG, Hari Kiran V. Multi-criteria decision model for selection of a material suitable to lightning strike protection in aerospace applications. Materials Today Proc. 2022;59: 725-733.
2. Polmear I. Light Alloy - From traditional Alloys to Nanocrystals. Butterworth-Heinemann: Oxford 2006.
3. Davies G. Materials for Automobile Bodies. Butterworth-Heinemann: Oxford 2003.
4. Atluri SN, Sampath SG, Tong P. Structural Integrity of Aging Airplanes. Springer Verlag: Berlin/Heidelberg 1991.
5. Pantelakis SpG, Chamos AN, Setsika D. Tolerable corrosion damage on aircraft aluminium structures: Local cladding patterns. Theor. Appl. Fracture Mech. 2012;58:55-64.
6. Zinonga T, Binga Z, Junb J, Zhiqianga L, Jianguob L. A study on the hot roll bonding of aluminium alloys. Procedia Manufacturing. 2020; 50:56-62.
7. Kučera V, Vojtěch D. Influence of the Heat Treatment on Corrosion Behavior and Mechanical properties of the AA 7075 Alloy. Manufacturing Technology. 2017;17:747-752.
8. Miller WS, Zhuang L, Bottema J, Wittebrood AJ, Smet PD, Haszler A, et al. Recent development in aluminium alloys for the automotive industry. Compos Sci. Technol. 2000;280:37-49.
9. May A, Belouchrani MA, Taharboucht S,Boudras A. Influence of heat treatment on the fatigue behaviour of two aluminium alloys 2024 and 2024 plated. Procedia Engineering. 2010; 2:1795-1804.
10. Sun S, Fang Y, Zhang L, Li C, Hu S. Effects of aging treatment and peripheral coarse grain on the exfoliation corrosion behaviour of 2024 aluminium alloy using SR-CT. J. Mater. Res. Technol. 2020;9:3219-3229.
11. ASM Handbook, Volume 4. Heat Treating ASM Handbook Committee, p. 841-879. DOI: 10.1361/asmhba0001205
12. Sobotka J, Solfronk P, Kolnerova M, Korecek D. Influence of technological parameters on ageing of aluminium alloy AW-2024. Manufacturing Technology. 2018;18:1023-1028.
13. Fallah Tafti M, Sedighi M, Hashemi R. Effects of natural ageing treatment on mechanical, microstructural and forming properties of Al 2024 aluminum alloy sheets. Iranian J. Mater. Sci. Engng. 2018;15:1-10. doi: 10.22068/ijmse.15.4.1
14. Kut S, Pasowicz G, Stachowicz F. The influence of natural aging of the AlCu4Mg1 aluminum sheet alloy on the constitutive parameters of selected models of flow stress. Adv. Sci. Technol. Res. J. 2022;16: 216-229. doi.org/10.12913/22998624/154792
15. Kut S, Pasowicz G, Stachowicz F. On the springback and load in three-point air bending of the AW-2024 aluminium alloy sheet with AW-1050A aluminium cladding. Materials. 2023;16:2945. doi. 10.3390/ma16082945.
16. Sharma PK, Gautam V, Agrawal AK. Analytical and numerical prediction of Springback of SS/Al-alloy cladded sheet in V-Bending. J. Manuf. Sci. Eng. 2021;143(3):031011.
17. https://doi.org/10.1115/1.4048953
18. Zhu YX, Liu YL, Yang H, Li HP. Development and application of the material constitutive model in springback prediction of cold bending. Materials Designe. 2012;42:245-258.
19. Wu Z, Gong J, Chen Y, Wang J, Wei Y, Gao J. Springback prediction of dieless forming of AZM120 sheet metal based on constitutive model. Metals. 2020;10:780. doi:10.3390/met10060780.
20. Vorkov V, Aerens R, Vandepitte D, Duflou JR. Springback prediction of high-strength steels in large radius air bending using finite element modeling approach. Procedia Eng. 2014;81:1005-1010. doi:10.1016/j.proeng.2014.10.132

21. Lin J, Hou Y, Min J, Tang H, Carsley JE, Stoughton TB. Effect of constitutive model on springback prediction of MP980 and AA6022-T4. Int. J. Material Forming. 2020;13:1-13. doi.org/10.1007/s12289-018-01468-x
22. Sharma PK, Gautam V, Agrawal AK. Experimental and numerical investigations of springback and residual stresses in bending of a three-ply clad sheet. Proc IMechE Part L: J. Materials: Design Applications. 2021;235,2823-2838 https://doi.org/10.1177/14644207211037006
23. Trzepieciński T, Lemu HG. Improving prediction of springback in sheet metal forming using multilayer perceptron-based genetic algorithm. Materials. 2020;13:3129. doi.org/10.3390/ma13143129.
24. Yilamua K, Hino R, Hamasaki H, Yoshida F. Air bending and springback of stainless steel clad aluminium sheet. J. Mater. Proc. Technol. 2010;210:272-278. doi.org/10.1016/j.jmatprotec.2009.09.010.
25. AMS2770. Heat Treatment of Wrought Aluminum Alloy Parts. Rev. 2015-09.

Stanisław Kut: https://orcid.org/0000-0003-0870-7548

Grzegorz Pasowicz: https://orcid.org/0000-0002-7932-0044

Feliks Stachowicz: https://orcid.org/0000-0003-2756-0414