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NUMERICAL ANALYSIS OF THE EXTRUSION RATE INFLUENCE ON COURSE OF THE DEFORMATION PROCESS OF AZ31 MAGNESIUM ALLOY ROD BY MODIFIED ECAE METHOD

Plastic working of magnesium alloys is complicated, due to the specific arrangement of atoms in crystallographic lattice that is the reason of low ductility caused by a limited number of slip planes allowed at room temperature. Magnesium as a representative of metals with hexagonal close packed structure (HCP) has c/a ratio close to the ideal value, and since there is insufficient amount of slip and twin systems to realize any plastic deformation at ambient temperature. Deformation is realized only by slip in the basal plane, which offers a limited number of deformation systems. Therefore, the deformation of AZ31 alloy is usually carried out in the temperature range of 250–350°C, where the number of operating deformation systems is higher than at ambient temperature that allows achieving needed properties in deformed material [1–5].

In many industries there is observed an increasing demand for lightweight engineering alloys, which include magnesium alloys due to economic reasons e.g. reduction of fuel consumption in the automotive industry. However, more than 90% of the components are produced in casting process of magnesium alloys. AZ series alloys due to their high strength properties and good ductility find their application in manufacturing of some components in aerospace, automotive, and electronics. In addition, these alloys have excellent stiffness, good dimensional stability, high capability for vibration damping and good recycling capacity, which is currently widely discussed among Polish scientists and entrepreneurs [6–10]. For this reason, there can be observed increased interest in magnesium processing technology and manufacturing of high quality products with low specific gravity. Increased usage of magnesium alloys in different industrial applications is one of the reasons for multi-parameter analysis of deformability in order to improve the mechanical properties.

In a many research centres, the studies in field of deformability of the magnesium alloys in various plastic-working processes such as: rolling, forging, drawing and extrusion at elevated temperatures are being conducted. Many FEM-based analyses have been performed to determine the deformation behaviour of materials and to estimate the developed strain and stress during the ECAP process. The research included the effect of extrusion rate and temperature on the deformability and microstructure evolution of AZ31 alloy. The magnesium samples that underwent tensile and compression tests were subject of studies of many researchers [3–4, 10–15]. The final products from magnesium alloys that were obtained by extrusion or hot-rolling process exhibited by good mechanical properties. However, the methods of preparation of the finished products, which are carried out at room temperature are problematic, e.g. production of thin wires and tubes due to rapid straightening of deformed material [15]. Experimental studies of deformability of magnesium alloys in cold drawing process have shown that the process is possible to be realized using a feedstock with fine-grained material structure. Application of the interoperational heat treatment allows for material deformation with high total reduction.

The use of unconventional methods of the plastic working, *inter alia,* KOBO method [14–15], ECAP [6, 13] and ECAE methods, gives possibility to prepare a material with high refinement of structure. Additionally, it is also necessary to make interoperational heat treatment during the cold drawing process. Skilful selection of extrusion and drawing process parameters such as strain rate, temperature, temperature range of interoperational heat treatment and unit draft allow to obtain the final product with a small diameter and good mechanical properties [15].

This part of research concerns a numerical analysis of AZ31 alloy extrusion process in conventional and modified ECAE device, with particular attention to influence the extrusion rate on properties of the product assigned to further processing for example by cold drawing process.

The scope of this study concerns the numerical analysis of the influence of extrusion rate on stress intensity and temperature distribution inside deformed material. The material used for numerical simulations with Forge 2008 ® program was AZ31 magnesium alloy with the chemical composition as shown in Tab. 1.

Table 1

Chemical composition

Alloy	Content of elements, % wt							
	Mg	Al	Mn	Nd	Sb	Zn	Fe	Si
AZ31	96.284	2.58	0.12	0.005	0.017	0.99	0.002	0.02

The process of theoretical analysis was conducted on the base of the results of computer simulations performed by FEM-based program Forge2008®. The geometry of initial material and tools was drawn in AutoCad2009® while the mesh of finite elements was generated using Preprocess module at Forge2008® program.

On the basis of the plastometric tests made at the Institute of Plastic Working and Safety Engineering, Czestochowa, Poland, the coefficients of Hansel-Spittel yield equation were determined [11]. The plasticity equation that was used:

$$\delta_p = A \cdot e^{m1 \cdot T} \cdot T^{m9} \cdot \varepsilon^{m2} \cdot e^{\frac{m4}{\varepsilon}} \cdot (1+\varepsilon)^{m5 \cdot T} \cdot e^{m7 \cdot \varepsilon} \cdot \dot{\varepsilon}^{m3} \cdot \dot{\varepsilon}^{m8 \cdot T}$$

where A, m_1-m_9 – coefficients.

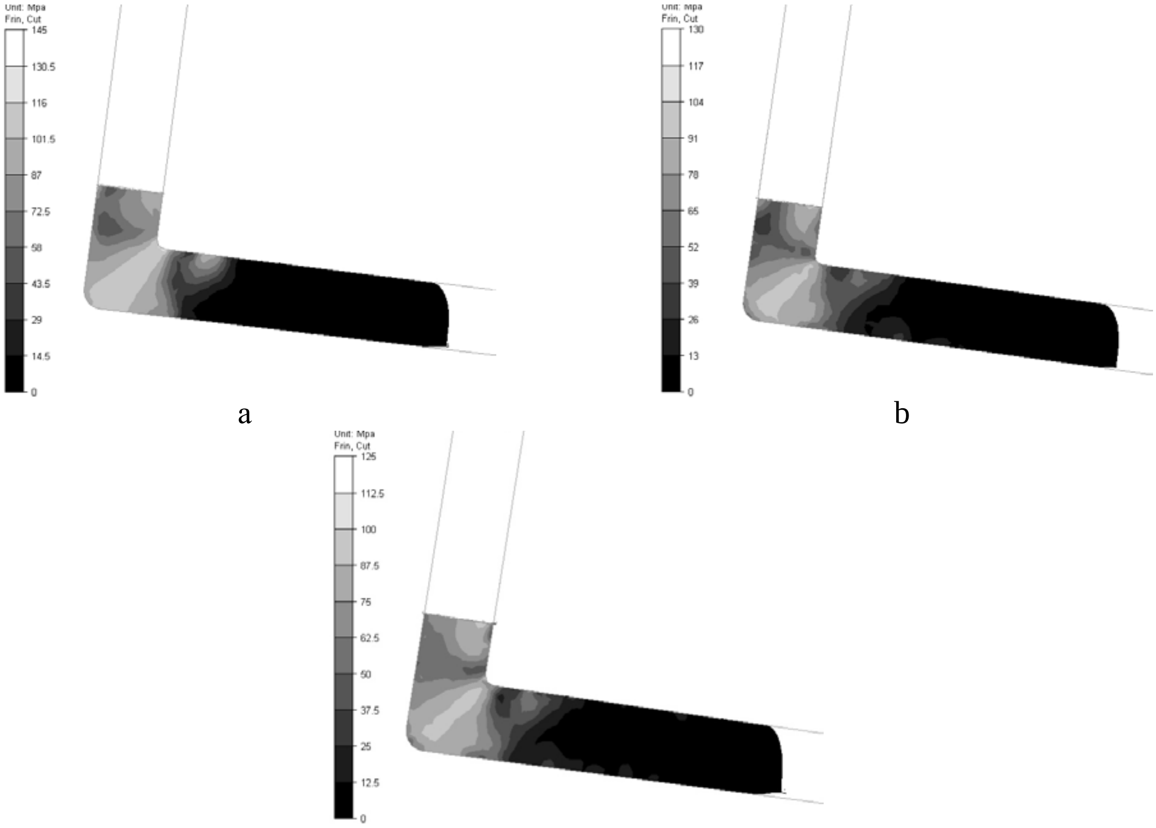
The coefficients in the equation were determined using inverse approach with the least squares method. The appointed empirical coefficient of yields stress function: A = 120, m_1 = - 0.005605, m_2 = - 0.645555, m_3 = - 0.142709, m_4 = - 0.115967, m_5 = 0.001591, m_6 = 0, m_7 = 0.070869, m_8 = 0.000577, m_9 = 0.194354. Those values were applied to the numerical program.

Theoretical analysis was carried out for the real conditions of conventional and modified ECAE methods. The friction conditions were defined using Coulomb’s model. Thermal conductivity between material and dies equals 2000 W/m^2K. The viscoplastic model of material flow described by Norton-Hoff equation was applied. The normalized Cockroft-Latham criterion was applied.

In order to select the appropriate conditions for the extrusion process using conventional and modified ECAE, numerical studies were performed using several variants of temperature-velocity conditions. Three extrusion rates were used respectively: 1mm/s, 10mm/s and 20mm/s. Also three different extrusion temperatures were adopted: 250°C, 300°C and 350°C.

Extrusion process was realised for two variants of ECAE matrix – conventional and modified one. The modification of matrix based on the fact that the output channel was narrowed to obtain thinner rod that could be used for further deformation processes.

The fields of stress distribution in the material deformed at 350°C in conventional ECAE process for various punch velocities is presented in Fig. 1.



c

Fig. 1. Stress distribution in the material during deformation by conventional ECAE method at temperature 350°C and extrusion rate:

a – 1mm/s, b – 10 mm/s; c – 20 mm/s

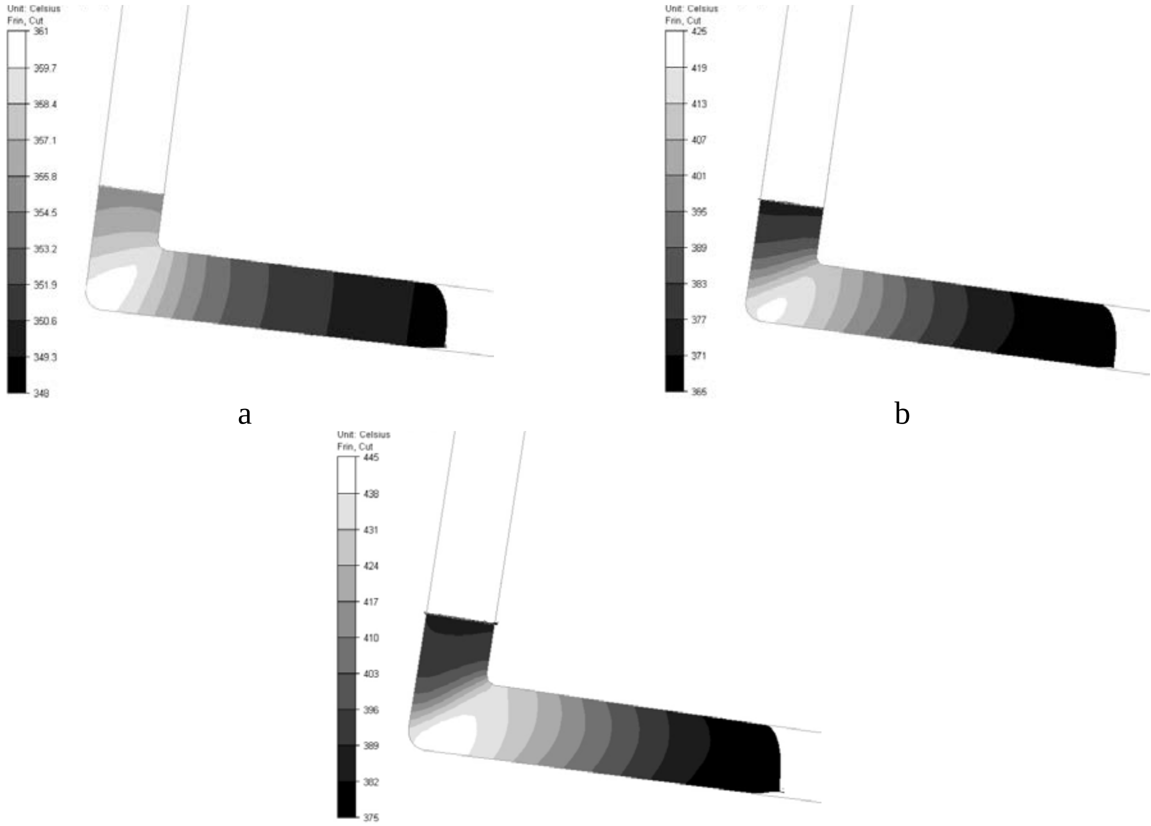


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Fig. 2. Temperature distribution in the material during deformation by conventional ECAE method at temperature 350°C and extrusion rate:

a – 1mm/s, b – 10 mm/s; c – 20 mm/s

The higher extrusion rate causes a decrease of stress intensity in the analysed material. It can be the result of temperature growth as an effect of deformation process that causes softening of the material. For lower extrusion rate the distribution of stress is more heterogeneous across longitudinal section of the material. Changes in concentration of stress in deformed specimen can be observed while material passes through the angular channel. The increase of extrusion rate causes loss of uniform distribution of stress fields at deformed material. It also causes temperature growth inside the material from 360°C to 441°C, as shown in Fig. 2.

The next stage of conducted research was numerical analysis of the ECAE method for the modified matrix. After one pass through the angular channel the reduction coefficient was λ = 1.6. An analysis of strain rate effect on stress distribution on the longitudinal section of deformed specimen (Fig. 3) and temperature distribution (Fig. 4) during applied extrusion process was carried out.

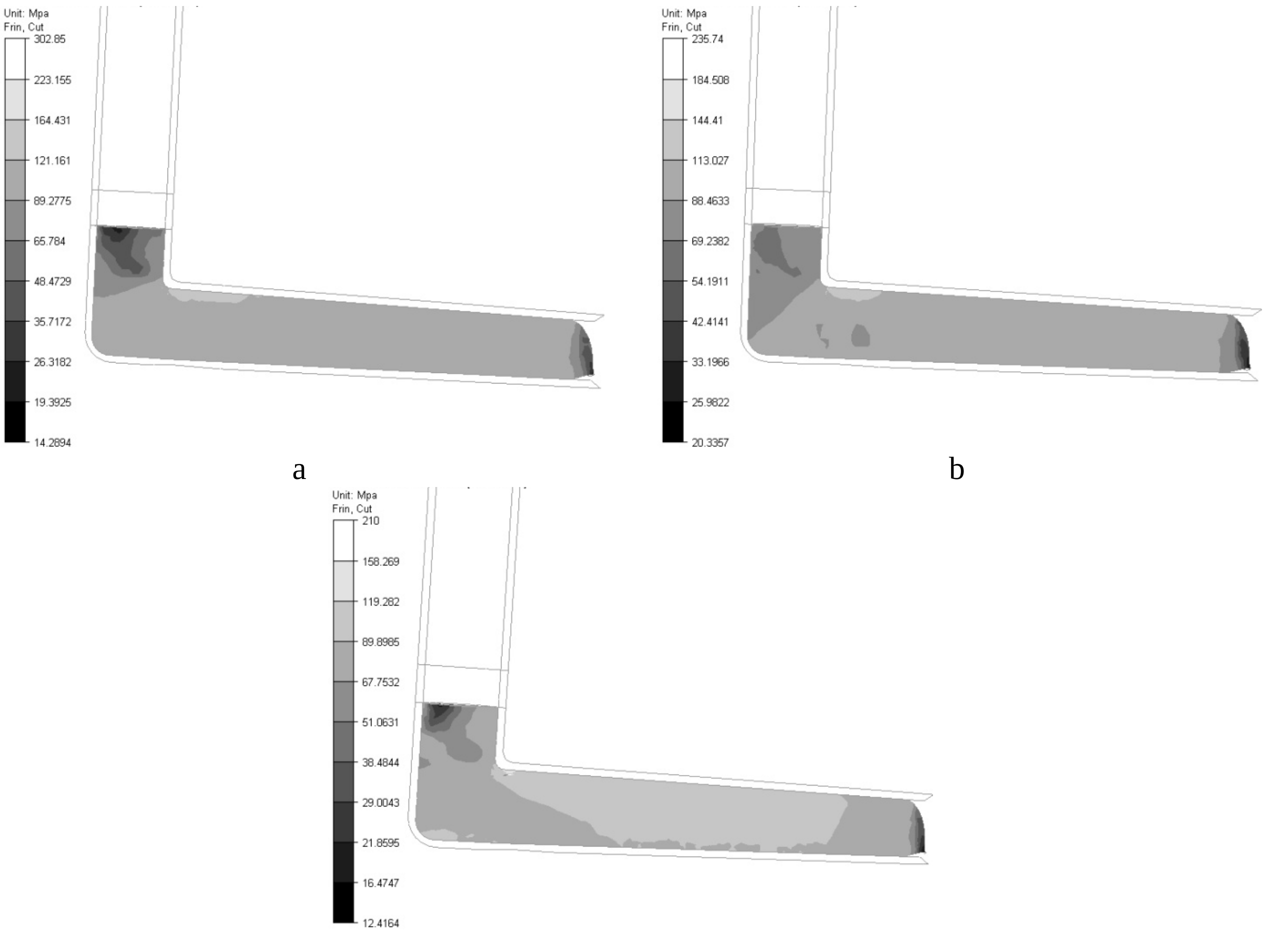

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Fig. 3. Stress distribution in the material during deformation by modified ECAE method at temperature 350°C using extrusion rate:
a – 1mm/s, b – 10 mm/s; c – 20 mm/s

Concentration of stress in deformed specimen, in this case, was observed during passage through the angular channel and in whole shaping zone. The increase of extrusion rate caused loss of uniformity in distribution of stress fields at deformed material. It also causes temperature growth inside the material from 360°C to 458°C, as shown in Figure 4. The most uniform level of stress distribution was observed at the lowest extrusion rate but the level of those stress values was the highest. It can be explained by small (about 9°C) gradient of temperature changes in shaping zone. Increase of extrusion rate causes growth of temperature gradient in whole shaping zone and decrease of stress level what can be explained by the effect of material softening.

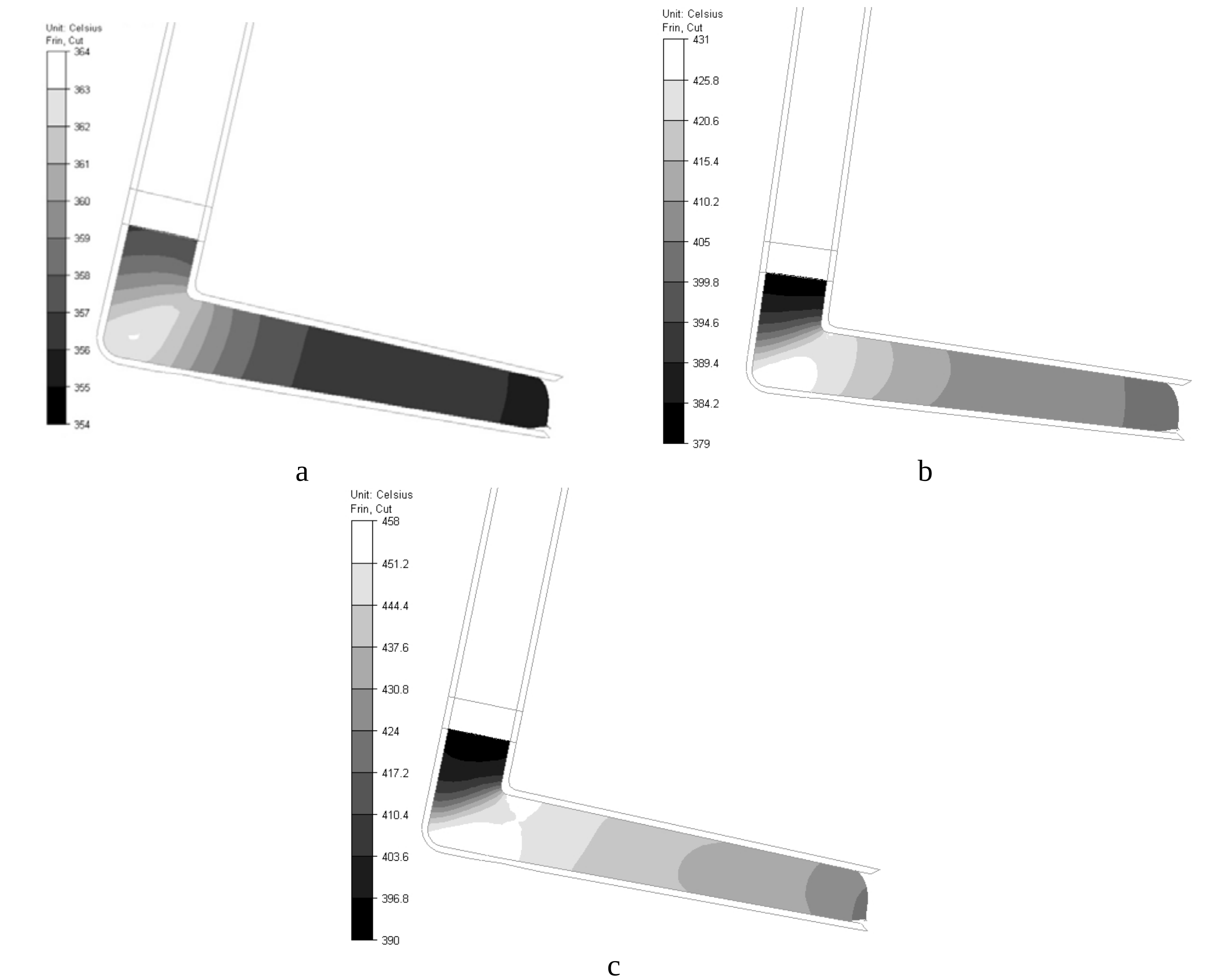

Fig. 4. Temperature distribution in the material during deformation by modified ECAE method at temperature 350°C and extrusion rate:

a – 1mm/s, b – 10 mm/s; c – 20 mm/s

In the case of extrusion process using conventional ECAE, the accumulation of stress occurred mainly at the place of the material passage through the angular channel. Application of the modified matrix causes a significant increase in the stress intensity. Various behaviour of the material during investigated extrusion processes by ECAE method (stress and temperature distribution) will significantly impact on mechanical properties of obtained products, which can be dedicated to further plastic working. It can be assumed that modified matrix application will allow to obtain the material with high structure refinement. It seems to be closely connected with increase of a plasticity range. Fine grained structure is a very important factor raising the value of the yield point, tensile strength and plastic properties of magnesium alloys. Physical modelling of investigated deformation processes will allow for confirmation of made assumptions.

SUMMARY

Using the ECAE method, there appeared a necessity to deal with high levels of deformation in the material during passage through the angular channel, which is applied to the high level of local stress in each of analyzed cases. Increase of extrusion rate have an important influence on the temperature level of the process, which is associated with accumulation of energy in deformed material. Application of 350°C temperature and 10mm/s extrusion rate allowed to obtain a product with an uniform flow stress distribution on longitudinal section and simultaneously relatively low level of stress values.

On the basis of results of numerical tests, it can be noticed that using a tapered angular matrix allows to obtain the material suitable for further processing. There was not observed any discontinuities or cracks in the metal during transition by the angular channel in both analyzed cases. The increase of the extrusion rate causes higher level of temperature decomposition and higher stress concentration inside deformed material. Observed increase of stress concentration is justified and results from a strong grid reconstruction inside the material. It can be assumed that application of complex deformation scheme using the modified ECAE method gives a product with good reserve of plasticity.

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