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A computational investigation of Equal Channel Angular Pressing of molybdenum validated by experiments

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ABSTRACT

Equal Channel Angular Pressing (ECAP) is a metal forming process which is commonly used to refine grain structure in metals. The process involves pushing a billet, under high pressures, through a curved channel. Metal forming of molybdenum necessitates high forming temperatures so as to sufficiently lower the flow stress and increase ductility. These high temperatures are greater than the maximal temperature of the steel tools which are heated to a lower temperature then the billet. As a result great thermal gradients may develop during the forming process.

In this study, the thermo-mechanical coupling between the temperature and deformation fields in ECAP of molybdenum was investigated using a computational/experimental methodology. First, the flow stress of molybdenum and copper (used as a dummy-block in the ECAP process) and the friction conditions with the steel tools at different temperatures were determined using cylindrical and ring compression tests in conjunction with an iterative coupled finite element analysis. Finally, a multi-stage finite element model of molybdenum ECAP was developed and validated by comparison to experiments. The computational results show that, in each pass, large temperature gradients develop across the specimen. While material points at the front and back of the billet may undergo similar equivalent plastic strains they deform at very different temperatures of T = 600 °C and T = 480 °C respectively. As a result, even after a single pass, each material point may have undergone a very different thermo-mechanical process. These differences in thermo-mechanical histories may lead to different microstructural changes along the specimen.

1. Introduction

In recent years, there has been a growing interest in severe plastic deformation (SPD) methods, in which bulk billets undergo large plastic strains in order to obtain ultrafine-grain structured materials. The high strains cause high densities of lattice defects and as a result the grain refinement may reach even nano-scale Zehetbauer and Zhu (2009).

SPD techniques available include: Equal-channel angular pressing (ECAP) in which a billet is pushed under high pressures through a curved channel. In high-pressure torsion (HPT) and ring torsion, torsion is applied under high compressive hydrostatic loads in order to achieve large plastic strains. Multidirectional forging (MDF) uses a deformation cycle that recreates the original geometry of the billet. Accumulative roll bonding (ARB) uses cycles of rolling, cutting, and stacking which are performed repeatedly. Cyclic extrusion and compression (CEC) similarly involve alternating cycles of extrusion and upsetting to accumulate strain. Furthermore, new methods or variations of classical methods for achieving SPD are constantly proposed as described in Alexander (2007).

The most developed and common SPD processing technique is the ECAP. As reported by Alexander (2007), compared to other SPD methods ECAP is simple, and may be used on relatively large or long billets, with different cross sections (as opposed to HPT which is limited to very small samples or ARB which is limited to a particular configuration). It also enables processing multiple billets simultaneously. However ECAP has several limitations. For example, when the size of the billet increases large forces are required to complete the process. Another limitation reported by Ivanov (2008) is that a larger grain size is obtained in ECAP compared with HPT. Nevertheless, it should be noted that a different degree of deformation was reported for each

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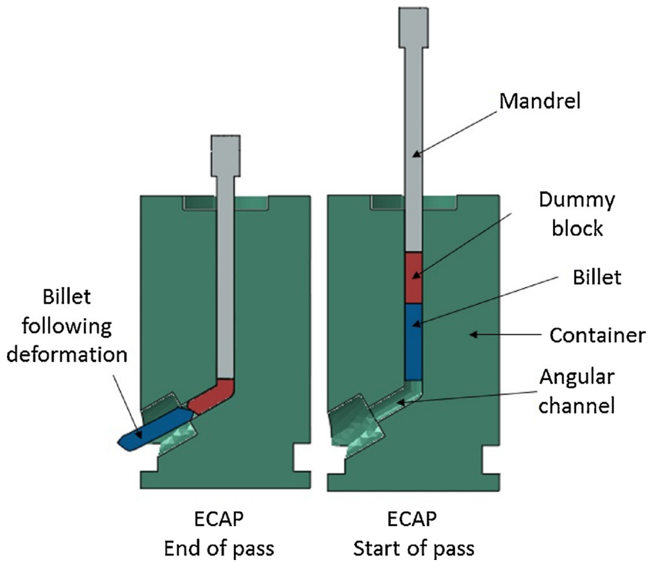

Fig. 1. A schematic representation of an ECAP assembly.

method in Ivanov (2008), which hinders the ability to compare between the SPD methods.

The current study deals with investigation of the ECAP process. A schematic representation of the process is shown in Fig. 1.

The forming process is commonly conducted several times, and the billet orientation with respect to the channel is changed between consecutive passes. As the billet passes through the curved part of the channel it is plastically deformed. The amount of average plastic deformation which develops during a single pass was shown to depend on two angles ψ, Φ which construct the channel curvature as can be seen in Fig. 2.

Iwahashi et al. (1996) provided an expression for the value of average equivalent plastic strain:

$$\bar{\varepsilon}_p = \frac{1}{\sqrt{3}}\left[2\cot\left(\frac{\Phi}{2}+\frac{\Psi}{2}\right)+\psi\cos ec\left(\frac{\Phi}{2}+\frac{\Psi}{2}\right)\right] \tag{1}$$

The accumulated plastic strain in the specimen increases the dislocation density considerably, which leads to processes of static or dynamic recrystallization (grain refinement). The process of grain refinement is conducted in order to increase the strength of the component. The process can be conducted at room temperatures for materials of high ductility such as aluminum. For materials of lower ductility, in order to ensure the ECAP process completes successfully without cracking or fracture of the specimen, the tools and the specimen are pre-heated to elevated temperatures.

In Furukawa et al. (2001) an analytical method was proposed for

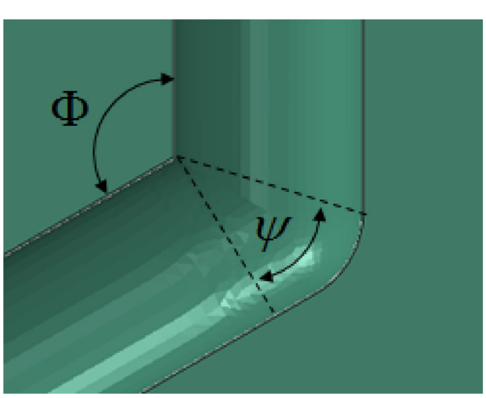

Fig. 2. Curvature angles assumed to govern the amount of plastic strain in the ECAP process.

calculating the location of the shear plane during ECAP. The method was utilized later in Furukawa et al. (2002) to investigate the shear patterns in ECAP using several processing routes and channels with $\Phi = 90^0$, $\psi = 0^0$ and $\Phi = 120^0$, $\psi = 0^0$. In each processing route the specimen orientation was changed either along the longitudinal or the transverse axis. The study concluded that for obtaining an optimal microstructure with equiaxed grains it is recommended to change the specimen orientation by 90^0 around the longitudinal axis between passes (termed a Bc4 processing route).

In Mallikarjuna et al. (2009) the ability of the ECAP process to refine grain size in aluminum 2014 was investigated. The experiments were conducted at room temperature using $\Phi = 120^0$, $\psi = 0^0$ with a change in specimen orientation of 180^0 around the longitudinal direction between passes (termed a c2 processing route). It was reported that grain size changes drastically during the three initial passes with subsequent passes showing only a moderate decrease.

The equations that govern deformation during the ECAP process are highly non-linear due to large displacements, large strains and friction between the billet and tools. As a result, finite element (FE) methods have been utilized to study local mechanical field values during the ECAP process.

In Suo et al. (2006) the ECAP process of a theoretical material was investigated using a 3D finite element model. Emphasis was placed on the influence of friction coefficients on the computed deformation fields. The study concluded that friction plays a major role in the ECAP process, with average plastic strains increasing significantly as the friction coefficient increases. Mahallawy et al. (2010) employed the finite element method to investigate the optimal processing route in ECAP of pure aluminum. The study concluded that better plastic strain homogeneity is obtained if there is no change in specimen orientation between passes. It should be noted that the findings in Mahallawy et al. (2010) are conflicting with previous experimental results reported in Furukawa et al. (2002). Silva et al. (2012) investigated a non-isothermal ECAP process of tantalum using a 2D finite element model. The study showed that the thermo-mechanical coupling plays a role in decreasing pressure forces and that the temperature gradients that develop during the process are linked to the die geometry.

Molybdenum is a refractory metal capable of withstanding extreme temperatures without losing its strength. This makes molybdenum especially attractive as an engineering material for components which must perform under high temperatures. This includes combustion chambers, aircraft parts, industrial motors and more. Nevertheless, the ability of the material to withstand high temperatures with no reduction in strength makes it challenging to use ECAP for refining the materials grain structure. The main challenge is tool heating, as tool steels such as H12, H13 or H21, commonly used in metal forming processes, begin to decrease in strength at $T \approx 600^0C$. As a result, in ECAP processes of molybdenum, while the billet is heated to $T > 900^0C$ the tools are heated to a temperature of $T = 400^0C$. This heating of the tools to such a temperature eliminates the possibility of opening the container for stock ejection therefore a copper billet was used as an intermediate stock between molybdenum passes. These initial temperature gradients make the determination of the plastic strain fields that develop during the process difficult due to the close coupling between the thermal and mechanical fields.

The ECAP process of molybdenum was investigated in this study using a 3D coupled thermo-mechanical finite element model validated by experiments. Initially, compression tests of cylindrical specimens and Ring Compression Tests (RCT) were conducted on molybdenum and copper. Each experiment was represented by a finite element model, and both were used to determine the flow stress (FS) at different temperatures as well as the friction coefficient at the interface between the specimen and the Tool steel, by means of an iterative process. Finally, a two stage finite element model of molybdenum ECAP was developed and validated using ECAP experiments. Following validation, the model was used to investigate how the thermo-mechanical