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PRECISION FORGING OF THIN-WALLED PARTS OF AZ31 MAGNESIUM ALLOY

KUCIE PRECYZYJNE ODKUWEK CIENKOŚCIENNYCH ZE STOPU MAGNEZU AZ31

Tests of closed-die forging in various temperatures, ranging from 350 to 150°C were performed with a use of high speed forging equipment. As research material as-cast and as-extruded AZ31 alloy was used. After successful efforts in 250°C, additional spring-attached tool was used to exert hydrostatic state of stress, which allowed decreasing forging temperature. The experiments were supplemented with numerical analysis, which helped to estimate the level and state of stress during forging, explaining origin of reported defects.

Keywords: wrought magnesium alloy, AZ31, precision forging, warm forging, forgeability

Przeprowadzono próby kucia w matrycach zamkniętych w różnych temperaturach kucia, w zakresie od 350 do 150°C. Jako materiał do badań użyto stop magnezu AZ31 w stanie lanym oraz po wyciskaniu. Po udanych próbach przeprowadzonych w 250°C, zastosowano dodatkowe narzędzie podtrzymywane sprężyną, które wprowadzając naprężenia ściskające pozwoliło na obniżenie temperatury kucia. Doświadczenia wspomagano modelowaniem numerycznym, które pozwoliło określić wielkość i stan naprężeń w odkuwce podczas kucia oraz wyjaśnić pochodzenie zaobserwowanych defektów.

1. Introduction

Magnesium alloys, as one of the lightest commercially used structural materials, traditionally have been used in aircraft, spacecraft and military applications. Present trends to reduce energy consumption arise minimization of both dead weight and the weight of moving part of vehicles. Therefore, lately, to an increasing rate, wrought magnesium alloys in automotive applications are considered, which can significantly decrease the weight of vehicles [1, 2]. Magnesium alloys are also used for manufacture of housings of many portable electronic devices, such as, cellular phones or notebooks, not only for the material lightness but also for the easiness of recycling and good electromagnetic shielding capabilities [3].

These days, the most common technology of manufacturing part made of magnesium alloys are casting techniques, which limits the range of application of those materials. To increase mechanical properties of magnesium, increasing thereby its competitiveness in relation to ferrous and/or aluminium alloys, efforts are made to replace castings with wrought products, including complex shape precision forgings [4].

Modern forging technologies tend to provide dimensions equal or insignificantly differing from final dimension of a finished part in net shape or near-net shape forging processes. Since the final shape is to be attained in forging operations only, so are the final properties. On the other hand, economical balance calls for minimization of stages' number, as well as, use of possibly cheap forging stock, hence, the tendency to use as-cast material, in the form of continuously cast billets or DC ingots. Thus, the task of forging process is to provide superior properties from less favourable as-received material.

In case of emerging materials, such as magnesium alloys, the situation is even more demanding. The forging stock is more costly and the difference between typical and required properties, which could make this material competitive in relation to conventional alloys, is bigger. For high strength, alloys containing rare earth elements, often modified for finer grain, are in charge. To prevent from oxidation, costly ceramic coatings are developed. To obtain high strength in combination with good ductility, for complex configurations of forged parts more ex-

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pensive zirconium containing alloys are first considered. Therefore, magnesium alloys are still far from finding wide popularity in common automotive applications.

Magnesium alloys have low ductility at room temperature associated with their crystallographic structure and texture. For this reason, magnesium alloys are generally hot-worked above temperature 250°C, with application of solid lubricants. Hence, the idea of the work is to benefit from special technologies of closed-die forging to overcome low plasticity setbacks and allow warm-working of as-extruded or even cast structures of magnesium alloys.

Closed-die forging workability of magnesium alloys depend on many factors, among which the most important are process parameters, such as forging temperature, tool temperature, the rate of straining and intrinsic workability, resulting from material condition and deformation history and, so called, s-o-s workability, involving state of stress during forging [1, 5]. With decreasing forging temperature, ductile fractures in most instances tend to occur in free surfaces, set up by secondary tensile stresses [5]. Hence, the idea of the work is to reduce the secondary tensile stresses, taking advantage of possibility offered by employing additional tool in closed die, held by spring. The tool, which is designed for proper metal flow in a die impression, limits free surface during forging, exerting pressure on the head surface of extruded metal, controlled by stiffness of the spring.

The subject of the paper is estimation of effect of major forging process parameters in the aspect of feasibility of obtaining thin-walled complex-shape parts in advanced forging process. These variables, taken into analysis in this work, include forging temperature, deformation prior to forging and state of stress.

The goal of this research is investigation on the possibility of utilization of forging equipment used in traditional forging technologies. For this reason, forging tests were carried out in conditions according with industrial processes, that is, tool temperature insignificantly higher than room temperature and high working speed provided by screw press.

2. Experimental procedures

2.1. Research material

The investigation includes forging as-cast material and as-extruded material, varying in degree of deformation obtained in forward extrusion process. Three variants of material condition were used in the research, with reduction ratio R equal to: 0, 3 and 4,5; defined as:

$$R = \frac{A_0}{A_1},$$

where: A_0 is initial, and A_1 is final cross section of extruded bar.

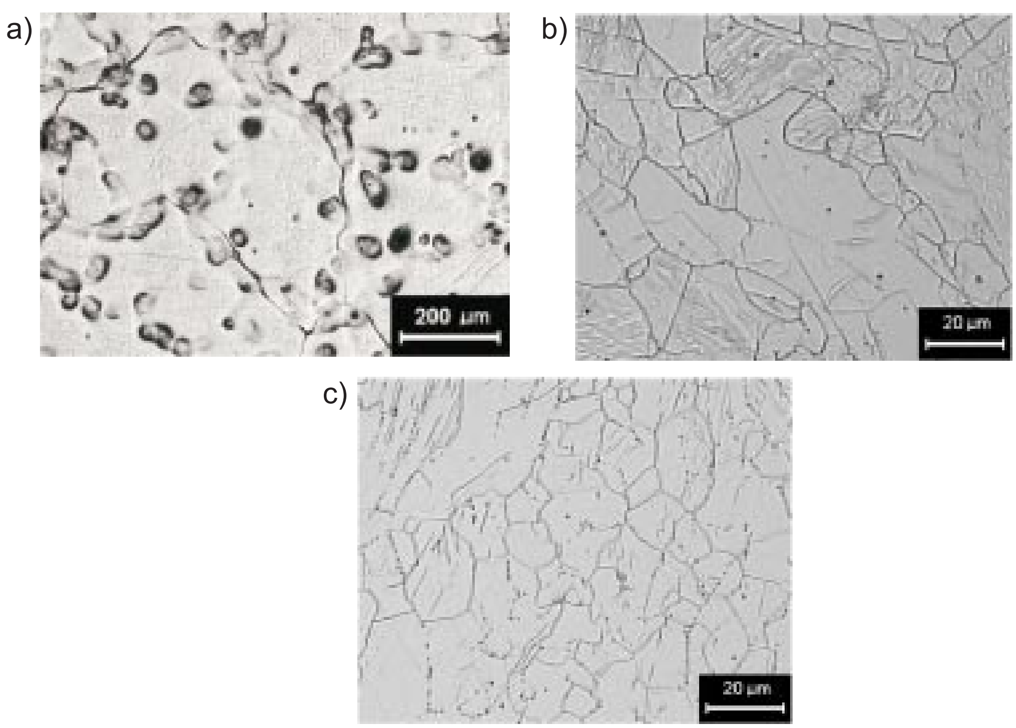


Fig. 1. Material used in the study: a) as-cast homogenized, b) as-extruded with $R = 3$, c) as-extruded with $R = 4,5$

Microstructures of the used specimens, in respective order, are shown in Fig. 1. As seen in micrographs, cast structure of AZ31 alloy contains numerous precipitates of β-phase Fig. 1a). After extrusion in 300°C with $R = 3$ the cast structure has been broken and the precipitates scarcely present in the structure. The grain structure was not uniform, with large non recrystallised grain occurring (Fig. 1b). Slightly more favourable structure in that respect was reported after extrusion with $R = 4,5$ (Fig. 1c).

2.2. Compression tests

First part of the investigation included traditional compression tests, which showed the effect of working temperature, strain and strain rate effect on stress. Simultaneously, it was to supply information on behaviour of the material in uni-axial state of stress. In accordance with ANSI standards, height/diameter ratio of 1,5 was used. The tests were conducted for temperatures 200, 250 and 300°C. The compression was continued when barrelling occurred until cracking was observed. As frictional restrain at the end faces hampered lateral flow of the metal, it could be regarded as simple forgeability test, where the measure of ductility could be the deformation at failure [7, 8].

2.3. Closed-die forging experiments

Simple upsetting tests helped preliminary estimation of forging temperature, however, on account of much more complex state of stress occurring in closed-die forging process, to investigate behaviour of the material in a three-axial state of strain closed-die forging tests were conducted. For the tests, non-axisymmetrical geometry of a model was selected, characterized by thin walls, very thin web and large strains during deformation. It was assumed that the pattern of metal flow should be typical of closed die forging processes with three main methods of filling up die impression, backward extrusion, upsetting and punching, expected to occur. The forged geometry is shown in Fig. 2.

Forging tests were conducted in wide range of temperature, from 350°C, defined by maximum temperature taking into consideration deformation heat, to 170°C defined by cracking occurrence and predicted excessive stresses in tools in the warm-working range.

The forging experiments were carried out on a screw press allowing variation in forging energy. To ensure sufficient deformation energy for all forging temperatures, the velocity was preset on a basis of the lowest temperature, 170°C. All tests used the same preset forging energy, and the difference in deformation work due to variable forging temperature was absorbed by energy compensator. The difference in tool velocity associated with it was neglected in the analysis. The scheme of tool set used in experiment in shown in Fig. 3.

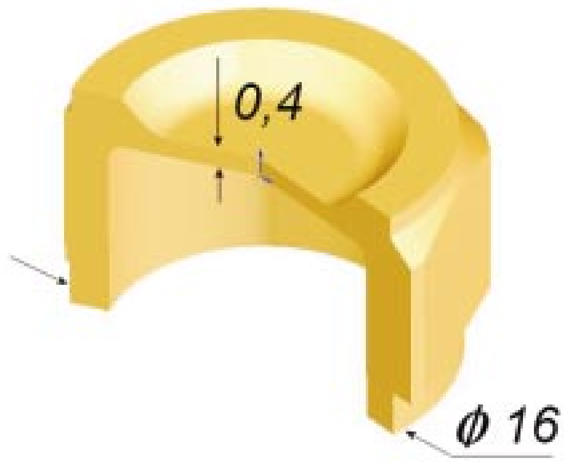


Fig. 2. Geometry and major dimensions of forged part

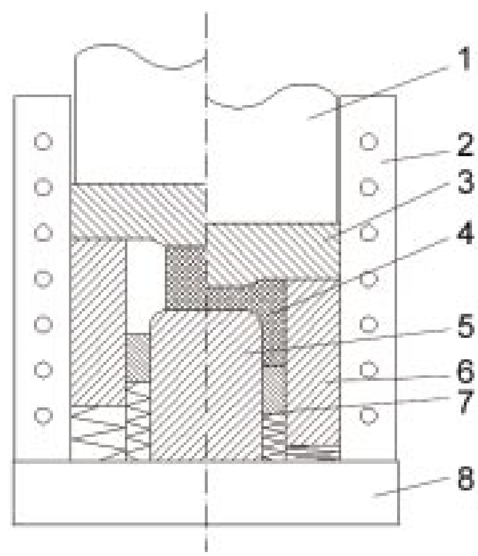


Fig. 3. Scheme of tooling set used for screw press, where: 1– ram, 2 – heating system, 3 – upper die, 4 – workpiece, 5 – bottom tool, 6 – container, 7 – spring-attached die, 8 – bed

Effect of state of stress was investigated with two different workpiece geometries of slenderness 2,5 and 1. In addition to the slenderness, which determined the pattern of the metal flow, to estimate effect of state of strain in the peripheral free surface of deformed metal, effect of the presence of hydrostatic stress constituents was taken into consideration. For this purpose, two cases of stiffness of the die were analysed: the minimum stiffness allowing free movement of the tool forced by deformed metal and proper filling the cavity, and the stiffness providing pressure of about 4 MPa.

2.4. Numerical modelling

To determine state of stress and the level of stresses, experimental tests were illustrated with numerical modelling. The modelling involved a use of a commercial software QForm 3D, which is successfully used for bulk working processes simulation [9, 10]. The simulations, in accordance with experiment, were performed for variable forging temperature. Boundary conditions assumed, which came along with experiment, were: friction factor 0,4 (Levanov friction model), estimated in a ring method; effective heat transfer coefficient 3500 W/m^2; heat conductivity 80÷100 W/m; tool temperature 100°C, upper tool energy 3,5 kJ. The flow curves obtained from upsetting test, after thermal correction with an inverse method and regression, are shown in Fig. 4.

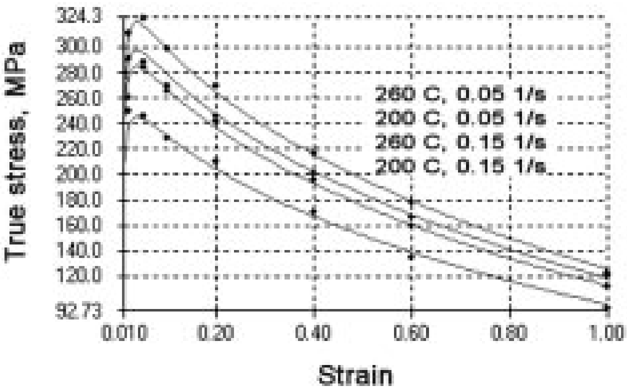


Fig. 4. Flow curves for as-cast alloy AZ31

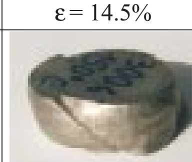
The numerical analysis helped in presetting forging energy, as well as, gave information as for the level and distribution of mean stress, which was the basis for plotting maximum tensile stresses versus height reduction for analysed forging process conditions.

3. Results

3.1. Compression tests

For basic information on behaviour of AZ31 magnesium alloy, traditional compression tests were performed. Examples of specimens after deformation at various temperatures are shown in Table.

TABLE

<table>
<tr><td colspan="2" rowspan="2">AZ31</td><td colspan="4">Temperature</td></tr>
<tr><td>150°C</td><td>200°C</td><td>250°C</td><td>300°C</td></tr>
<tr><td rowspan="4">Material condition</td><td rowspan="2">R = 3</td><td></td><td></td><td></td><td></td></tr>
<tr><td>ε = 14.5%</td><td>ε = 16.6%</td><td>ε = 50.6%</td><td>ε = 80% (no fracture)</td></tr>
<tr><td rowspan="2">R = 4,5</td><td></td><td></td><td></td><td></td></tr>
<tr><td>ε = 20.2%</td><td>ε = 37.6%</td><td>ε = 80% (no fracture)</td><td>ε = 80% (no fracture)</td></tr>
</table>

3.2. Closed-die forgeability

The forgings obtained in closed dies in various forging temperatures are shown in Figs 5÷7. As the results show, critical region, as for failures occurrence, is the free surface of the forging, which in the last stage of forging is restrained by the spring-hold die. This is also a region of location of maximum positive mean stresses. Therefore only bottom sides of the parts are shown in figures.

As it can be seen in Fig. 6, there is no difference between 300 and 350°C (Fig. 5 c) and d). The free surface is smooth and underfilling results from no pressure exerted by spring-attached tool, which was very elastic in this variant. At 250°C (Fig. 5 b) some cracks, and at 200°C (Fig. 5a) severe cracking occurred.

To reduce forging temperature, as-extruded material was used, however, the analysed forging stock was extruded with low extrusion ratios. Condition of the bottom surface of the forgings obtained at variable temperature for reduction ratio R = 3 is shown in Figs 6 a)÷c). Only at 200°C some ductile fractures in the free surface were observed. In none of the cases of forging temperature fractures in the area of the inner radius were reported, contrary to as-cast material forgings. To estimate influence of the amount of deformation of applied workpiece, also specimens extruded with $R = 4,5$ was used as a forging stock. The results for temperature 200°C, are shown for comparison in Fig. 6 d). Inspection of the fracture indicated its evident ductile character. The defect is insignificantly deeper than that at 250°C for $R = 3$, which in respect to temperature decrease of 50 degrees indicate significant ductility enhancement.

As it was obvious that, except some cases of cracks in the inner surface, the cause of all of the fractures is unfavourable state of stress, the idea was to eradicate them with introducing hydrostatic strain components by increasing stiffness of spring beneath the floating die. The spring was pre-stressed without change in the time of contact of backward extruded metal with the spring-hold die, however, the pressure exerted by the tool increased to approximate 80 kN. The forgings obtained in this part for as-extruded workpiece of experiment are shown in Fig. 7. Due to satisfactory results obtained for temperature 200°C the same test was made to investigate behaviour of as-cast material. This effort, however, did not succeed. As shown in macrographs in Fig. 8, temperature 200°C turned out too low for as-cast material to be forged on high-speed equipment, such as screw press, even if additional facilities are applied.

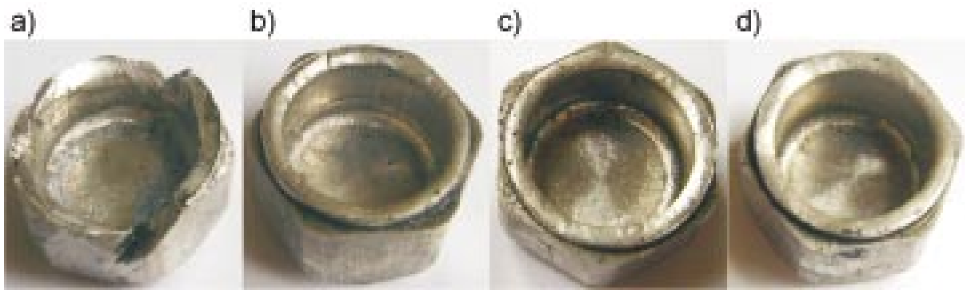


Fig. 5. As-cast specimens forged in: a) 200°C, b) 250°C, c) 300°C and d) 350°C

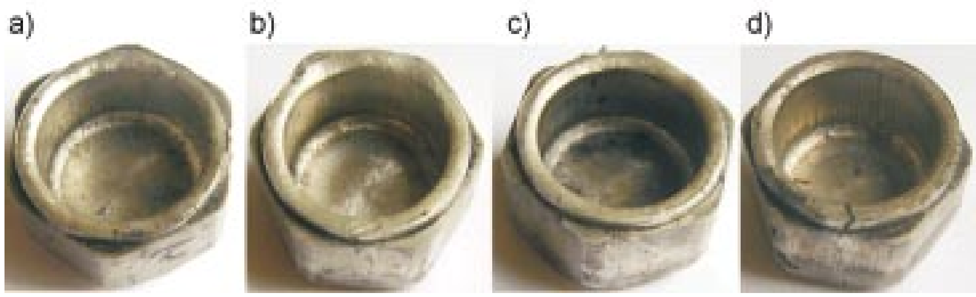


Fig. 6. As-extruded specimens of R = 3 forged in: a) 200°C, b) 250°C, c) 300°C and d) as-extruded with R = 4,5 forged in 200°C

Fig. 7. As-extruded specimens of R = 3 forged in: a) 170°C, b) 200°C, c) 250°C with a use of spring-hold die

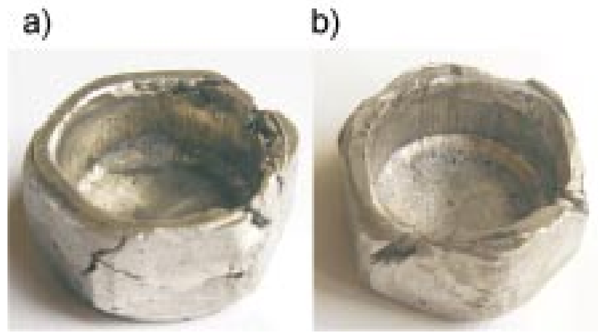


Fig. 8. As-cast specimens forged in: a) 170°C, b) 200°C with a use of spring-hold die

3.3. Numerical analysis

To illustrate the state of stress during forging, numerical modelling was carried out for investigated process conditions. Simulation of the first part of the experiment was carried out with unrestricted backward extrusion of the peripheral region of the forging. The obtained distribution of mean stress in consecutive stages of the forging process show that the moment the process is commenced, the tensile stresses are present in the free surface, as well as, in the inside surface in the vicinity of the fillet of the punch. As results showed, the tensile stresses in this temperature exceeded 60 MPa. In other cases, performed for different temperatures, similar changes of maximum mean stress during process were observed, reaching its peak at start of backward extrusion stage, differing in the level of stress.

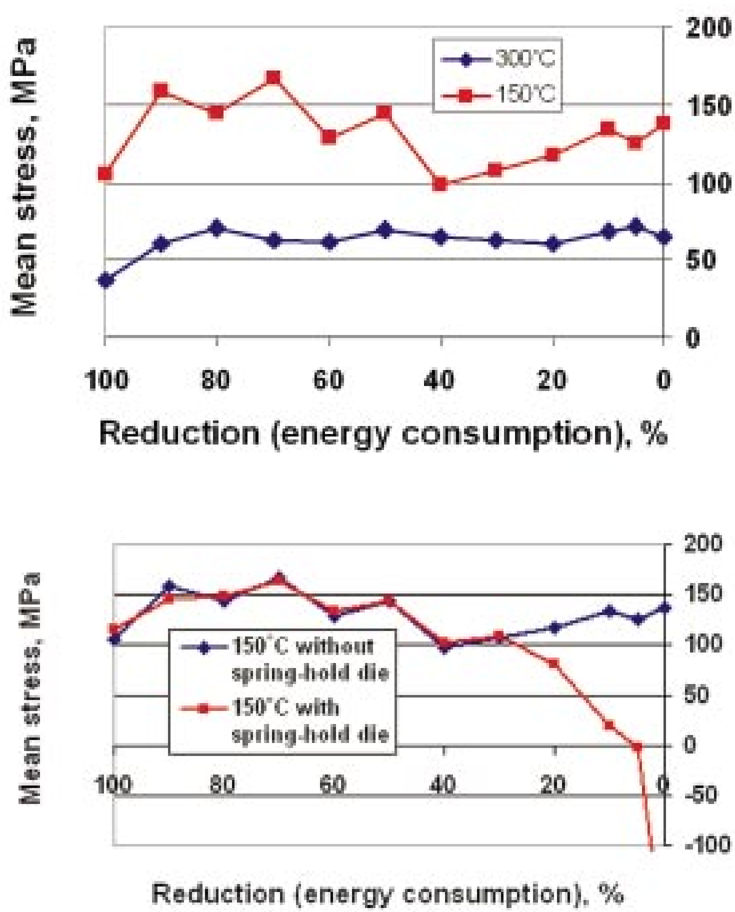


Fig. 9. a) Plots of mean stress in the free surface in consecutive stages of the process (in accordance with energy consumption) for border temperatures, b) plots of mean stress in the free surface in consecutive stages – effect of use of spring-hold die

The same simulations were performed for the process with spring-hold die used. The dependence of the stress level on forging temperature is depicted in Fig. 9, which shows plots of mean stress value in the peripheral free surface of the extruded metal (versus energy consumption) numerically estimated for 300 and 150°C for unrestricted metal flow Fig. 9 a) and the same dependence compared to the case of metal flow restrained by the spring-hold tool Fig. 9 b). As it can be seen, the restrain in the ending stages of the process makes tensile stress diminish and eventually take on negative values, reaching – 160 MPa.

4. Discussion

The authors' idea was to estimate the ability of one of the cheapest of commercially used magnesium alloys to undergo large plastic deformations in a complex state of stress, commonly met in impression forging processes. In the light of abovementioned trends, as-cast material and complex net shape of a model forging was selected, while the forging temperatures used were to provide high precision, surface quality and mechanical properties, which are to be evaluated in incoming studies.

Results of the previous researches [6], conducted at slow strain rates for alloys AZ31 and AZ61, both as-cast and as-extruded, brought encouraging results, despite demanding geometry of analysed part. This time, attention was focused only on soft AZ31 alloy, whereas, the applied velocities, resulting in strain rate values, were over one order of magnitude higher, which gives more pragmatic results in aspect of employing high-speed machines.

As the results of experiments show, the most common location of defects was a peripheral face of the wall. Only in part forged in as-cast alloy, fractures on the inner surface in the area of fillet are noticed (Fig. 5 a), b) and in as-extruded stock forging at 200°C (Fig. 6 d). With numerical modelling analysis, in all these regions positive values of tensile stresses were reported. In higher temperatures their level exceeded 60 MPa, reaching over 160 MPa in 150°C.

It is worth noting that similar research performed on zirconium containing wrought alloy ZK60 by Ogawa and co-authors [7] also attribute crack formation to occurrence of tensile stresses in locations corresponding to inner radius of the analysed part. In both cases dominant process was backward extrusion, however, velocities and geometrical parameters and resultant state of stress in the free surface, were different, and the latter problem did not come up.

On the basis of these notices, to prevent from arising high level of tensile stress, hydrostatic components were introduced, which reduced the level of tensile stress in the last stage of forging, and eventually, brought hydrostatic state of stress in the whole volume. The forgings obtained in this part of the experiment are characterized by fully filled corners and good quality of surface. The spring-hold die allowed also lowering forging temperature for as-extruded stock.

As far as non-worked forging stock in concerned, the efforts were still unsuccessful. However, in may be noticed that the fractures seem to have been formed before action of the spring-hold die, and so, high level of tensile stress were observed. This suggests further experiments aimed at appropriate preset of the position of the spring-attached die, as well as, the stiffness of the spring, which produces the desired state of strain.

5. Summary and conclusions

The presented study shows feasibility of high speed closed-die forging of as-extruded and as-cast AZ31 magnesium alloy. Net forging, as such, is an advanced forging technique, especially if it requires additional tools or equipment. Such a situation is found in application of spring-hold dies to ensure complete filling of die cavities. Applicability of this technique makes the analysed problem an innovative attempt in forging magnesium alloys.

As the results show, favourable state of stress allows forging this hard-to-deformation alloy both in as-extruded and as-cast condition. Non-worked stock allowed forging in 250°C, while as-extruded stock enabled obtaining forgings in temperature as low as 250°C with surface cracks observed. Implementation of spring-hold die allowed decrease the temperature to obtain sound and fully formed part in temperature of 200°C.

Obtained results proved feasibility of forging AZ31 magnesium alloy in warm-working range of temperature with insignificant amount of preliminary working of the forging stock. Experimental results, with their numerical analysis, can form the guidelines for design of technology of forging thin-walled parts made of magnesium alloys. In this respect implementation of holding die seems to be an innovative solution to increase plasticity of brittle materials in forging to complex and thin-walled geometries.

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