

A. DZIUBIŃSKA^{*,#}, A. GONTARZ^{*}, K. DZIEDZIC^{**}**QUALITATIVE RESEARCH OF AZ31 MAGNESIUM ALLOY AIRCRAFT BRACKETS PRODUCED BY A NEW FORGING METHOD**

The paper reports a selection of numerical and experimental results of a new closed-die forging method for producing AZ31 magnesium alloy aircraft brackets with one rib. The numerical modelling of the new forming process was performed by the finite element method. The distributions of stresses, strains, temperature and forces were examined. The numerical results confirmed that the forgings produced by the new forming method are correct. For this reason, the new forming process was verified experimentally. The experimental results showed good agreement with the numerical results. The produced forgings of AZ31 magnesium alloy aircraft brackets with one rib were then subjected to qualitative tests.

Keywords: forming, aircraft brackets, AZ31 magnesium alloy, three-slide forging press, FEM simulations, experiments

1. Introduction

Magnesium alloy brackets with one rib are widely used in the aircraft industry, mainly for aircraft control systems [1]. These parts are also made of other materials in the automotive, machine-building and building industries. At present, flat parts with ribs are mainly produced by casting and machining methods. However, given lower strength properties of casting products and substantial material losses in machining, new methods, including metal forming processes, for producing parts of this type are being developed. This paper reports the results of research on developing a new and effective metal forming method for producing flat parts with one rib by closed-die forging in a three-slide forging press (TSFP). This machine has three independently working movable slides (one vertical slide and two horizontal slides), which enables forming products with complex shapes. The proposed new metal forming-based production method enables producing brackets that have higher strength properties than parts of this type produced by currently used techniques. The results demonstrate that the new method can be applied to forge brackets with a high, thin-walled rib, something which cannot be done using conventional metal forming processes. The main objective of developing the new production technique was to invent a viable method for forming aircraft brackets made of light metal alloys.

2. Numerical analysis of the new forming process for producing brackets with one rib**2.1. Scope of the research**

The numerical modelling of the closed-die forging process for producing brackets with one rib in a three-slide forging press was performed using the Deform 3D simulation software that is based on the finite element method (FEM). The design of the forming process is schematically illustrated in Figure 1.

At the beginning, a cuboid-shaped billet is mounted in a closed pass of the lower die between the tools. Next, it undergoes upsetting by the side tools which approach each other with a translational motion at constant velocity. The moving side tools extrude the central part of the billet into the upper space of the die, which enables formation of a higher rib [2].

The numerical modelling was performed in a three-dimensional state of strain for the complete thermo-mechanical model. The cuboid-shaped starting material had a thickness t of 9.5 mm, a width w of 50 mm and a length l of 74 mm. It was modelled as a plastic-rigid object composed of 100 thousand tetragonal elements. In the modelling, we used the material model of AZ31 magnesium alloy determined in the studies [3–5]. The magnesium alloy billet was heated to a temperature of 410°C, while the temperature of the tools during the process was maintained constant at 250°C. As for other parameters applied in the modelling, the tool velocity v was set to 6 mm/s, as this value corresponded to the parameters of the TSFP; the friction factor m on the metal-tool contact surface was set to

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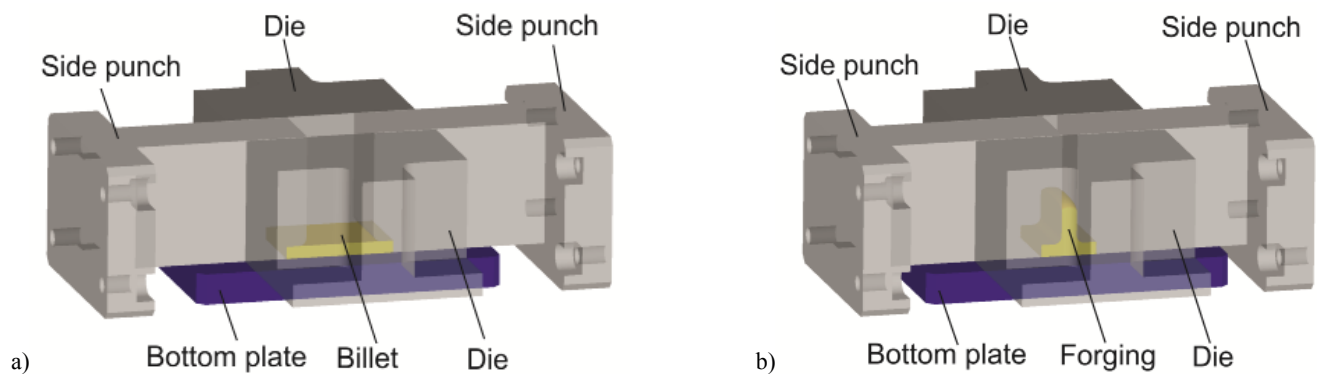


Fig. 1. Design of the closed-die forging process for producing brackets with one rib: a) start of the process, b) end of the process

0.9 without lubrication and to 0.25 when talrow with graphite were used as a lubricant (the values were applied in compliance with the results reported in the study [6,7]; the material-tool heat exchange coefficient was set to $4.5 \text{ kW/m}^2\text{K}$, while the heat exchange coefficient between the material and the environment was set to $0.03 \text{ kW/m}^2\text{K}$ [8].

The main objective of the numerical modeling was to verify the correctness of the designed forming method and to determine the effect of basic technological parameters on the forging process for producing a bracket with one rib using a three-slide forging press.

2.2. Numerical results

The numerical results confirm the suitability of the developed forming method for producing brackets with one rib. Based on the numerical results, we also determined the range of technological parameters that ensure process stability. The AZ31 alloy brackets with one rib produced by the developed forming method and the distributions of temperatures, strains and the C-L damage criterion are illustrated in Figure 2.

The changes in shape of the workpiece during the forming process are shown in Figure 3.

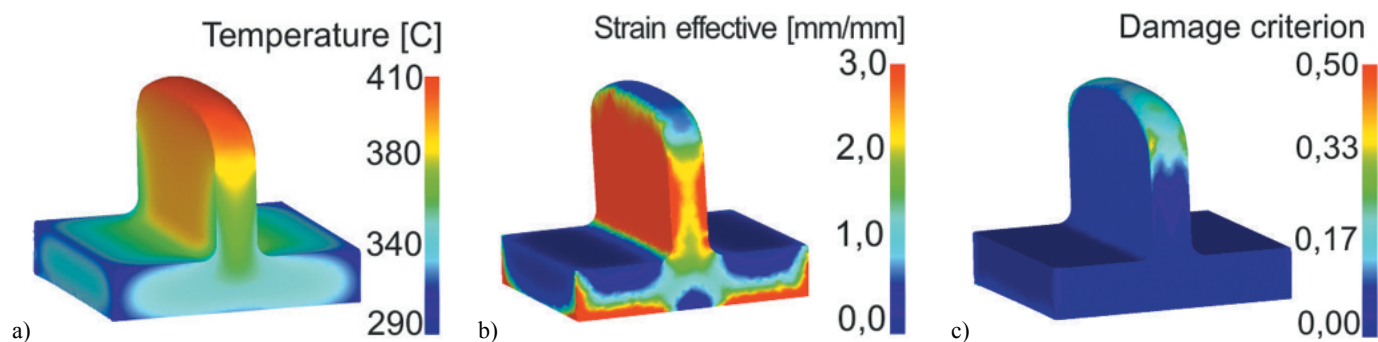


Fig. 2. Correctly shaped AZ31 alloy bracket with one rib and the distribution of: a) temperature, b) strain, c) damage criterion

The results demonstrate that the highest strains occur in the region of the rib (Fig. 2b). This results from the fact that the material in this region is intensively extruded upwards into an open space confined by the surface of the tools. The specific distribution of the temperature is connected with the nature of strains in the workpiece (Fig. 2a). The temperature of the forgings ranged from 290°C to 410°C .

Along with examining the distributions of strains and temperature, we investigated the probability of fracture in the product. To this end, we applied the Cockcroft-Latham (C-L) criterion from the library database of the Deform 3D software

[9]. Examples of the distributions of the Cockcroft-Latham criterion in the workpiece are given in Figure 2c. The results indicate that fracture is most likely to occur on the upper surface of the rib. During the entire process, this region is subjected to tensile stresses, which is undesired as it can cause loss of material cohesion.

The application of FEM enabled determination variations in forces during the process. The numerical results with respect to forces will be presented in a subsequent part of the present paper, in the discussion of experimental results. The numerical and experimental results will be compared in one diagram.

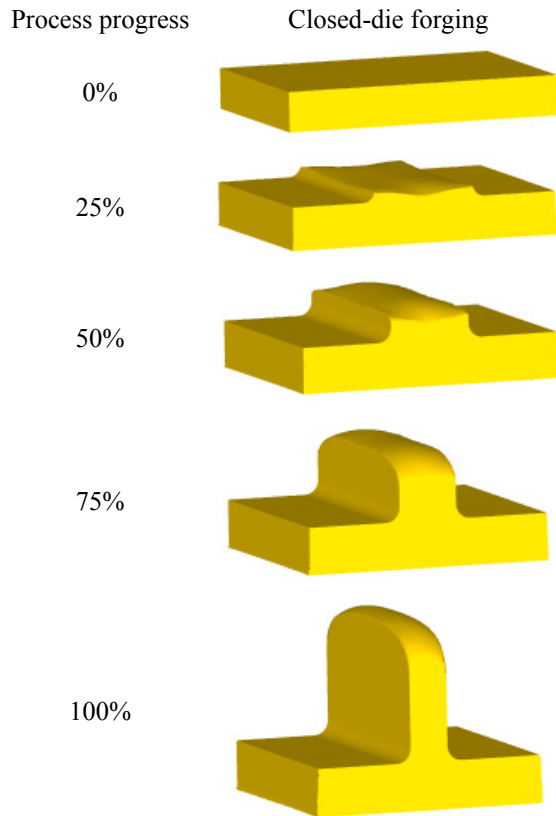


Fig. 3. Shape progression of a bracket with one rib produced by closed-die forging

3. Experimental verification of the numerical results

3.1. Experimental details

The suitability of the developed closed-die forging method for producing AZ31 alloy brackets and the accuracy of the numerical results were verified experimentally at the Lublin University of Technology using a prototype three-slide forging press (Fig. 4). The experiments were conducted using forging tools equipped with a heating system (Fig. 5) that were specially designed and constructed for forming brackets with one rib. In the experiment, we measured variations in forces. The experimental results were then compared with the FEM results.



Fig. 4. Three-slide forging press: 1 – mechanical part of the press, 2 – control cabinet, 3 – hydraulic power system

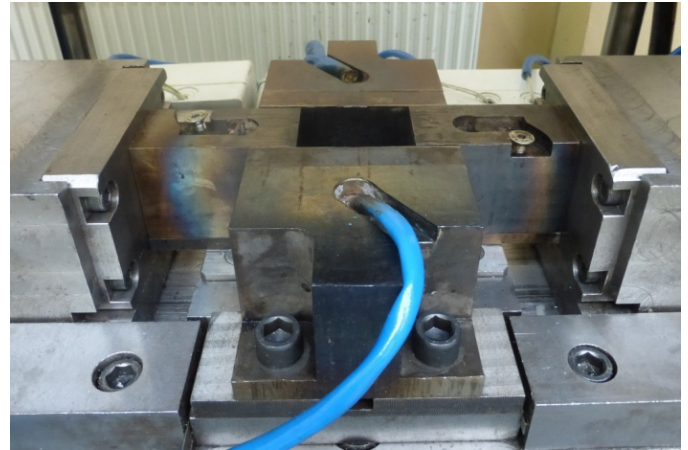


Fig. 5. Tools used in the investigation of the closed-die forging process for producing brackets with one rib

The experiment was performed using specimens made of AZ31 magnesium alloy for plastic working, the chemical composition of which is given in Table 1. This alloy is widely used in the aircraft industry. The starting material was in the form of $920 \times 920 \times 9.5$ mm plates that were produced by rolling and supplied in annealed state. The specimens cut out of the billet were $74 \times 50 \times 9.5$ mm. Some of the specimens used in the experiment are shown in Figure 6.

TABLE 1

Chemical composition of AZ31 magnesium alloy used in the experiment (wt%)

Al	Mn	Zn	Si	Cu	Ni	Si	Fe	Ca	Mg	Other
2,5÷3,5	0,2÷1	0,6÷1,4	0,1	0,05	0,005	0,1	0,005	0,04	93,5÷96,1	0,3



Fig. 6. Photograph of a selection of AZ31 alloy specimens used in the experiment

The experiment was performed in a three-slide forging press under the same conditions as in the numerical modelling.

3.2. Experimental results of the closed-die forging process

The experimental results confirm the suitability of the proposed closed-die forging method for producing AZ31 alloy brackets with one rib in a three-slide forging press.

Figure 7 shows correctly-shaped forgings produced in the experiment.

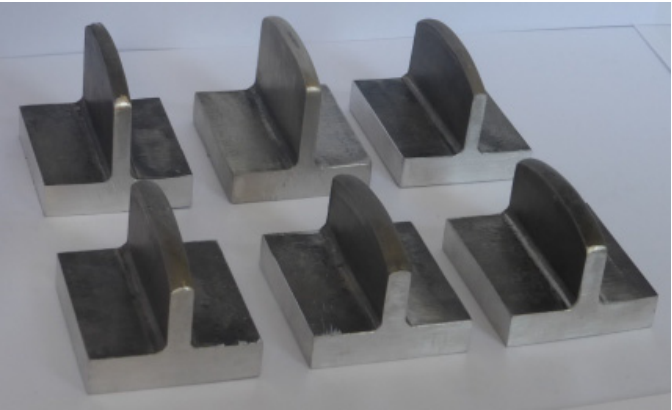


Fig. 7. AZ31 alloy brackets with one rib produced by closed-die forging in a three-slide forging press

The forgings produced in the FEM numerical modelling and experiment have a similar shape, as shown in Figure 8.

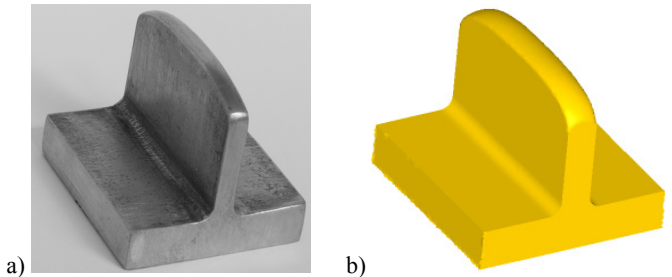


Fig. 8. Shape of the AZ31 alloy bracket with one rib: a) experiment, b) FEM analysis

The variations in forces measured in the investigated forging process for AZ31 alloy brackets with one rib are illustrated in Figure 9. The force distributions are typical of upsetting

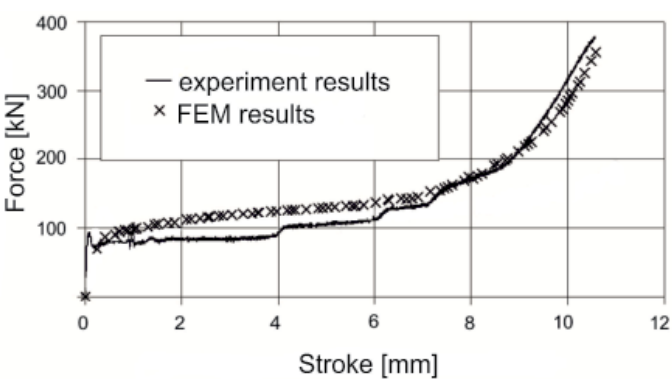


Fig. 9. Variations in forces in the closed-die forging process for producing an AZ31 alloy bracket with one rib

processes. The force increases with decreasing the rib thickness. The numerical and experimental results of the forces show good agreement in terms of quality and quantity, which proves that the force values applied in the numerical model of the process were correct.

4. Qualitative research of produced brackets

4.1. Scope of the research

The qualitative analysis of produced forgings of aircraft brackets involved microstructure examination and investigation of mechanical properties. We examined the microstructure of both magnesium alloy billet and forgings produced thereof by hot forging. As the starting material (billet), we used AZ31 magnesium alloy specimens cut out from a plate previously subjected to metal forming (rolling). The tests were performed on forgings of brackets with one rib formed by closed-die forging in a three-slide forging press according to the design schematically illustrated in Figure 1. To examine the microstructure of the test pieces, metallographic sections were made on the cross sections of the specimens cut out from the plate and produced forgings (Fig. 10). Mechanical properties of brackets with ribs were determined by performing static tensile test in compliance with the PN-EN 10002-1:2004 standard and by measuring hardness on the surface of the forging. Figure 11 illustrates examples of specimens used in the experiment. The following variables were determined: tensile strength R_m , yield strength R_e , elongation A_5 and hardness.

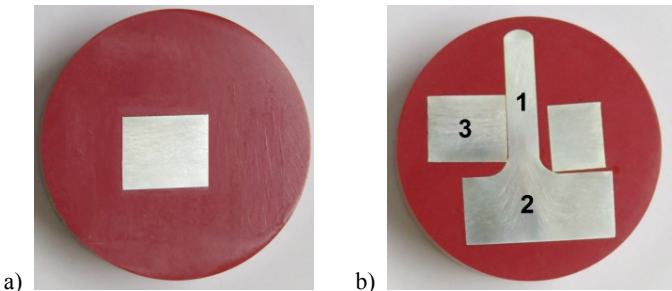


Fig. 10. Metallographic sections on the cross section of the specimens cut out from the billet (a) and produced forging (b)

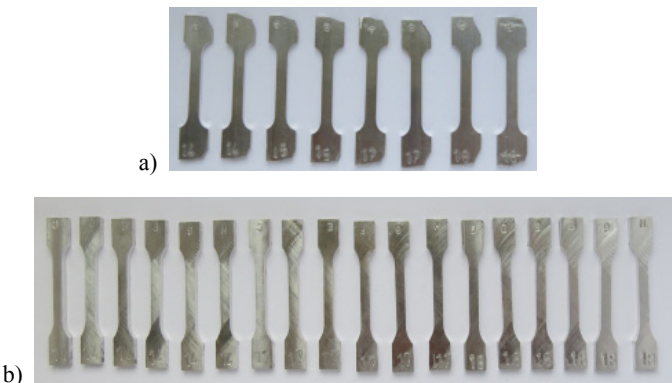


Fig. 11. Examples of specimens used for strength tests taken from: a) rib, b) forging base

4.2. Results of the qualitative analysis

The results demonstrate that the input material made of AZ31 alloy has a homogenous microstructure consisting of equiaxial grains, which is characteristic of annealed state (Fig. 12).

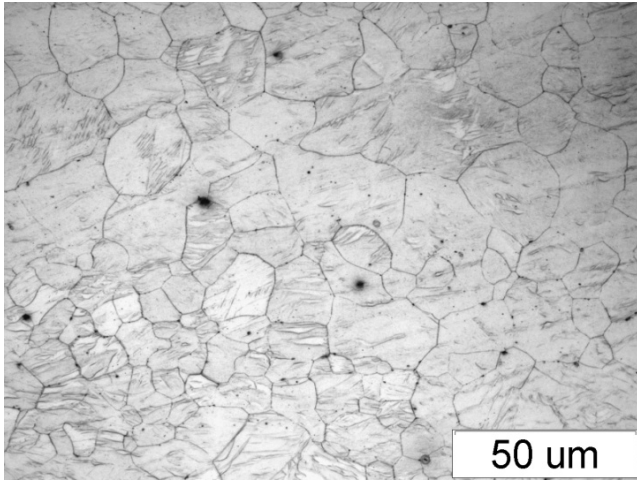


Fig. 12. Microstructure of initial material for research on alloy AZ31

The cross sections of the forgings reveal the presence of high strains in the regions of metal flow in the vicinity of the rib and in the base under the rib (points 1 and 2, Fig. 10b). In these regions, the material undergoes upsetting and is extruded upwards into an open space confined by the surface of the side tools. The microscopic examination reveals that regions 1 and 2 are characterized by the presence of very fine dynamically recrystallized grains resulting from high strains in these regions (Figs. 13a and 13b). In these regions, the process of recrystallization is advanced to the highest extent. What is more, the microstructure of ribs in region 1 reveals the presence of primary grains that are elongated towards strains, which demonstrates that the process of recrystallization in this region is not complete yet (Fig. 13a).

In the microstructure of forgings base in the area 3 a region, which underwent a small deformation was localized. In this area grains are slightly deformed, what is confirmed by their small elongation in comparison with initial state (Fig. 13c).

Visible darker places (spots) on the placed microstructures (Fig. 13) can mean appearance of micro hollows or impurity in initial material.

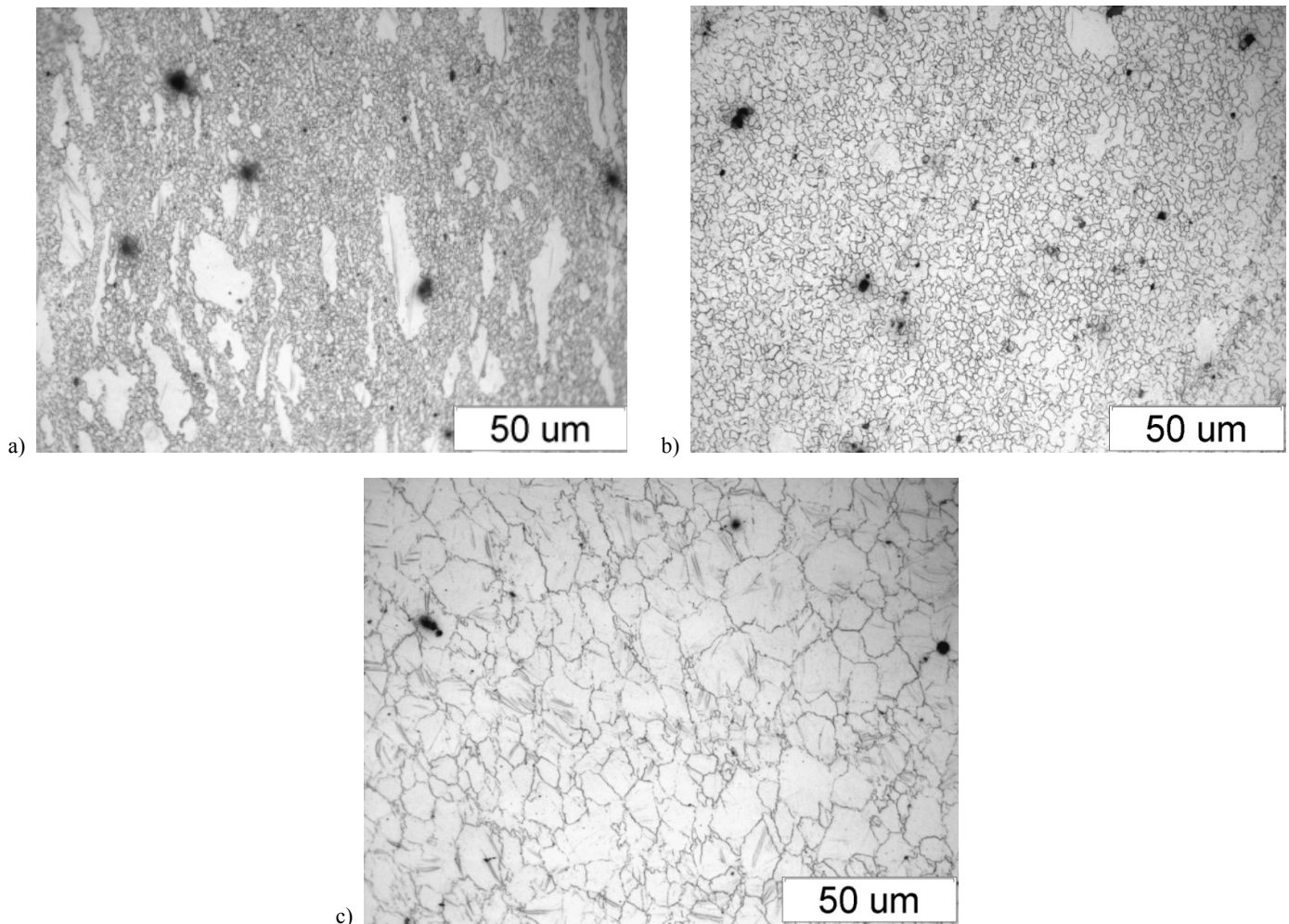


Fig. 13. Microstructure of bracket forging with one rib from AZ31 alloy read in the area: a) Region 1 – in the vicinity of the rib, b) Region 2 – in the base under the rib, c) Region 3 – forging base

Examples of test specimens after fracture are shown in Figure 14. The results of the investigated mechanical properties of the billet and produced forgings are given in Table 2.



Fig. 14. Test specimens after fracture

TABLE 2

Mechanical properties of the input material and produced AZ31 alloy brackets with ribs

Material used in research	Tensile strength R_m [MPa]	Yield strength R_e [MPa]	Elongation A_5 [%]	Hardness [HB]
Initial material	290	171	11	64
Region 1 – in the vicinity of the rib of forging	360	290	15	75
Region 2 – in the base under the rib of forging	333	272	14	73
Region 3 – forging base	312	221	12	68

The results indicate that the produced brackets do not have uniform mechanical properties. In the region of rib, the strength properties and hardness are significantly higher than in other regions of the semi-finished product and the billet. This results from the nature of the designed forming process, wherein the highest strain is assumed to occur in the central part of the workpiece in order to enable formation of a rib in the space between the side tools. The highest properties of the forgings are located in the region subjected to the highest strains, i.e. regions 1 and 2, where the elongation A_5 is between 11% and 15%. The high plasticity in these regions results from a fine-grained, predominantly recrystallized structure. In the region where the strains are the lowest (Region 3), the elongation A_5 equals 12%, i.e. it is equal to that of the starting material. Based on the results, it was found, that strength properties of the produced magnesium alloy brackets with ribs can be made uniform if an additional heat treatment is applied following the forging process.

5. Summary and conclusions

The paper presented a new method for producing AZ31 magnesium alloy aircraft brackets with one rib using a three-slide forging press. Based on the numerical and experimental results, it was found that the proposed closed-die forging process is suitable for producing correctly-shaped forgings of brackets.

The application of the proposed forming method for aircraft brackets ensures significant material savings and higher product properties when compared with the currently used technologies for producing these parts. In addition, the new method means reduced labour consumption, as brackets can be produced within one work cycle of the press, which results in increased efficiency of the process. As for other advantages, the new forming technology enables forming regularly rectangular high ribs and regularly shaped base, which means no material losses. The results of the qualitative analysis demonstrate that the structure and mechanical properties of AZ31 alloy brackets with one rib produced by the proposed method are not entirely uniform, which is typical of forging processes. However, if products are required to have entirely uniform structure and mechanical properties, it is recommended that the forming process be followed by an additional heat treatment, the type and parameters of which can be investigated in further research on the proposed new forming method.

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