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T. BULZAK*, J. TOMCZAK*, Z. PATER*

THEORETICAL AND EXPERIMENTAL RESEARCH ON FORGE ROLLING PROCESS OF PREFORMS FROM MAGNESIUM ALLOY AZ31

BADANIA TEORETYCZNE I DOŚWIADCZALNE PROCESU WALCOWANIA KUŹNICZEGO PRZEDKUWEK ZE STOPU MAGNEZU AZ31

This paper presents results of theoretical and experimental research works on the rolling process of a lever preform from magnesium alloy AZ31. The forge rolling process of the preform was realized in the system oval-circle. The paper focuses mainly on kinematics of material flow and proper filling of rolling impressions. Research aiming at determining possibilities of faults presence in the form of cracks, overlapping and improper filling of the impressions were also conducted. During experimental research it was noticed that material cracking took place at the moment of material clamping by rolls. Moreover, it was stated that this cracking may be the result of large shearing stresses action, appearing at the moment of material clamping by rolls. Shearing stresses values were determined on the basis of numerical calculations. Next, tools were modified in order to lower tangential stresses at the moment of material clamping by rolls. The further experimental research with modified tools confirmed the rightness of the assumptions. On the basis of conducted works on the forge rolling process of magnesium alloy AZ31, it was stated that when material is clamped by tools tangential stresses intensification should not take place.
Keywords: forge rolling, rolled forgings, magnesium alloys, cracking, FEM, experiment

Artykuł przedstawia wyniki badań teoretyczno – doświadczalnych procesu walcowania przedkuwki dźwigni ze stopu magnezu AZ31. Proces walcowania kuźniczego przedkuwki realizowano w systemie owal – koło. W opracowaniu skupiono się przede wszystkim na kinematyce płynięcia materiału oraz poprawności wypełnienia wykrojów walcowniczych. Prowadzono również badania pod kątem określenia możliwości powstawania wad w postaci pęknięć, zawalcowań oraz niewłaściwego wypełnienia wykrojów. Badania doświadczalne wykazały, że w momencie chwytu materiału przez walce, w wyniku działania zbyt dużych naprężeń ściskających, występuje jego pękanie. Stąd w pracy na podstawie obliczeń numerycznych wyznaczono wartości naprężeń ścinających. W oparciu o uzyskane wyniki dokonano modyfikacji narzędzi. Badania doświadczalne z wykorzystaniem zmodyfikowanych narzędzi potwierdziły poprawność przyjętych założeń. Na podstawie przeprowadzonych prac nad procesem walcowania kuźniczego stopu magnezu AZ31 stwierdzono, że w momencie chwytu materiału przez narzędzia nie powinno dochodzić do intensyfikacji naprężeń stycznych.

1. Introduction

Aspirations of aircraft and automotive industries to lower construction weight are a widely spread tendency observed around the world. Reduction of weight of aircrafts, cars and other machines providesbenefits in the form of: reduction of fuel consumption, increase of dynamics and improvement of exploitation conditions. In the era of intensive development of light materials, the basic way of weight reduction is application in the place of steel high resistance materials, characterized by considerably lower density. These materials include aluminum, titanium and magnesium alloys. They are characterized by favourable designing parameter-high resistance to specific gravity ratio, which is considerably larger than for steel. Limiting phenomena in application of this material are connected mainly with high price and difficulties at machining.

Recently it can be observed the increase of magnesium alloys interest, due to possibility of their wide scope of application in different industrial branches. Thanks to magnesium usage, which density equals 1.74 g/cm^3, the product weight decrease of 30% is achieved [1]. Magnesium alloys are formed in casting, machining and metal forming processes. Because of difficulties appearing during metal forming of magnesium alloys, majority of machine parts made from this group of materials is formed by means of casting [2]. The disadvantage of magnesium alloys is small formability in the environmental temperatures, which results from the type of crystallographic lattice. Magnesium crystallize in hexagonal dense network A3 of parameters a = 0.321 nm and c = 0.521 nm [3, 4]. The scope of temperatures in which magnesium can easily undergo metal forming is 350-450°C [5, 6].

Metal forming of magnesium alloys is realized mainly in processes of forging, extrusion and rolling of flat products.

* LUBLIN UNIVERSITY OF TECHNOLOGY, MECHANICAL DEPARTMENT, 36 NADBYSTRZYCKA, 20-618 LUBLIN, POLAND

For realization of die forging processes, especially of elongated forgings, billet in the form of initially formed preforms is often used. One of the most effective preforms manufacturing processes is longitudinal forge rolling.

This paper presents results of tests of preforms from magnesium alloy AZ31 forge rolling. The research works were realized in real conditions, employing a laboratory frame-console rolling mill [8]. For the rolling process optimization, results of FEM numerical modelling were applied.

2. Research method

The main aim of research was rolling in real conditions of preform from magnesium alloy AZ31, which shape and dimensions are given in Fig. 1.

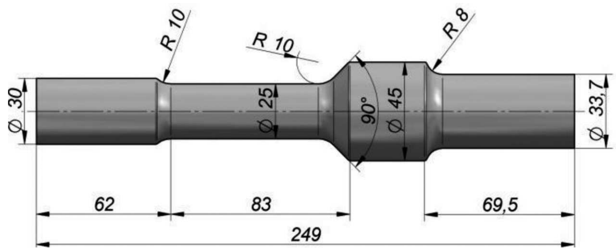
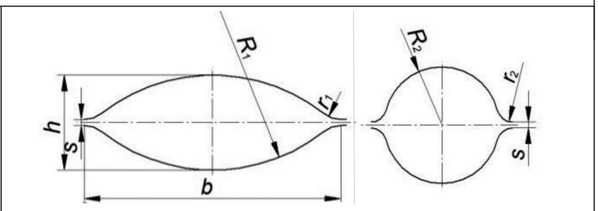


Fig. 1. Shape and dimensions of the lever preform [9]

Dimensions of designed impressions for subsequent roll passes are presented in Table 1. Sizing of working impressions, placed on rolling segments, was worked out according to methodology described in the paper [10]. However, it should be noticed that all known sizing methods of impressions made on forging segments were worked out for the steel rolling needs. Moreover, there is not any method considering all factors influencing the rolling course. This causes that each newly worked out technological process of forge rolling requires experimental verification in order to correct eventual faults.

TABLE 1

Dimensions and size of rolling segments



Pass No.	h	b	R_1	r_1	s	R_2	r_2
	mm						
1	24	62	45	7	1.5	15	4
2	29	76	55	7	1.5	16.85	4
3	20	42	24	5	1.5	12.5	2

Semi-finished products for the lever preform forging were bars from magnesium alloy AZ31 of dimensions Ø45×132 mm. The diameter of billet material was chosen in such a way that the step of the preform with the largest diameter did not undergo rolling. This allowed for reduction of number of treatments and values of maximal reduction ratio at particular steps of the preform. Rolling tests for billet with diameter Ø42 mm were also made. The application of billet with such a diameter resulted in change of the rolled preform diameters. The usage of billet with different diameter was only to demonstrate reduction ratio value influence on flash presence in the place of rolling segments splitting. The material was heated to the temperature 420°C before rolling. Rolling tests were realized with initial heating oftools to the temperature about 150°C by means of a gas burner. Tools temperature value was estimated using indication of thermo-electric-thermocouple indicator. During the process, tools were lubricated with mixture of tallow and graphite. Research works were conducted in the following sequence: 1 – experimental tests of preform rolling from billet Ø45 mm, 2 – numerical modelling, 3 – tools optimization and repeated experimental research, 4 – rolling tests from billet with diameter Ø42 mm.

Numerical modelling based on finite element method was made applying the software DEFORM 3D. For the description of rheology of magnesium alloy AZ31 flow curves presented in paper [7] were used. Boundary conditions describing the numerical model were assumed according to the real ones. Discretization of the formed product was made employing tetragonal elements in number of 45000. The contact between billet and rigid tools was described by friction factor m = 0.3 [11]. For the description of heat exchange between billet and tools, coefficient of heat exchange equal 24 kW/m^{2}K was assumed, yet, between billet and environment 0.2 kW/m^{2}K. Rotary velocity of rolls was n = 28.1 rot/min. The schema of geometrical model used during modelling is presented in Fig. 2.

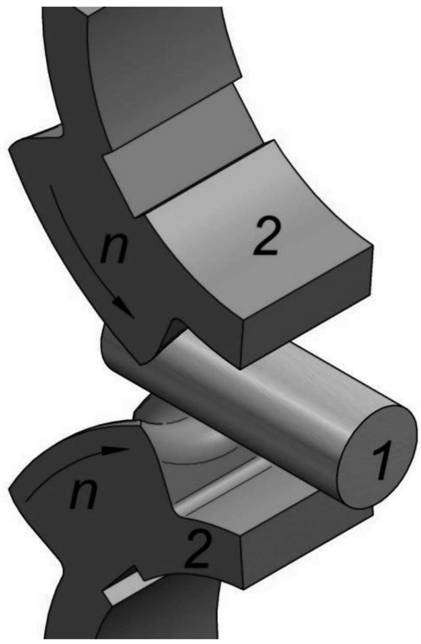


Fig. 2. Geometrical model of the forge rolling process: 1 – billet, 2 – rolling segments

3. Results of initial research

The first rolling tests were made for the semi-finished product with diameter Ø45 mm on segments, which clamping area had radius R10. These tests finished negatively. During rolling in the oval impression of the first roll pass the material coherence was disturbed. The appeared crack in the rolled into oval semi-finished product is shown in Fig. 3.

Fig. 3. Crack on the rolled oval for the roll pass 1

The crack presented in Fig. 3 has typical features of slide scraps. The loss of material coherence was caused in the plane inclined at the angle 45° to the rolling direction. The plane in which material splitting took place is also the plane where the largest tangential stresses act at the moment of material clamping by rolls. The surface of the scrap is typical for the distributive fracture. The beginning of cracking was preceded by small plastic deformations, which is visible in the area of crack initiation. The rest of the scrap surface is rough with clearly visible grains. Macroscopic photo of the crack caused during rolling in the first roll pass is presented in Fig. 4.

Fig. 4. Photo of the scrap surface obtained during rolling in the oval impression for the roll pass 1

Large tangential stresses at the moment of material clamping by tools can be caused by relatively too small rounding radius of rolling segments in the place where they clamp material. Shape optimization of the entrance area of rolling segments was conducted basing on the numerical modelling results. Numerical modelling was performed for segments with initial radii R = 10 mm, at which cracking appeared during experimental research, R = 20 mm and for the segment with gradually increasing reduction ratio, the segments are illustrated in Fig. 5. On the basis of numerical calculations results, correction of tools geometry was made, and, next, basing on the modified impressions, experimental tests were made.

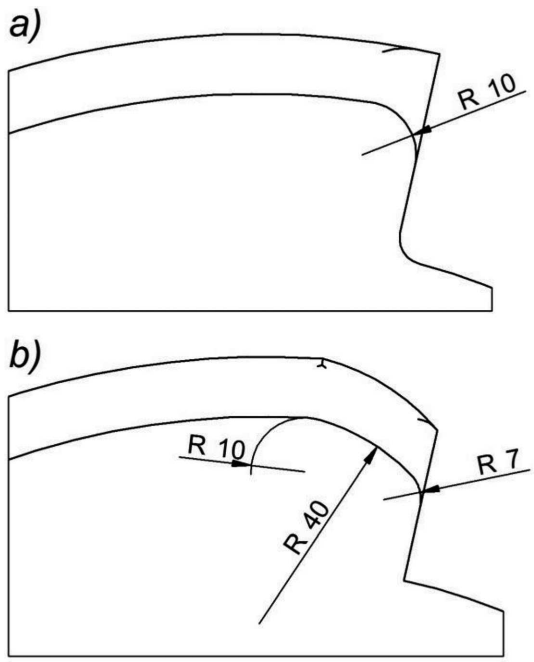


Fig. 5. Tools entrance area for the first roll pass: a) R = 10 mm, b) segment with gradually increasing reduction ratio

In the applied for simulations software FEM it is possible to foresee cracking of the formed material basing on various criteria. Cockroft-Latham empiric criterion is widely used in metal forming, described by the equation:

$$C = \int_0^{\varepsilon} \frac{\sigma_1}{\sigma_i} d\varepsilon, \tag{1}$$

where:

σ_1 – the largest mains tress,

σ_i – stresses intensity,

ε – strain intensity,

C – Cockroft-Latham integral value.

Determined numerically Cockroft-Latham damage criterion distribution for the analyzed rolling cases in the first roll pass is presented in Fig. 6. From these damage distributions result that the areas exposed to cracking are side areas of the oval placed in the rolling segments division plane. In these areas during rolling tensile stresses, which can lead to material coherence disturbance, act on the material. However, the conducted experimental research confirm that in these areas coherence was not disturbed. Because of that, it was deduced that Cocroft-Latham criterion is inadequate for foreseeing areas in which cracking may take place during rolling of magnesium alloys. Therefore, it was taken for granted that cracks foreseeing will be analyzed on the basis of tangential stress distribution.

Distribution of tangential stresses for the segment with initial radius R10, in which during rolling crack appeared, and other segments is presented in Fig. 7. From the data shown in the Figure 7 result that at the moment of material clamping by tools intensive compression happens, which may lead to magnesium alloy AZ31 cracking while rolling takes place. The change of the impression entrance area shape had a crucial influence on tangential stresses reduction, which resulted only in a small change of their distribution. The largest change of tangential stresses at the moment of material clamping by rolls was observed for the segment with gradually increasing reduction ratio. During rolling in such impressions, not only distribution but value of tangential stresses changed as well.

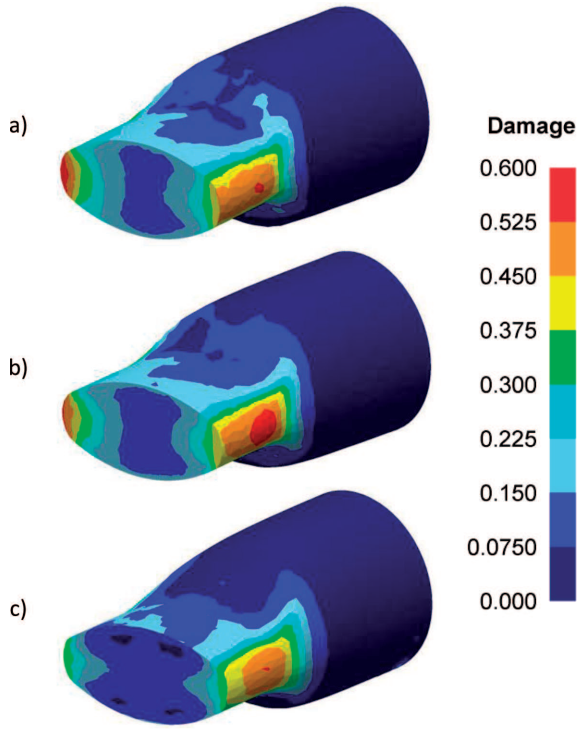


Fig. 6. Distribution of Cockroft-Latham integral value: a) segment with radius R =10 mm, b) R = 20 mm, c) segment with gradually increasing reduction ratio

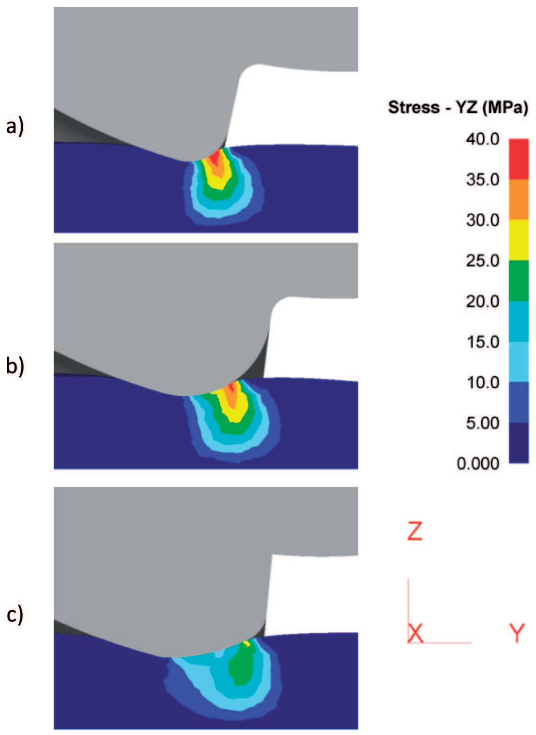


Fig. 7. Shearing stresses distribution at the moment of material clamping by segments: a) segment with radius R = 10 mm, b) R = 20 mm, c) optimized segment

Tangential stresses reduced of about 10 MPa in comparison with rolling by means of segments, in which impressions in the clamping area had only the rounding radius. The stress reduction is considerably large and equal 25% of the maximal values.

Distribution of non-dilatational strains, determined during rolling in the first roll pass is illustrated in Fig. 8.

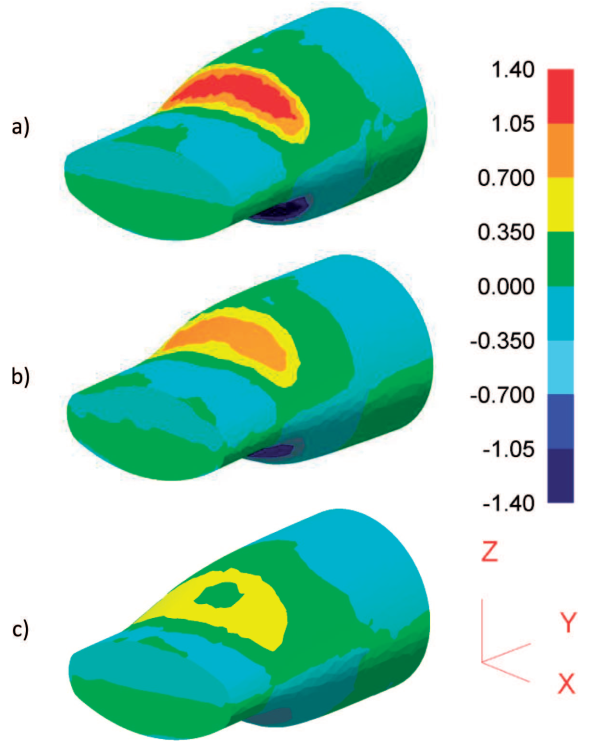


Fig. 8. Non-dilatational strains γ_{yz} distribution: a) segment with radius R = 10 mm, b) R = 20 mm, c) optimized segment

Redundant strains, being the result of tangential stresses action, are localized in the area I which rolls clamp the material. According to the presented results of numerical modelling, the value of non-dilatational strains depends on the geometry of rolling segments clamping part. The largest values of redundant strains in the preform was noticed during rolling with segment with initial radius R10. The increase of the initial radius allowed for reduction of these strains value. The smallest non-dilatational strains were obtained during rolling with segment of modified geometry of the clamping part.

Determined numerically distribution of mean stresses on the rolled preform section in the first roll pass is given in Fig. 9. According to the prediction, on the cross section larger part compressive stresses dominate. However, tensile stresses localize themselves only in the side areas and reach the maximal value at the level 25 MPa. Tensile stresses in cross section of the rolled forging localize exactly in the same areas as maximal values of Cockroft-Latham integral. Tensile stresses action in these areas lead to the increase of Cockroft-Latham integral values. Conducted earlier experimental research confirm that at such a value of tensile stresses, cracks in the formed preform side areas were not observed. Therefore, it was stated that at the value of mean tensile stresses similar to the shearing stresses value, acting on material at the moment of its clamping by tools, material cracking should not take place. For this reason, before the further rolling attempts correction of initial radii on all rolling impressions for each roll pass was made. The shape of the clamping area geometry after correction, according to which all impressions were modified, is presented in Fig. 5b.

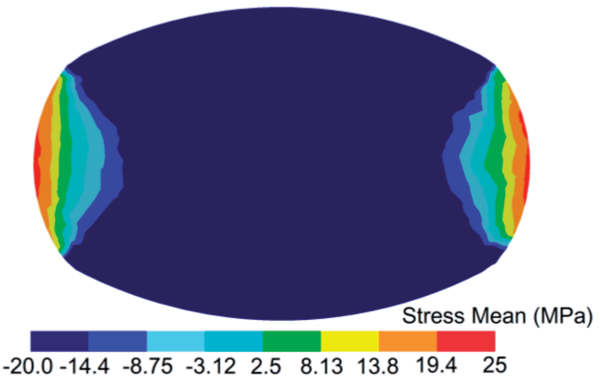


Fig. 9. Mean stresses distribution during rolling in the oval impression for the first roll pass

4. Experimental research results

Modification of rolling segments entrance area brought the desired results. The semi-finished product rolled in the first roll pass onto oval is shown in Fig. 10. The preform formed in modified tools did not possess faults in the form of cracks. However, it was observed that small flash appeared at division line of rolling impressions, which may cause overlapping during the next rolling operation in the circular impression. Apart from flash, the rolled semi-finished part bending was noticed. This bending may be the result of diverse value of the slot s along the impression width, caused by the rolling mill design imperfections or tools manufacturing inaccuracy, yet, it may also result from difficulties at axial positioning of billet during the process.

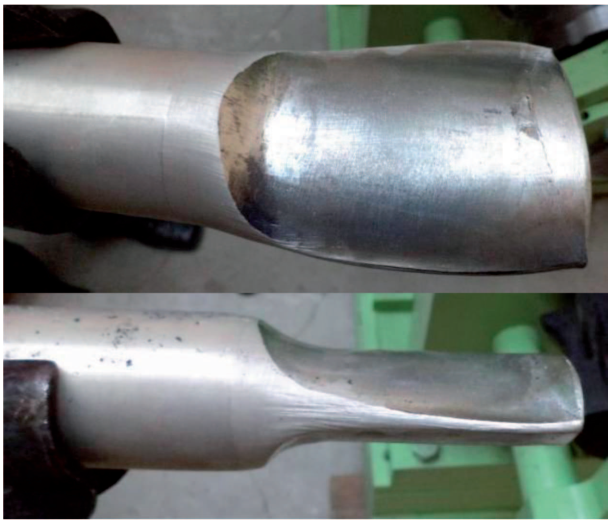


Fig. 10. Semi-finished product after rolling in oval impression for the first roll pass in the modified tools

Next stages of the preform rolling from the bar with diameter Ø45 mm is presented in Fig. 11. In any of the conducted roll passes of rolling cracks in the formed semi-finished product were observed. During rolling in circular impressions, the impression overfilling took place only for the first roll pass. In other oval impressions the presence of flash was not noticed.

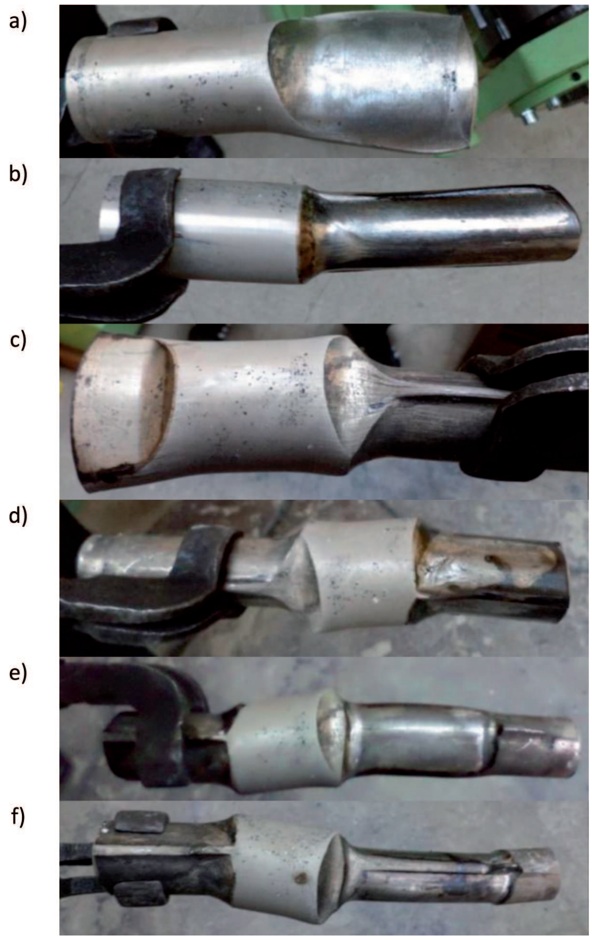


Fig. 11. Subsequent roll passes during rolling of the preform from bilet with diameter Ø 45 mm: a) oval - I, b) circle - I, c) oval - II, d) circle - II, e) oval - III, f) circle - III

During rolling in circular impression, overfilling of the impression was foundfor each case, due to which flash on every rolled step of the preform is visible. Flash obtained during rolling in the first roll pass in the oval impression, at the next stage, after the semi-finished product rotation at 90°, was rolled in the circular impression. As it can be seen in Fig. 11b, flash overlapping did not bring any undesired effects in the form of cracks or overlaps. A similar situation took place during rolling in the oval impression for the third roll pass, where flash present during rolling in the circular impression of the first roll pass was rolled. As a consequence, it was noticed that if flash is relatively small it can be overlapped. Flash present during preforms rolling may be the cause of overlaps during die forging. Flash appearance during rolling of magnesium alloys means that the character of these material plastic flow is completely different than in the case of steel. This is also confirmed by the statement that magnesium alloys during rolling have a greater tendency to widening than other materials [6]. Because of that tools for forge rolling of these materials should have oval impressions wider in relation to tools designed for steel rolling. The oval impressions height should be lower than the diameter of circular impressions. The tendency to intensive widening of these materials during rolling is also the cause of improper bumpers setting.

This causes that material clamping for the next roll passes takes place in the completely different areas along the length of the rolled semi-finished product. Apart from appropriate designing of rolling impressions, flash can be eliminated by: reduction of rolls diameter, increase of rolling velocity (yet, large strain velocities in the case of magnesium alloys can lead to cracks), increase of the semi-finished product and tools temperature (magnesium alloys are good conductors and they transmit heat to cooler tools very fast), decrease of friction forces between tools and the rolled semi-finished product.

The character of magnesium alloys flow differs considerably from steel flow, hence, for example ,during rolling unfavourable flash appears on the rolling segments division plate. Because of that, also tests of the preform rolling from magnesium alloy at smaller rate of cross section reduction:

$$R_p = 1 - \left(\frac{d}{d_0}\right)^2 \times 100\%, \qquad (2)$$

where: d – billet diameter after rolling, d_o – billet diameter before rolling.

Decreasing of reduction ratio in particular roll passes during forge rolling was obtained by billet material diameter reduction from Ø45 mm to Ø42 mm. Billet diameter reduction resulted in decreasing of the largest diameter of the preform step, which does not undergo rolling, and in decreasing of widening and elongation. The conducted research on rolling at smaller reduction ratio aimed only at checking how the reduction ratio value would influence flash appearance. The influence of billet diameter reduction on cross section reduction rate is presented in Table 2.

TABLE 2

Rate of cross section reduction for various billet diameters

	Rate of cross reduction section R_p		
Billet diameter	Roll pass I	Roll pass II	Roll pass III
Ø45 mm	55,5%	43,5%	69%
Ø42 mm	48,9%	35,6%	64,5%

The change of forging shape during rolling in particular impressions is given in Fig. 12. The decrease of reduction ratio value did not eliminate completelyflash appearance during rolling. Flash did not form only during forming on oval in the second and third roll pass. In other cases flash presence was noticed as it was during rolling from billet Ø45 mm. Lower reduction ratio values at particular preform steps caused only decrease of dimensions of flash.

Preforms rolled from billet of diameter Ø45 mm and Ø42 mm is presented in Fig. 13. The whole length of both formed forgings is similar, which results from the fact that the preform step, which did not undergo rolling, for the preform rolled from billet with diameter Ø42 mm is shorter. Reduction of billet diameter resulted in later material clamping, which led to billet part elongation subjected to rolling.

Also in both preforms during rolling flash appeared at the rolls division line. Moreover, the preforms bending during rolling was observed. Forgings bending is not, however, a fault which can disqualified them, as before die forging process forgings require larger bending in the bending impression.

a)
b)
c)
d)
e)
f)

Fig. 12. Subsequent roll passes during rolling of the preform from billet with diameter Ø 42 mm: a) oval - I, b) circle - I, c) oval - II, d) circle - II, e) oval - III, f) circle - III

a)
b)

Fig. 13. Forgings from magnesium alloy AZ31 rolled in the forge rolling process: from billet with diameter Ø 45 mm, b) from billet with diameter Ø 42 mm

5. Summary

The conducted research works confirmed the possibility of magnesium alloys forming (on the example of alloy AZ31) in the longitudinal forge rolling process. The longitudinal forge rolling process for the analyzed preform was realized in the system oval-wheel. In order to obtain preforms without cracks it was necessary to: optimize tools in the clamping area, reheating of the formed material between rolling in subsequent impressions and initial tools heating. Tools heating at the end of rolling tests led to the mill working rolls heating, which widened due to heat. During forge rolling in impressions of traditional geometry, cracks appeared in the area of material clamping by tools each time. In these areas, apart from intensive cooling of material caused by temperatures difference between billet and tools, intensive material cutting by clamping it rolls takes place. Hence, apart from reheating of tools, it is important that the material clamping by tools will be gentle.

The character of plastic flow of magnesium alloys has a decisive meaning for the metal forming processes proper realization, mainly for rolling technology. As the conducted rolling tests showed, magnesium alloys have a larger tendency to widening than other material groups, e.g: aluminum alloys [12]. During rolling of aluminum alloys by the same set of tools, there was no flash observed. Due to lack of guidelines concerning sizing of impressions for forge rolling of magnesium alloys, sizing was performed according to the guidelines for steel. The obtained results revealed that, in order to optimize this process of preforms from magnesium alloys manufacturing, it is necessary to work out new sizing methods of impressions, taking into consideration character of this material group flow. Mastering of magnesium alloys rolling processes is connected with knowledge of dependencies describing the relation between reduction ratio, widening and elongation.

Considering the result of the forge rolling process of preform from magnesium alloy AZ31, which was based on numerical modeling, it can be stated that Cockroft-Latham criterion does not fully reflect phenomena present in reality, especially in the case of alloy AZ31. According to this criterion, cracking of the preform during forge rolling should take place at the rolling segments division plane in the areas near the surface, therefore, in the preform areas where mean stresses during rolling reach positive values. During realization of experimental research in any of the cases cracks forming in this area was not observed. Hence, conclusion can be drawn that magnesium alloys cracking, especially alloy AZ31, during metal forming can be caused mainly by tangential stresses action.

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