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THERMO-MECHANICAL ANALYSIS OF A LEVER PREFORM FORMING FROM MAGNESIUM ALLOY AZ31

TERMOMECHANICZNA ANALIZA KSZTAŁTOWANIA PRZEDKUWKI DŹWIGNI ZE STOPU MAGNEZU AZ31

This paper presents the results of numerical analysis of metal forming process of a lever preform from magnesium alloy AZ31, which will be used as a semi-finished product in the forging process of a lever part. Presently, the lever forging is formed from semi-finished product in the form of a bar, which is connected with large material losses. Numerical simulations were made for two different metal forming methods: forging longitudinal rolling and cross-wedge rolling. Calculations were conducted basing on finite element method (FEM), applying commercial software DEFORM-3D. Geometrical models used in calculations were discussed. Simulations, made in conditions of three dimensional state of strain, allowed for determining distributions of strain intensity, temperature, cracking criterion, and mainly for determining the possibility of a lever preform manufacturing on the basis of rolling processes. Considering the obtained results of numerical simulations, the design of tools for semi-finished products rolling was worked out; these semi-finished products will be used for experimental verification of the lever preforms forming.

Keywords: cross-wedge rolling, longitudinal forging process, preform, FEM, magnesium alloy AZ31

W artykule przedstawiono wyniki analizy numerycznej procesu kształtowania plastycznego przedkuwki dźwigni ze stopu magnezu AZ31, która posłuży jako półfabrykat w procesie kucia odkuwki dźwigni. Obecnie odkuwkę dźwigni kształtuje się z półfabrykatu w kształcie pręta, co związane jest z dużymi stratami materiałowymi. Symulacje numeryczne wykonano dla dwóch różnych metod kształtowania plastycznego: kuźniczego walcowania wzdłużnego oraz walcowania poprzeczno-klinowego. Obliczenia przeprowadzono w oparciu o metodę elementów skończonych (MES), wykorzystując komercyjny pakiet oprogramowania DEFORM-3D. Omówiono modele geometryczne zastosowane w obliczeniach. Symulacje przeprowadzone w warunkach przestrzennego stanu odkształcenia umożliwiły wyznaczenie rozkładów intensywności odkształcenia, temperatury, kryterium pękania, a przede wszystkim określenie możliwości wytwarzania przedkuwki dźwigni w oparciu o procesy walcownicze. W oparciu o uzyskane wyniki symulacji numerycznych opracowano konstrukcję narzędzi do walcowania półfabrykatów, które posłużą do weryfikacji doświadczalnej kształtowania przedkuwki dźwigni.

1. Introduction

The aim to lower material consumption and construction weight at the improvement of exploitation parameters at the same time is a widely spread tendency, observed in the world industry. It is well visible in the case of elements applied in automotive and aviation industry, where lowering of vehicles and flying machines weight allows for increasing their technical possibilities (power, speed, capacity, maneuverability, etc.) and lowering exploitation costs at the same time. One of the ways of construction mass lowering is the application of highly resistant materials, characterized by relatively small density. They include, for example, light metal alloys (aluminum, titanium and magnesium). These materials are characterized by favorable design parameters – high relation of resistance to specific gravity, which is considerably larger than for steel [1, 2]. However, apart from numerous advantages metals alloys (especially magnesium and titanium) are rarely applied. This results from a high price of these materials and large difficulties during their forming and machining. Hence, an important issue becomes the application of manufacturing techniques which will allow for reduction of materials and energy consumption. One of such methods, which, apart from reduction of material consumption, allows for increase of elements resistance properties is metal forming technology.

Within the scope of conducted research-implementation works of metal forming of light metals alloys ap-

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plied in aviation constructions, die forging process of a lever forging from magnesium alloy AZ31 was worked out at Lublin University of Technology (Fig. 1) [3]. This type of element has been manufactured so far from aluminum alloys in machining processes. However, after the conducted analysis of working conditions and state of lever load, works were conducted which aimed at changing of forming technology (into metal forming processes) and material type into magnesium alloy (almost 40% lighter than aluminum alloy). The worked out forging process of lever forging (implemented in one of the domestic forging plants) is realized on hammer from a semi-finished product in the form of a bar and allows for reducing material consumption and labour of about 30%. The further savings can be searched in limiting of technological allowance (flash) due to more optimal material usage. In the result, die forging process of the lever forging on the press from a semi-finished product initially formed – rolled perform was worked out. In this way the number of forging operations was lowered and material consumption was reduced of over 65% in comparison with machining.

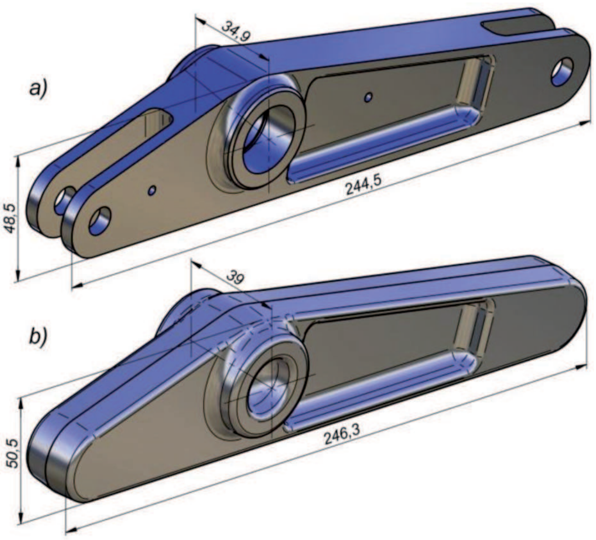

Fig. 1. Shape and dimensions of a lever-a and of forming-b made from magnesium alloy AZ31

Such a worked out technology was numerically analyzed, simulating the preform forming process, and next, basing on determined semi-finished product shape, the part forging process was modeled. The process of the lever preform manufacturing was analyzed for two forming variants: cross-wedge rolling and forging longitudinal rolling. The obtained results of numerical research works were used during designing of tools for the lever preform rolling. The designed tools will be used for experimental verification of the forming process of the lever preform from magnesium alloy of AZ31 type.

2. Forming processes of lever preform

Die forging processes of longitudinal forgings on presses require the application of specially formed billets-preform. The best economical- technical results of the forging process, that is high efficiency and quality of products and the smallest material consumption, are achieved when preforms have the shape close to the forging outline in the parting plane, and particular sections of the semi-finished part are equal the sum of appropriate sections of forging and flash [4]. In the result, properly designed preform allows for lowering of forming force in the forging process and increases the die impression durability [5].

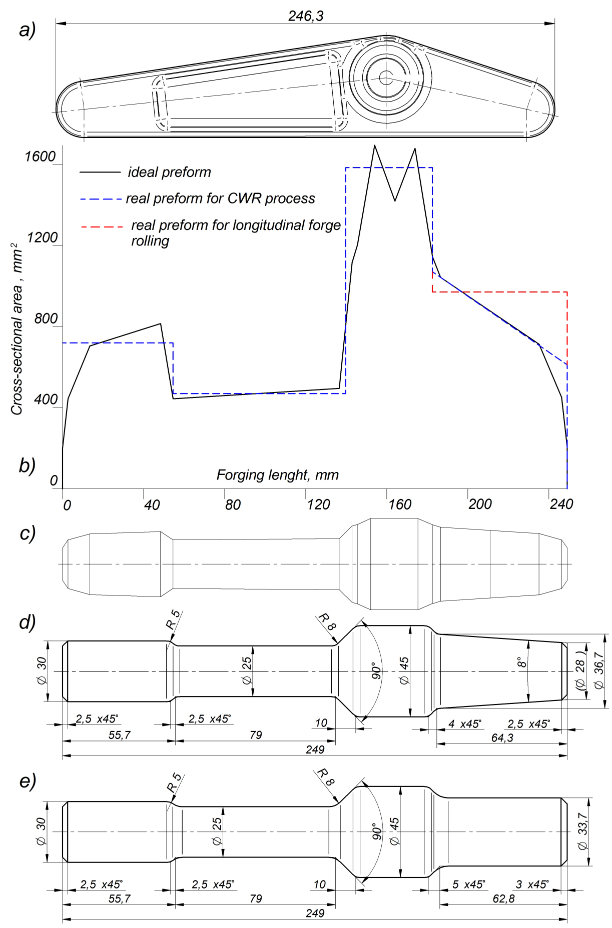

Fig. 2. Process of preform outline determining: a) shape of lever forging, b) diagram of ideal preform sections, c) shape of ideal preform, d) real preform manufactured in CWR process, e) real preform manufactured in longitudinal forge rolling

Basing on the lever forming figure, diagram was made presenting ideal and real preform (Fig. 2), which allowed for working out of shape and dimensions of preforms formed in the processes: CWR (Fig. 2d) and longitudinal forge rolling (Fig. 2e). Both of the designed preforms have similar shape and volume and the main difference is connected with the shape of the external pivot. For the semi-finished product rolled in the CWR process the pivot has a conical shape, close to the ideal preform outline (Fig. 2c). However, in the preform rolled longitudinally simplification was used, instead of conical pivot a cylindrical one was used. This allowed for simplification of the preform manufacturing, eliminating the necessity of designing of impressions with changeable cross section on tools circumference.

Basing on determined preforms shape tools were worked out allowing for semi-finished products forming in the CWR processes and longitudinal forge rolling.

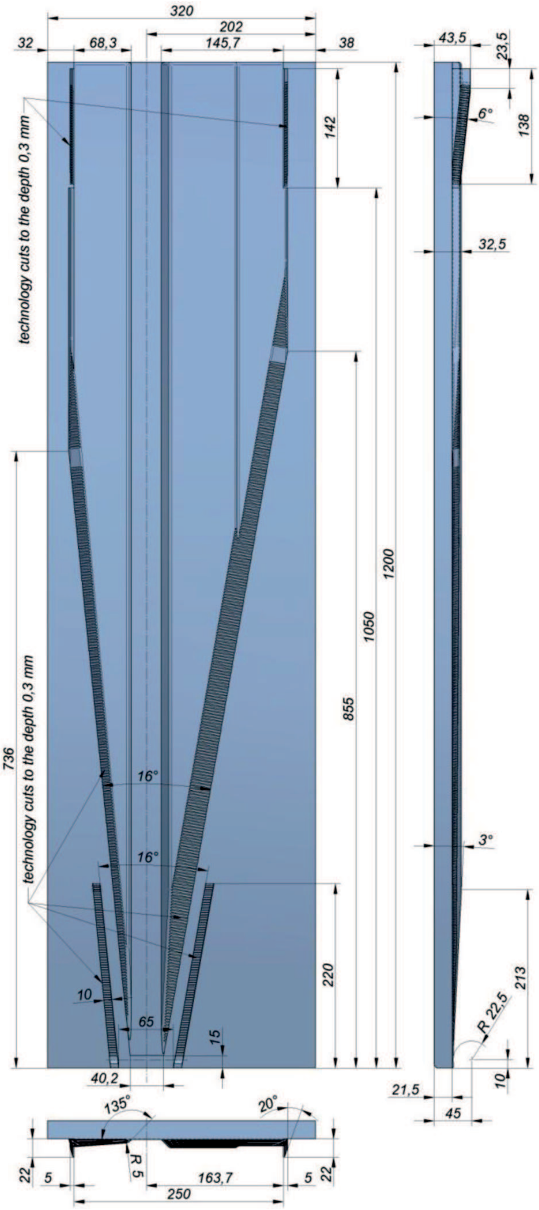

Fig. 3. Flat-wedge tool segment for CWR of lever preform

Figure 3 presents the shape of a flat-wedge tool segment which was designed for the cross-wedge rolling process of lever preform. The semi-finished product is formed in one passage between two plates,which have wedge protrusions on their surfaces and move in the opposite directions.

The tool working surface consists of four basic areas: initial (cutting), forming, sizing and splitting. The aim of initial area is forming on the whole circumference of the billet two ring-shaped grooves of conical side surfaces. In the forming area, the section reduction is developed on the whole length of the semi-finished product, due to which the further steps of preform are formed. The product shape unevenness, appearing during rolling, are removed in the sizing area. Yet, separation of external waste (allowance) from the formed semi-finished product takes place in the splitting area by means of cutting knives. In order to increase the stability of rolling, at the beginning of the process two guiding paths were placed in the cutting area. Additionally, on the forming surfaces (in the cutting and forming areas) and on the guiding paths technological notches were made.

The shape of impressions for longitudinal rolling of lever preform is shown in Fig. 4 Considering circular sections of the preform all steps, the system of rolling oval - circle was assumed. The rolling of particular pivots was conducted at the following reductions of cross section R_p (where $R_p = (1-(d/d_o)^2)100\%$, d – the pivot diameter after rolling in oval and circular impression, d_o – the diameter before rolling): $R_p = 55{,}5\%$; $R_p = 69\%$; $R_p = 43{,}5\%$. Obtaining the required shape and dimensions of external pivots of semi-finished product is realized in two impressions-oval and circular. Yet, the central part is rolled in four impressions in the system of oval – circle – oval – circle.

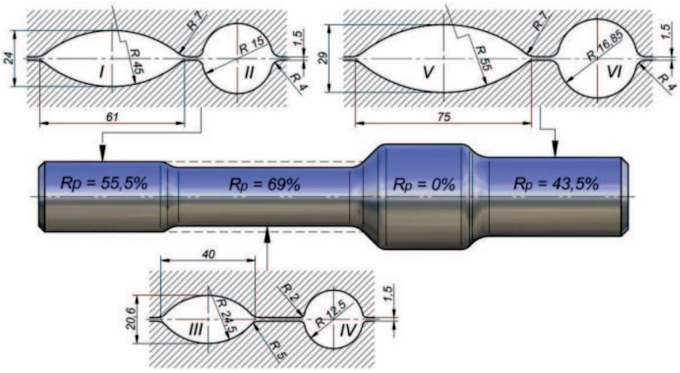

Fig. 4. Schema presenting forming impressions for particular preform steps

3. Lever preform forming in the cross-wedge rolling process

Cross-wedge rolling process belongs to rotational metal forming processes, in which products are formed by means of tools in the shape of wedges. These tools are mounted on rolling mills or on rolling mills planes.

Cross-wedge rolling processes are characterized by numerous advantages in comparison with traditional metal forming methods [6-8, 12]. The most important include: high efficiency, lower material losses and energy consumption, high resistance properties of products and relatively easy process automation. However, from economical point of view, the CWR technology, especially at the application of flat-wedge tools segments, is connected with considerably smaller costs connected with tools manufacturing. Hence, the CWR can be successfully applied in mass production (automotive industry) and at a smaller scale, which is characteristic for the aviation industry.

Estimation of correctness of the worked out technology was made numerically, simulating the CWR process of lever preform. Calculations were made by means of finite element method (FEM), using the commercial software DEFORM-3D. For the analysis needs, a geometrical model of the cross-wedge rolling process of a semi-finished product was worked out, which is shown in Fig. 5. This model consists of two wedge tools, upper – 1 and bottom – 2 and of billet – 3. A bar from magnesium AZ31 of diameter ∅ 44 and length l = 160 mm, modeled by means of hexahedral elements of the first type, was assumed as billet. The material model of alloy AZ31 was determined experimentally in plastometric experiments [9]. Billet initial temperature was 400°C, tools temperature during rolling became constant and equal 100°C. Flat-wedge tools segments, during the process, moved in the opposite directions with constant velocity v = 0,2 mm/s. Moreover, in calculations was assumed model of constant friction, defined by friction factor of limiting value m = 1 at tool – billet surface of contact, which resulted from lack of lubrication of tools during the process. Yet, heat exchange coefficient between material and tools was assumed at the level 8 kW/m^{2}K, between billet and the environment 0.2 kW/m^{2}K.

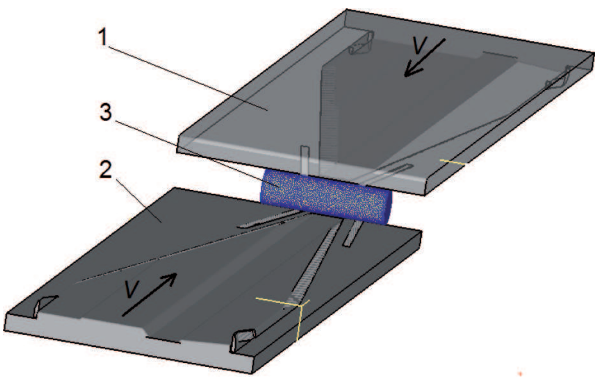

Fig. 5. Geometrical model of CWR process of lever preform

In the result of conducted numerical simulations metal flow kinematics in the process was analyzed, shown in Fig. 6. At the beginning of the process, wedge

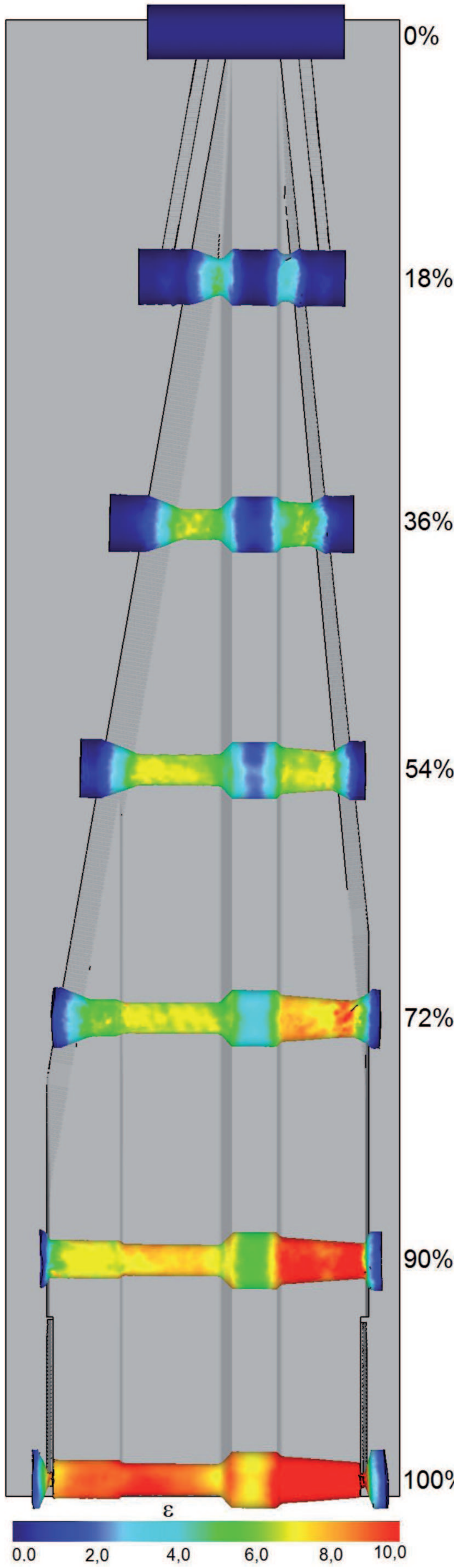

Fig. 6. Lever preform shape progression determined numerically during CWR simulation with marked strain intensity distribution

protrusions cut into the semi-finished product and put it into rotary motion. Two ring-shaped grooves are formed at billet circumference, which, at the further stages of the process, are widened by tools wedge side surfaces at the assumed rolling length. At the end of the process, external edges constituting technological allowance are cut from the formed preform. Determined numerically shape of the preform is characterized by large convergence with theoretical outline, worked out on the basis of the ideal preform diagram. Due to difficulties of numerical character, the process of allowance cutting has not been fully finished yet. In real process, realized in laboratory conditions, allowance will be completely cut off from the formed semi-finished product.

The next Figure 7 presents distributions of strain intensity, temperature and damage (according to Cockcroft-Latham criterion), which was determined during numerical simulations for the final stage of the CWR process. It can be seen that the strains (Fig. 7a) reach large values. The largest values of strains are localized in the area of external conical pivot, which can be explained by relatively large unnecessary deformations in this area, which are the result of material intensive flow in circumferential direction. The rest of the semi-finished product areas undergo smaller deformations, yet the material is worked plastically in the whole volume, apart from external areas which constitute allowance cut at the end of the process.

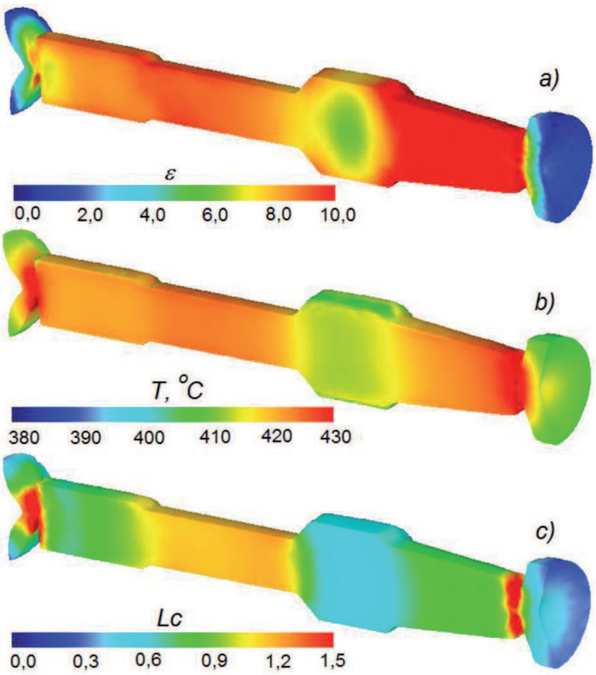

Fig. 7. Determined in CWR process simulation of lever preform distributions; a) strain intensity, b) temperature, c) damage criterion according to Cockcroft-Latham (at the end of rolling)

The temperature distribution (Fig. 7b) is strictly connected with the deformations character in the formed semi-finished product. A characteristic feature is relatively high and equal value of the temperature, both at the surface and in sections of the formed product. The temperature of the obtained preform oscillates within the scope of 410-430°C. This is especially important due to long time of the process (about 6s) and allows to assume that the material even at the end of the process will remain good plastic properties.

Such large values of temperature are connected with generating of large heat amounts during the metal plastic deformation. It is also crucial that the difference between maximal and minimal value of the temperature is relatively small (about 20°C), which is extremely important in metal forming processes of light metals alloys. During numerical calculations CWR of lever preform, the possibility of cracks appearance was forecast on the basis of damage criterion according to Cockcroft-Latham (Fig. 7c). The obtained calculations results show that in the analyzed CWR process the danger of metal cracking appears. The area most exposed to cracking is internal step of the preform, in which the largest cross section reduction takes place. The values of Cockcroft-Latham integral in this area exceeds permissible values (about 0.7 for light metals alloys), which probably leads to the semi-finished product cracking.

4. Lever preform forming in longitudinal forge rolling process

Using numerical techniques the correctness of considered design-technological assumptions of the preform longitudinal rolling process was verified. As it was in the CWR process, calculations were made basing on finite element method, with the application of software DEFORM-3D. For calculations needs six geometrical models of the preform rolling process were built (for six roll passes). The models differed between themselves only in type of applied tools (shape and length of impressions), depending on which step and its outline was rolled, and in type of billet, which, for next roll passes, were semi-finished products rolled in the former impressions. One of the geometrical model (rolling in the first roll pass in oval impression) used in calculations is shown in Fig. 8. This model consists of billet, two tools-segments with made on their circumference impressions of oval outline, and guiding ring. Billet for the first roll pass was the bar of diameter ∅ 45 mm and length l = 132 mm, made from magnesium alloy AZ31, modeled by means of hexahedral elements. Material model of alloy AZ31 was determined experimentally in plastometric research works [9-11]. Billet initial temperature was

420°C, yet, tools temperature during rolling was constant and equal 150°C. Upper and bottom segments rotated with constant velocity n = 60 rot/min in the opposite directions, according to markings presented in Fig. 8.

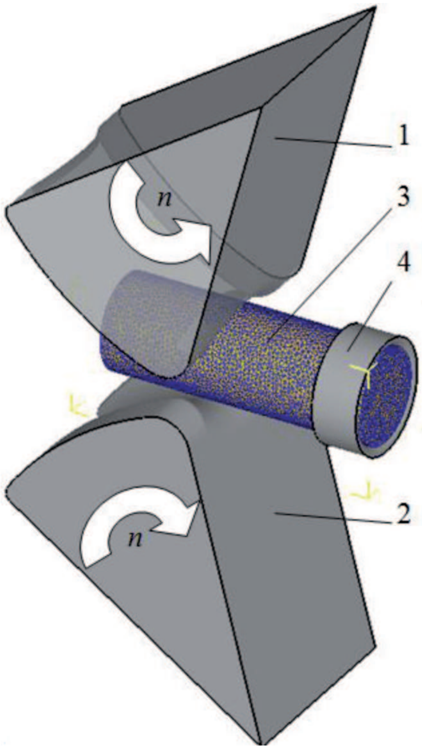

Fig. 8. Geometrical model of longitudinal forge rolling process of lever preform in the first roll pass in oval impression: 1,2-tools segments, 3-semi-finished product, 4-guiding ring

On the tool – semi-finished product surface of contact constant friction factor was assumed m = 0.8. Additionally, heat exchange coefficient between billet and tools was assumed at the level 8 kW/m^{2}K, between billet and the environment 0.2 kW/m^{2}K.

In the result of conducted numerical simulations preform shapes after each roll pass were determined. The further stages of the preform rolling process are presented in Fig. 9. The obtained calculations results confirm the rightness of assumed technological and design assumptions during tools designing. The preform determined shape is characterized by large convergence with the shape worked out at the designing stage. Phenomena which could disturb the rolling process course were not observed.

The obtained preform is free from overlapping, bendings, flash which appears during the impression overfilling. Also the impression filling is satisfactory. Hence, it can be stated that the designed impressions will allow, with a large probability, for forming of preforms of assumed parameters.

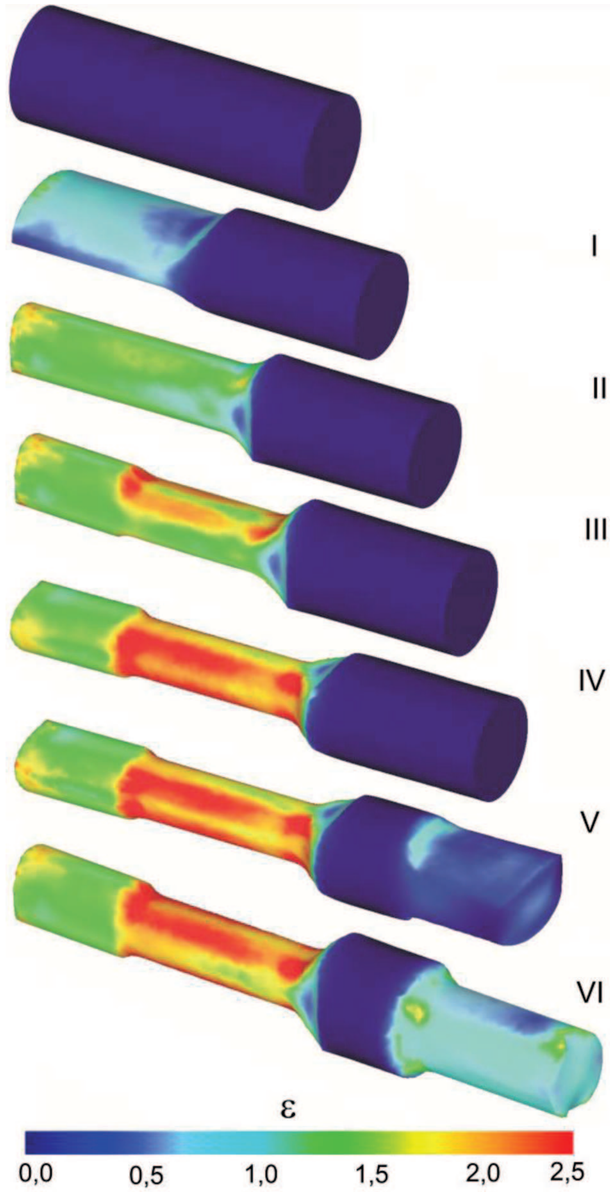

Fig. 9. Lever preform progression of shape determined numerically after each roll pass during simulation of longitudinal rolling process with marked distribution of strain intensity

The next Figure 10 shows determined numerically distributions of strain intensity, temperature and cracking (according to Cockcroft-Latham) for rolled preform after the sixth roll pass. It can be seen that in the areas of formed steps the material is worked plastically in the whole volume.However, the observed deformations are not homogeneous. The cause of such a distribution is various values of reduction ratio, which depended on the degree of the semi-finished product cross section reduction. The largest values of strains are localized in the areas of the preform smallest diameter (formed in four roll passes). Yet, the preform central step of the largest diameter during rolling does not undergo deformation (its diameter equals billet initial diameter). The distribution of temperature (Fig. 10b) is connected with deformations present during rolling. It can be observed that the temperature remains at relatively large level (although the rolling takes place in six roll passes), within the scope of 400°C – 430°C.

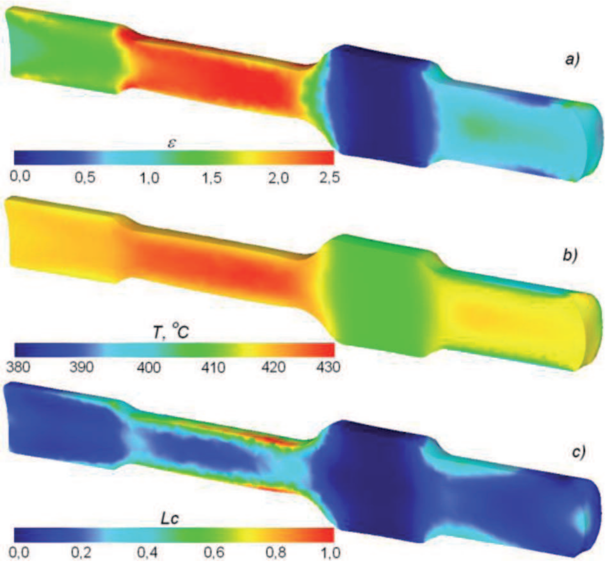

Fig. 10. Determined numerically during simulations of longitudinal rolling process of lever preform distributions; a) strain intensity, b) temperature, c) damage criterion according to Cockcroft-Latham (after the last roll pass)

The noticed decrease of temperature is of surface character and is caused by material contact with cooler tools. In the areas of the largest reduction of cross section, the increase of temperature above the initial value can be observed, which can be explained by change of plastic deformation work into heat. The values of Cockcroft-Latham integral (Fig. 10c) are relatively smaller in comparison with values noticed in the CWR process. Similarly as in the previous process, the largest integral values concentrate in the area of the step of the smallest diameter, hence, in the area of the largest plastic deformations. The range of Cockcroft-Latham criterion maximal values is small. The largest values are localized in the surface areas, which allows to presume that cracking should not take place in the formed preform. In the other areas the values of Cockcroft-Latham criterion are relatively small.

5. Simulation of lever forming process from semi-finished product in the shape of preform

The obtained results of numerical simulations of lever preform forming for both rolling processes confirmed the rightness of technological assumptions. In the CWR process as well as in longitudinal rolling it is possible to get preforms of assumed geometrical parameters. However, considering the possibility of internal cracks presence in the preform formed in the CWR process, only the longitudinal rolling process will be verified experimentally. Hence, in order to finally confirm the rightness of the worked out preform shape, simulation of lever forging from the semi-finished product formed in the longitudinal rolling process was made. As it was in the processes realized earlier, calculations were made by means of finite element method with the application of software DEFORM-3D. The process was realized in two impressions (bending and die), with preserving the same edge conditions. In the first impression bending of the preform takes place, next the bended preform is transferred into the second impression-die impression-where finished lever forging part. The billet temperature at the beginning of the process was assumed $T = 420°C$. Yet, tools temperature became constant and equal $T = 150°C$. Other parameters considered in the analysis include: friction factor between tools and billet $m = 0.3$, heat exchange coefficient between material and tools 10 kW/m^{2}K. Determined numerically shape of the lever forging from magnesium alloy AZ31 from optimal longitudinally rolled preform is shown in Fig. 11. A characteristic feature is large convergence with the theoretical outline (Fig. 1b). Faults in the form of overlapping or impression infilling were not observed and flash was relatively small.

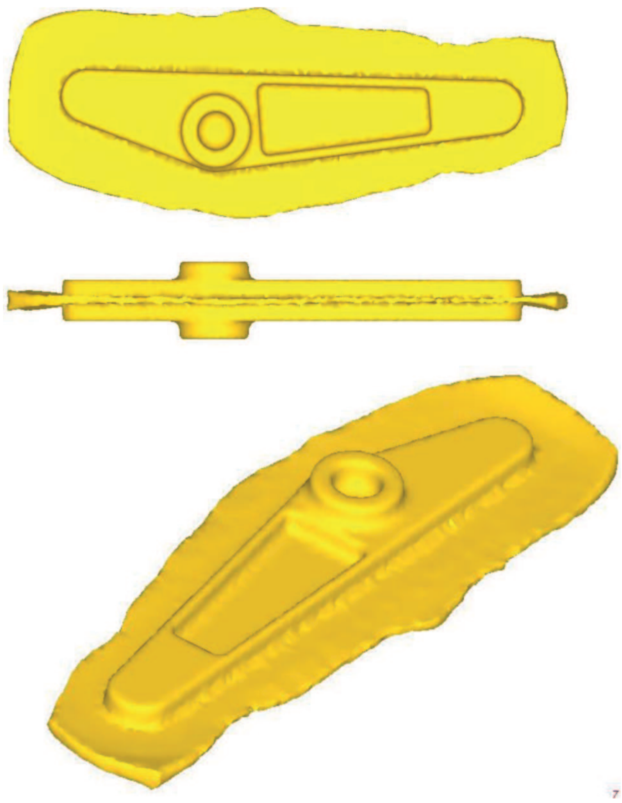

Fig. 11. Determined numerically shape of lever forging from magnesium alloy AZ31, forged from preform manufactured in longitudinal forge rolling process

6. Summary

Within the scope of conducted research works, two technological processes of lever preform from magnesium alloy AZ31 were worked out, which were later numerically simulated. The first of this process is based on forming of semi-finished product in the cross-wedge rolling process in one pass. However, the second way of lever preform forming longitudinal forge rolling processes are used in six passes (impressions).

The obtained results of numerical analysis for both cases of preforms manufacturing confirmed the rightness of technological assumptions. In the CWR process and in longitudinal rolling as well it is possible to obtain semi-finished products of assumed geometrical parameters, guaranteeing optimal course of the forging process and high quality of forgings. However, in the CWR of preforms, there exists the danger of internal cracks presence during rolling, which disqualifies the semi-finished product as billet for lever part forging. Hence, although the CWR processes have numerous advantages, it was finally assumed that the lever preform will be formed in longitudinal forge rolling.

Basing on numerical simulations results, tools segments construction was worked out for longitudinal rolling of the lever preform. These segments will be used for experimental verification of the semi-finished product forming, which is planned to be conducted at Lublin University of Technology.

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