STABILITY OF PLASTIC FLOW IN MAGNESIUM ALLOYS DURING ECAP PROCESS

Radim KOCICH ě, Miroslav GREGER ě, Adéla MACHÁČKOVÁ ğ

a Department of Materials Forming, FMME, VŠB TU Ostrava 17.listopadu 15, CZ 70833 Ostrava-Poruba, Czech Republic, radim.kocich@vsb.cz, miroslav.greger@vsb.cz
b Department of Thermal Engineering, FMME, VŠB TU Ostrava 17.listopadu 15, CZ 70833 Ostrava-Poruba, Czech Republic, adela.machackova@vsb.cz

Abstract

Magnesium alloys based on Mg-Al-Zn system are very attractive materials in many industries due to its properties. One of common forming manner suitable for this kind of material is application of SPD (severe plastic deformation) method. Paper is focused on deformation behavior at ECAP (equal channel angular pressing) process. For this purpose FEA (finite element analysis) was used. Among other were monitored the flow process during ECAP as well as its stability. As variables were chosen friction coefficient, strain rate, φ - angle or back pressure possibility. Results suggest that plastic instability of flow is dependent on more factors. Partial plastic instabilities remain in the materials even if back pressure is applied.

Keywords: ECAP, FEM, plastic flow

1. INTRODUCTION

We witness in the area of SPD technologies particularly during the last decade great effort of researchers to define as precisely as possible behaviour of various materials at ECAP process. By virtue of requirements of automotive and aircraft industries this research has been dominantly oriented namely to light metals and their alloys. One of very attractive possibilities suitable for these purposes consists also in use of Mg based alloys. In spite of the fact that some of these alloys were used for example in the above mentioned industries already for a long time (alloys AM60, AZ31…) we see the efforts to use also the alloys designated originally for foundries (AZ63, AZ91…). Optimum use of the given material requires knowledge not only of its mechanical characteristics, but also its behaviour at deformation. Deformation behaviour of material does not influence only distribution of deformation, but also distribution of stress and therefore also the tendency of material to formation of cracks and ruptures. [1].

Aim of this paper is to focus attention on the development of plastic flow at the ECAP process. Plastic stability of material flow at its extrusion plays and important role particularly at processing of hardenable alloys. As it turned out quantity of deformation invested into material is not uniform in respect to cross section of extruded material [2]. Quantity of deformation invested into the lower part of extruded material is smaller than that invested into the upper part. In materials that are hardenable by deformation a curvature occurs of the area of intersection between the channels, which contributes also to reduction of quantity of deformation invested into the lower part of the sample [3].

2. EXPERIMENTAL AND RESULTS

Experimental part of this paper is focused on realisation of numerical simulations, which should define behaviour of the alloys AZ91 at the ECAP process. The software Forge 2009 was used for this purpose, which enabled FEA (finite element analysis) of extrusion. Input dependence Stress-Strain of the investigated alloy was obtained from torsion plastometer SETARAM (Fig. 1). Simulation itself was based on an assumption that extrusion temperature was 280°C; moreover, on the basis of previous experiments [4, 5] three variants of friction between the sample and the matrix were assumed. (μ = 0, μ = 0,04, μ = 0,4).
Extrusion speed \( (v = 3 \text{ mm.s}^{-1}, v = 10 \text{ mm.s}^{-1}) \) was defined as the third variable factor. Due to the fact that comparatively large number of published works exists, which deal with application of FEM for possibly the most frequently used matrices \( (\Phi = 90^\circ) \), we have made numerical simulations for matrices with angles of 30°, 60° and 110°.

The mesh that was interposed on the extruded sample prior to start of the process was after completion of ECAP visibly deformed (Fig.1), particularly in the areas near the inner rounding, which is documented also in Fig.1a. The top half of the sample is accelerated in comparison to the bottom half in fact immediately behind the inner rounding. It is evident from the attached meshes, that in case of use of the matrix with the angle \( \Phi = 110^\circ \) differences exist at two different extrusion speeds. In both cases an area of instability of material flow exists at extrusion of the alloy AZ91. In the case of lower applied speed (3 mm/s) this area is situated namely in sub-surface layers of material. Peripheral layers show stable flow. Situation is somewhat different in the case of higher applied extrusion speed, where it is obvious that top surface of the sample (adhering closely to inner rounding) is undulated more than in the case of lower strain rate, which in case of the matrix with \( \Phi = 110^\circ \) indicates unfavourable influence of higher extrusion speed on plastic flow stability.

**Fig. 1** Plastic flow pattern of AZ91 on ECAP (\( \Phi = 110^\circ, \mu = 0,04 \)): a) \( v = 3 \text{ mm.s}^{-1} \) b) \( v = 10 \text{ mm.s}^{-1} \)

**Fig. 2** Plastic flow pattern of AZ91 on ECAP (\( \Phi = 60^\circ, \mu = 0,04 \)): a) \( v = 3 \text{ mm.s}^{-1} \) b) \( v = 10 \text{ mm.s}^{-1} \)
What concerns the matrix with the angle \( \Phi = 60^\circ \), it is possible to state, that although in this case higher intensity of deformation (almost double) has been achieved in comparison with the previous case [5], we see here high non-homogeneity of deformation. This is demonstrated by the deformed mesh (Fig. 2), which shows us that the sample does not adhere perfectly to the walls of matrix in the output part of the channel, especially to its top surface. It is also obvious that the alloy shows here also areas of unstable flow. What concerns this angle in the matrix, it is evident in comparison with the previous case, that these areas have been situated exclusively in the top half of the sample, however, right under the surface. However, different applied extrusion speed contrary to the previous case did not cause more distinct differences of material behaviour at its flow through the matrix.

![Deformed mesh](image)

**Obr. 3** Tok slitiny AZ91 při ECAP (\( \Phi = 30^\circ \), \( \mu = 0,04 \)): a) \( v = 3 \text{ mm.s}^{-1} \) b) \( v = 10 \text{ mm.s}^{-1} \)

**Fig. 3** Plastic flow pattern of AZ91 on ECAP (\( \Phi = 30^\circ \), \( \mu = 0,04 \)): a) \( v = 3 \text{ mm.s}^{-1} \) b) \( v = 10 \text{ mm.s}^{-1} \)

Matrix with the angle between the channels \( \Phi = 30^\circ \) in comparison to the case of (\( \Phi = 60^\circ \)) meant reduction of the area of unstable flow. It is obvious that at higher applied speed (10 mm/s) higher acceleration of these material layers occurs (higher curvature of individual cells). Maximal shift of threads (materials layers) towards the external surface of mat (external radius of matrix) occurs here as well, as Fig.3 manifests it. Elongation if cells particularly in the mentioned direction is clearly visible, which was caused by small angle \( \Phi \). The same factor is responsible also for change of the material flow at comparison of the places before entry to the bend and behind it. On the input side outer layers of the sample are accelerated, while behind the bend it is vice versa. This is, however, true only when the zone of deformation is filled, it means from the moment when the frontal surface of the sample gets past the bend.

Due to non-uniform distribution of deformation along cross-section and to other characteristics next simulations were devoted already only to the matrix with the angle \( \Phi = 110^\circ \) with assumption of lower extrusion speed. Aim of these subsequent simulations was particularly to determine the influence of the friction coefficient on distribution of plastically instable areas of material flow.
Different value of friction coefficient meant also somewhat different character of material flow. Unstable flow begins to manifest itself with an increasing friction closer to the surface areas adhering to the inner radius of the matrix. The highest defined friction brought comparative reduction of „undulation“ of central layers of the sample. This means that it approached by its behaviour the case, when factor of back pressure is used. However, as it is evident from the results of simulation, not even the back pressure caused a complete „erasing“ of the areas of unstable material flow.
Fig. 5 manifests also comparison of the material flow lines at all three different possibilities of extrusion. Different behaviour of volume of material in the area of dead zone at individual variants is evident. The variant, in which no friction was assumed, meant higher flow in the area of top surface of the sample (inner radius of the matrix). Detail of slip bands (Fig. 6) documents influence of increasing friction, or of back pressure. It is apparent that application of back pressure means the biggest deceleration of material surface layers (adhering to the inner rounding in the matrix) and also the maximum stabilisation of plastic flow.

It should be noted that use of matrix with the angle $\Phi = 110^\circ$ lead to formation of a „dead zone“. It was preserved even at the increased strain rate. Consequences of presence of a „dead zone“ had already been discussed before [6], showing that its influence on non-uniformity of deformation exactly in this area was obvious. As it was proved in ensuing simulations the decreasing angle $\Phi$ eliminated this zone, by which influence of deformation was homogenised and naturally material flow was also changed. What concerns material flow, in the case of use of matrix with $\Phi = 60^\circ$ the same character of changes in dependence on changes of speed did not occur, unlike the case when matrix with $\Phi = 30^\circ$ was used, when with increasing speed occurred gradually also acceleration of external material layers, which resulted in formation of a gap between extruding punch and material. Although an indication of the fact that external materials layers have a tendency to accelerate, it cannot bear comparison with the case of matrix with smaller angle. In the matrices with $\Phi = 110^\circ$ this trend is not perceptible at all.

Increasing friction results in reduction of size of “dead zone” (angle $\Psi$), or in an increase of deformation homogeneity. In other words it can be stated that deformation invested into the area of external rounding of the channel (dead zone) is at the highest tested friction coefficient almost identical with the surrounding areas. This can be with attributed with high probability to the influence of the „dead zone“, which was in the case of absence of friction delimited by the angle $\Psi = 36^\circ$, while in the case of friction given by the coefficient $\mu = 0.04$ value of the angle was $\Psi = 26.5^\circ$, and in the case of $\mu = 0.4$ no dead zone was created. It means that the dead zone influences significantly homogeneity of deformation in extruded samples. Validity of preceding sentences is proved among others also by the development of mesh during extrusion, where a tendency of the cells of the mesh placed near the external rounding to elongate towards the external rounding is quite evident. It means that material belonging to these areas behaves in the same manner and it fills much more the dead zone with an increasing friction. Typical undulations of original longitudinal boundaries of cells are well visible on deformed meshes (instability of plastic flow at deformation), when increasing friction increased this undulation namely in peripheral areas. To this higher acceleration was added of layers of material, which was situated into central and surface areas (adhering to the inner bend of the channel), which caused that the sample had a tendency to rotate downwards. The same findings were confirmed also by practical physical modelling of metal flow at ECAP.

Behaviour of the cells adhering to the external rounding can be attributed to the influence of the bend, when in the first instance (before the bend) these cells have a tendency to lag in respect to the rest of volume, and on the other hand to accelerate after the bend in direction towards the exit from the matrix. Such behaviour is the cause of tensile or compressive stresses.

3. SUMMARY AND DISCUSSION

As it was experimentally confirmed by Delo and Semiatin [7], material at the ECAP process shows signs of deformation softening, which may lead to plastic instability of the processed materials. Occurrence of plastic instability of flow subsequently entails certain probability of „unsuccessful“ processing of material and highly probable formation of heterogeneous structure. Formation of such softened zones is quite common process also at hot angular extrusion of magnesium [8], which was confirmed in the presented paper.

For the case of high friction, as well as for application of back pressure it is visible that the mesh has comparatively „sharper filling“ of the dead zone in comparison with the case of smaller friction. This factor
influenced significantly uniformity of the flow along cross-section of the extruded material. Occurrence of the deformation zone is in the case of sharper angles of the matrix $\Phi$ shifted even behind the inner radius. Application of back pressure lead to obtaining of possibly the „narrowest“ deformation (shear) zone and also to the best filling of the dead zone. Non-homogeneity of input deformation along the sample cross-section, caused among others by friction factor, extrusion speed or temperature of extruded material is of course the cause of difference between theoretical and real value of the invested deformation.

As it follows from the results, higher value of friction coefficient brought about higher homogeneity of deformation, which can be explained by reduction of the dead zone size. However, the highest homogeneity of the value of invested deformation was brought about by application of back pressure. This, nevertheless, does not mean that factor of back pressure could eliminate completely material instability. Thus “affected” areas occur locally even after application of back pressure. Higher friction therefore means narrower area of the deformation zone and at the same time also higher uniformity of deformation, however, it does not eliminate completely plastic instability of material.

ACKNOWLEDGMENTS

The presented results were obtained within the frame of solution of the research project GPCR 106/09/P395.

REFERENCES


