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EFFECT OF PRE-STRAINING ON THE SPRINGBACK BEHAVIOR OF THE AA5754-0 ALLOY

VPLIV PRENAPENJANJA NA POVRATNO ELASTIČNO IZRAVNAVO ZLITINE AA5754-0

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This study presents the effect of pre-straining on the springback behavior of the AA5754-0 aluminum-magnesium (Al-Mg) alloy sheet under V bending by an experimental and finite-element simulation studies. Pre-straining ranges from 0 % to 11 % were applied to the samples, which were bent on a 60° V-shaped die for the springback evaluation. Commercially available finite-element software, ETA/Dynaform, was used to simulate the 60° V-die bending process. The dynamic explicit finite-element method for pressing and the static implicit finite-element method for the unloading phase were used for the simulations. The results from both the experiment and the simulation indicate that the pre-straining has no positive effect on the springback compensation.

Keywords: pre-straining; springback; Al-Mg alloy; AA5754-O alloy

Delo obravnava vpliv prenapenjanja na povratno elastično izravnavo pločevine iz aluminij magnezijeve zlitine AA5754-0 pri V-upogibu eksperimentalno in s simulacijo s končnimi elementi. Za oceno povratne elastične izravnave so bili prednapetosti v razponu od 0 % do 11 % izpostavljeni vzorci, ki so bili upognjeni v V-utopu. Uporabljen je bil komercialno dosegljiv softver ETA Dyna form za simuliranje upogibanja v 60° V-utopu. Za simulacijo sta bili uporabljeni eksplicitna metoda končnih elementov za fazo tlačenja in statična implicitna metoda končnih elementov za razbremenitev. Rezultati preizkusov in simulacije kažejo, da prenapetost nima pozitivnega vpliva na kompenzacijo izravnave.

Ključne besede: prednapetost, povratna izravnava, AlMg zlitina, zlitina AA5754-O

1 INTRODUCTION

In recent years, lightweight structures have been a key target for automotive manufacturers in order to reduce fuel consumption and carbon dioxide emissions without sacrificing vehicle safety and performance. Therefore, lightweight materials, particularly aluminum alloys, have found more applications in auto-body structures. Many industries, such as aerospace, defense and ship building, prefer aluminum alloys because of their relatively light weight to high strength ratios and corrosion resistance [1–5]. However, there are some limitations in the usage of these materials in terms of low formability at room temperature (RT) and springback. The springback issue is the most common problem in the forming operations of these lightweight materials because of their low Young's modulus. It can lead to significant problems during assembly if the phenomenon is not well controlled, and so the manufacturing costs will increase [6–8]. In bending operations, after the release of the load, an elastic recovery occurs. The geometry of the part becomes quite different than the desired shape. The springback issue has been studied over the years to compensate for the undesired shape errors and to identify the effect of major factors, such as material parameters, tooling geometry, and process parameters, on the amount of springback, both experimentally and numerically. Asnafi [9] examined the effects of process parameters on the springback in the V-bending process by developing theoretical models for stainless-steel sheets. Asnafi [10] also studied the springback characterization of steel and aluminum sheets in double-curved autobody panels, both experimentally and theoretically. He reported that this springback could be reduced by increasing the blank holder force (BHF), sheet thickness, and die radius and decreasing the yield strength. One of the most important material parameters that affect the amount of springback is the Bauschinger effect. The Bauschinger effect is normally associated with conditions where the yield strength of a metal decreases when the direction of the strain is changed. The basic mechanism for the Bauschinger effect is related to the dislocation structure in the cold-worked metal. Gau and Kinzel [11] experimentally investigated the Bauschinger effect in steel and aluminum alloys using a simple bending process. They showed that the Baushinger effect on the springback of an aluminum alloy (AA6111-T4) is very significant. Chun et al. [12,13] also studied the Bauschinger effect on a sheet-metal forming process that was subjected to cyclic loading conditions for different hardening rules. Moreover, a similar method was also used by Xue et al. [14,15]. They developed a new analytical procedure to predict the springback of circular and square metal sheets after a double-curvature forming operation [14,15].

In recent years, finite-element analysis (FEA) software packages have become very popular as a rapid and cost-effective tool for sheet-metal forming processes. The developed models for the materials which are used in FEA software have significant effects on the accurate prediction of the forming results. For a numerical simulation of a springback analysis, the appropriate hardening model and the plastic yield criterion that properly describe the material behavior at a large strain are needed. There have been several studies in the literature to predict the springback of materials by using FEA programs based on the different hardening models, i.e., isotropic, kinematic, and mixed hardening models for different yield criteria and tool geometry, material properties, forming conditions, etc. [16–22]. Laurent et al. [22] compared several plastic yield criteria to show their relevance with respect to predicting the springback behavior for a AA5754-0 aluminum alloy, both experimentally and numerically. In their study, the effectiveness of the isotropic and kinematic hardening models, which are combined with one of the following plasticity criteria – von Mises, Hill'48 and Barlat'91 – are analyzed.

In the present study, the effects of pre-straining on the flow stress and the springback behavior of the 5754-O Al-Mg alloy were investigated. In addition to the experimental work, finite-element (FE) simulations were also used for the springback predictions and the comparison.

2 MATERIAL AND EXPERIMENTAL WORK

In this study, as-received Alcan 5754-O Al-Mg alloy sheet in the O-temper with a thickness of 1.88 mm was evaluated. The chemical composition of the material is given in **Table 1**.

Table 1: Chemical composition of 5754 Al-Mg alloy (in mass fractions, *w*/%)
Tabela 1: Kemična sestava AlMg zlitine 5754 (v masnih deležih, *w*/%)

Mg	Si	Mn	Fe	Cu	Al
3.17	0.112	0.51	0.1613	0.01	Balance

Initial material properties are given in **Table 2**.

Tensile and pre-straining tests were performed on a Shimadzu Autograph 100 kN testing machine with a data-acquisition system maintained by a digital interface board utilizing a specialized computer program. The material deformation was measured with a video-extensometer measurement system for tensile-test specimens with a 50-mm initial gauge length. Tensile-test samples were prepared according to the ASTM E8 standard in the rolling, "diagonal" and transverse directions. The tests were conducted at room temperature and a strain rate of 0.0083 s^{-1} (25 mm/min) in order to determine the initial properties of the material, which are shown in **Table 2**. The specimens in the rolling direction were also pre-strained by the tensile testing machine for six different pre-straining levels, ranging from 1 % to 11%, by an increment of 2 %. The pre-straining was performed at a constant deformation rate of 3 mm/min and then unloaded at the same deformation rate. It is generally known that the alloy shows serrated hardening curves, as commonly observed for 5XXX series aluminum alloy sheets [23]. The yield strength of the material was determined based on the 0.2 % proof stress. As mentioned before, the Young's modulus of the material has considerable affects on the springback behavior of the materials. However, determining the Young's modulus by performing tensile tests is very difficult because of the machine competence and software limitations. Research in the literature shows that the Young's modulus varies with the plastic deformation and therefore using a constant Young's modulus in springback calculations and simulations means less accurate results [24,25].

The 60° V-shaped die bending test samples were also prepared at a rolling direction in a rectangular shape of 30 mm × 200 mm. They were all pre-stained using the

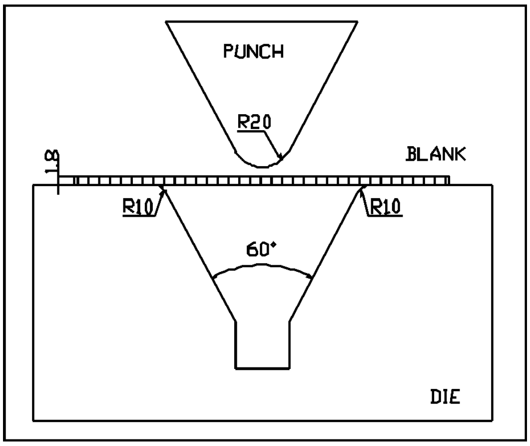

Figure 1: 60° V-shaped bending setup
Slika 1: 60° V-utop za upogibanje

Table 2: Initial material properties of 5754 Al-Mg alloy
Tabela 2: Začetne lastnosti AlMg zlitine 5754

	YS (0.2 %)/MPa	*UTS*/MPa	*UE*/%	*TE*/%	*r*	Lankford Parameter	*n*	*K*/MPa
Rolling (0°)	118	296	19.5	22.3	0.712	0.7325	0.306	492.2
Diagonal (45°)	106	234	23.2	26.2	0.754		0.304	462.5
Transverse (90°)	108	234	21.8	24.3	0.710		0.302	464.7

UE: Uniform elongation; TE: Total tensile elongation tensile testing machine, in the same way as the tensile test samples.

In this study the springback evaluation was made by a 60° V-shaped die bending test, as shown in **Figure 1**.

The bending tests were performed at a 25 mm/min deformation speed. The precision of the displacement and force measurements of the punch are 0.001 mm and ±2 N, respectively. No lubrication was applied to the die and blank surfaces. The punch was released after the forming. No soak time was assigned. The springback angle ($\Delta\theta$) was measured by a Mitutoyo 187-907 universal bevel protractor that has a ±5min measurement accuracy.

3 FINITE-ELEMENT STUDY

There have been many numerical approaches to defining the springback characterization of materials for bending operations. In general, these approaches are directly related to the material properties, which are the strain hardening coefficient (n), strength coefficient (K), thickness (t), anisotropy (R), Young's modulus (E), Baushinger effects, hardening models, etc. In this research, finite-element modeling was considered in addition to the experimental study.

The material properties, i.e., Young's modulus (E), yield stress (Y) and strength coefficient (K), were obtained from uniaxial tensile test and modified for the plane strain conditions using von Mises criterion. The bending process was also analyzed based on a consideration of the plane strain condition. Plane strain bending is a major sheet-forming process and it is practiced as air bending, U- and V-shaped die bending. The deformation in a bending process can be pronounced as a plane strain deformation. In a plane strain deformation, the sheet usually extends only in one direction. For this reason, the plane strain condition was also studied and compared with the tensile deformation in order to see the effect of the deformation mode.

The new E', Y', and K' for the plane strain calculation are as follows:

$$E^{l} = \frac{E}{1-v^{2}}$$

$$Y^{l} = \frac{2Y}{\sqrt{3}}$$

$$K^{l} = \frac{2K}{\sqrt{3}}$$

In the calculations and simulations it was assumed that the n values that were obtained under prescribed pre-straining conditions during the uniaxial tensile tests do not change with the uniaxial and plane strain conditions.

The 60° V-shaped bending process was modeled using a commercially available ETA/Dynaform finite-element simulation program, as shown in **Figure 2**. In the model, the die and punch were considered as rigid bodies, and the blank was a deformable body. A Belytschko-TSAY shell element was used for the blank and rigid tools in order to improve the effectiveness of the nonlinear numerical computation.

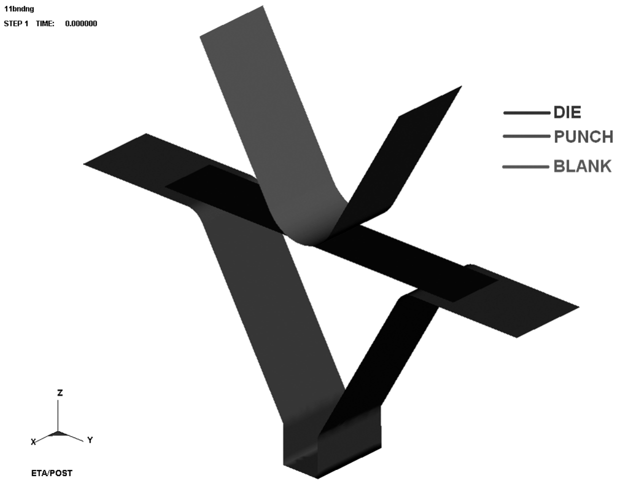

Figure 2: Finite element modeling of V bending process
Slika 2: Modeliranje V-upogibanja s končnimi elementi

Besides the element type, the number of elements can also affect the accuracy of the simulation results. In the study, 4012 elements were used with five integration points through the thickness of the deformable sheet. An adaptive mesh option was also used in order to reduce the errors during the calculation of the springback. In the adaptive mesh method the elements are subdivided into smaller elements during the analysis. This subdivision of the elements provides improved accuracy and in the study a two-times adaptivity was applied to the model.

The implicit and explicit solutions are two methods that are used for the springback simulations. In the simulation, the explicit loading and implicit unloading approaches were used to predict the springback characterization of the material. The implicit solution is realized by applying a reverse nodal force and an equivalent iteration. Due to the large deformations in the sheet-metal forming operations, the amount of springback is relatively large so the implicit solution is able to meet these kinds of convergence forming operations. When the accuracy of the stress field after the forming is poor, the convergence problem becomes more serious [26].

As a material model, the material Type 36 (MAT_3-PARAMETER_BARLAT) was used. This model was developed by Barlat and Lian [27] in 1989 for the modeling of anisotropic materials under plane stress-strain conditions. This material allows the use of Lankford parameters [28] for the definition of anisotropy. The criterion can be expressed as:

$$a|K_1 + K_2|^m + b|K_1 - K_2|^m + c|2K_2|^m = 2\sigma_e^m$$

where a, b and c are the material constants that depend on the anisotropy, K_1 and K_2 are the invariants of the stress tensor and m is the stress exponent that is

Table 3: Summary of material properties
Tabela 3: Povzetek lastnosti materiala

Pre-straining (%)	*Y*/MPa	*UTS*/MPa	*E*/MPa	*K*/MPa	*n*
0	118.56	296.80	47.17	492.2	0.310
1	125.66	296.80	57.46	516.3	0.323
3	174.62	297.75	58.61	512.6	0.328
5	204.89	296.53	61.34	497.4	0.305
7	225.81	306.30	65.55	482.8	0.297
9	245.85	308.56	74.72	455.1	0.263
11	259.18	300.94	81.24	449	0.260

calculated based on the crystallographic texture and is equal to 8 for FCC materials.

4 RESULTS AND DISCUSSION

In the experimental study, the pre-straining was applied to 5754-O Al-Mg alloy sheets at the prescribed values. The tensile load and extension data were converted to true stress vs. true strain data, which were obtained at different pre-straining values. The true stress vs. true strain diagrams were plotted, as seen in **Figure 3**. Each pre-straining path can be seen on the graph. The mechanical properties were measured for all pre-strained conditions at RT and a 0.0083 s^{-1} strain rate. The data was tabulated as seen in **Table 3**. As also seen in **Table 3**, the yield strength of the material was significantly increased from 118 MPa to 259 MPa. The change is twice that of the initial value. It is known that if the ratio of UTS/Y is high, a high springback is generally observed. Increased pre-straining creates a high elastic energy, which is the opposite to steels, is thought to be the major reason for a high springback observation. The change in UTS is not a large amount. It has an increasing tendency up to 9 % pre-straining, then it starts to decrease.

E is the one of the most important material properties that affects the springback of the materials. Some researchers have pointed out the effects of a variable Young's modulus on the formability of the materials [29–33]. The change in Young's modulus was plotted with respect to the pre-straining value, as shown in **Figure 4**. As seen from **Table 3**, the value was much lower than the known value. Normally, it is very difficult to determine the Young's modulus with a tensile test. The purpose of the study is to evaluate the springback variation with pre-straining relatively. For this reason it is not paid attention to the values. The same procedure was applied for each condition, which means it does not make any significant changes for the final outcome. The important point is that the tendency of the *E* based on pre-straining was determined. **Figure 4** indicates two linear curves and their equations. Although the Young's modulus of the material shows fluctuation with prescribed pre-straining levels, the trend of the values is increasing with plastic deformation.

Figures 5 and 6 show the variations of *K* and *n* with respect to the prescribed pre-straining.

Similar behaviors were observed in **Figures 5 and 6**. A minor increase was seen up to 3 % pre-straining and a minor decrease was seen after that. *K* has the highest value at 3 % pre-staining. As seen from the results, it is very complicated to clarify the changes. It may be

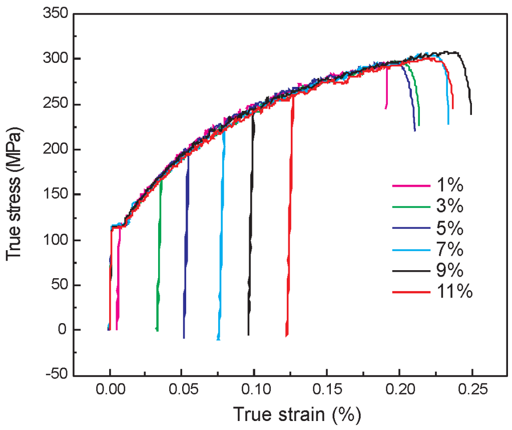

Figure 3: True stress vs. true strain curves for the 5754 Al-Mg alloy
Slika 3: Odvisnosti prava napetost – prava deformacija za zlitino AlMg 5754

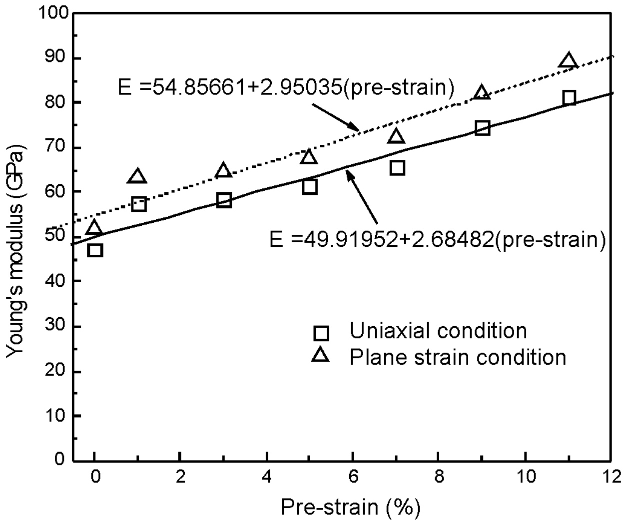

Figure 4: Variation of the Young's modulus vs. pre-straining
Slika 4: Sprememba Youngovega modula v odvisnosti od prednapetosti

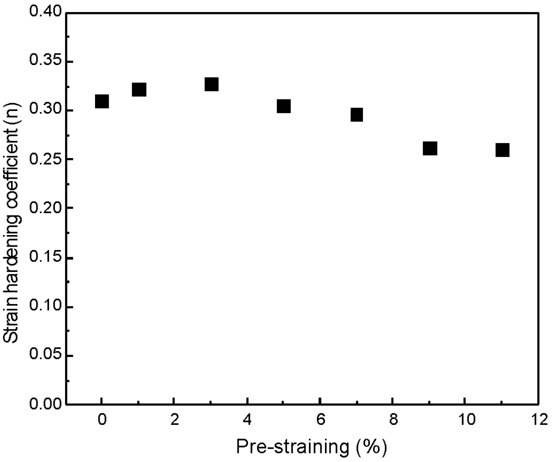

Figure 5: Variation of the strain hardening coefficient vs. pre-straining
Slika 5: Sprememba koeficienta deformacijske utrditve v odvisnosti od prenapetosti

explained with the changes in the microstructure, including the dislocation mechanism, porosities, inclusion, and deformation rate, etc.

Finally, the evaluation of the springback was investigated by experiment and finite-element methods. All the results were plotted on the same graph and displayed in **Figure 7**. The reference curve is the experimental curve. Any prediction that is close to this curve is considered to be a most accurate prediction.

The experimental data in **Figure 7** reveals that the springback is linearly increasing with increasing pre-straining. Pre-straining has no positive contribution on the springback compensation. It is related to the increasing elastic energy during the pre-straining.

Finite-element predictions were determined for the uniaxial and plane strain conditions. They were different from each other. The predictions at 1 % pre-straining were in good agreement with the experiments. But the predictions at no pre-straining and 5 % were higher than the experiments. At 3 % pre-straining, the FE prediction for the plane strain condition is almost the same as the experiment. At 7 % and over, the FE predictions for uniaxial were in accord with the experiment, except for the 11 % pre-straining. But the FE prediction for plane stress condition was lower than the experiments. In general, the FE predictions were close to the experimental results. The simulation results that were obtained for (1, 7 and 9) % pre-straining were close to the experimental results for the uniaxial strain condition. All these findings suggest that the pre-straining does not help the springback compensation.

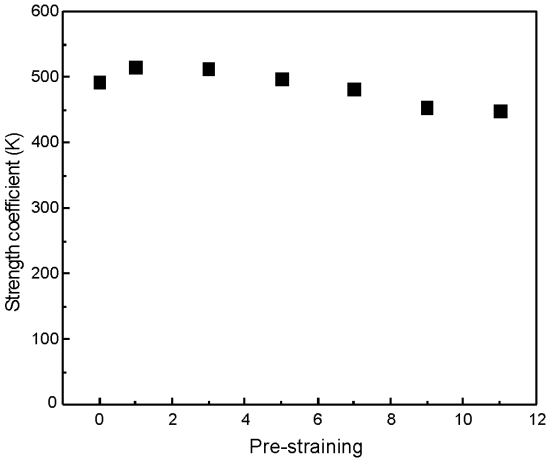

Figure 6: Variation of the strength coefficient vs. pre-straining
Slika 6: Sprememba koeficienta trdnosti v odvisnosti od prednapetosti

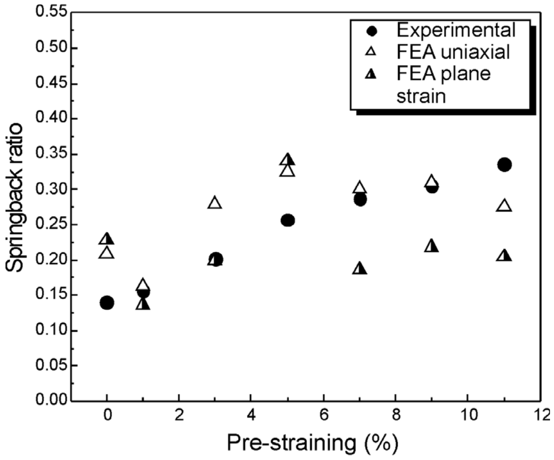

Figure 7: Variation of the springback with pre-straining
Slika 7: Sprememba povratne izravnave v odvisnosti od prednapetosti

5 CONCLUSION

In this study, the effect of pre-straining on springback was investigated for a 5754-O Al-Mg alloy, both experimentally and numerically. It was found that the springback was increased with increasing pre-straining. The finite-element predictions were in partially good agreement with the experimental data.

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