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An experimental study on optimum lubrication for large-scale severe plastic deformation of aluminum-based alloys

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ABSTRACT

Reducing friction plays a key role in the technological application of severe plastic deformation (SPD) techniques like equal-channel angular pressing (ECAP). In this paper, we report on an experimental study that investigates the suitability of various commercially available lubricants for SPD processing. We consider a custom-built friction test that allows the evaluation of the potential of different lubricants under typical SPD processing conditions. In order to determine an optimum lubrication system for the ECAP process, the friction test is specifically adapted with respect to the specific characteristics occurring during ECAP, such as large sliding distances and high pressure between the ECAP die and the processed material. We discuss how different lubricants influence the processing of the material with a focus on the pressing forces (during ECAP, and during an alternative SPD process, transverse impact extrusion) and the resulting surface quality of the processed ECAP billets. A wax-based lubricant is identified as an environmentally friendly and clean lubricant that provides excellent properties. With this lubricant, even for large sliding distances, low friction values are recorded and this results in low pressing forces and an excellent surface quality. Since lubricants play an important role in further developing SPD processes, the results presented here may help to optimize existing SPD processes and to scale up processes for future industrial applications.

1. Introduction

In recent years methods for producing high-strength metallic materials, e.g., the equal-channel angular pressing technology (ECAP), have gained growing interest. The ECAP technique was introduced by Segal et al. (1981) in the 1980s. In Segal et al. (1981), Segal applied this technique to introduce very high strains into bulk billets of pure copper and pure iron. This allowed the characterization of such severely cold worked materials by standard tensile samples for the first time. The fundamental principle of ECAP is that a billet (typically with square or round cross-section) is pressed through a rigid die, and forced to flow through an angled channel. A simple shear strain is introduced into the material in a thin zone at the intersection plane of the entrance and exit channels. For the typical case of a 90° angle, the equivalent strain, as calculated in Iwahashi et al. (1996), is 1.15 per pass. Segal (2004) pointed out that one of the key features of the ECAP technique is that the outer dimensions of the billet remain practically unchanged so that the pressing can be repeated several times with the same billet in order to reach very high cumulative strains. Today this basic concept for ECAP is well established. It is widely used in a laboratory scale for the improvement of different metallic materials.

Valiev et al. (2000) give an extensive overview on different methods of SPD processes and the structural characterization of SPD materials. The specific properties of ECAP materials are produced by extreme work hardening and by the formation of an ultrafine-grained microstructure. Particularly detailed descriptions of the principles of ECAP as a tool for grain refinement can be found in a review article of Valiev and Langdon (2006). In their paper Valiev and Langdon (2006) report on recent developments regarding the processing by ECAP, from conventional to continuous variations. Especially experimental factors influencing ECAP – like the channel angle, the angle of the outer curvature, the pressing speed and temperature, as well as the influence of a backpressure – are discussed in detail.

But until now the lubrication during ECAP, an essential aspect for successful processing, has not been investigated systematically. The interplay of the lubricant with the materials (both in the workpiece and the tool itself) plays a key role and determines, e.g., pressing forces and also limitations in terms of pressing velocity. The solid

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lubricants molybdenum disulfide and graphite are well known for the reduction of friction during ECAP and are commonly used. El-Danaf (2008) for example processed commercially pure aluminum by ECAP with a 90° die using route B_C. The die was manufactured from a hot-work tool steel. The aluminum samples in this study were lubricated using a graphite-based lubricant. Mathieu et al. (2006) report on the reduction of pressing forces during ECAP by using a new die design. In this study, pure materials like copper, aluminum and titanium were processed using different temperatures ranging from RT to 450 °C. Even in this temperature range, a molybdenum disulfide lubricant was used. Iwahashi et al. (1997) used repetitive ECAP pressings to introduce high strains in aluminum samples of 99.99% purity. The 90° ECAP die was made from SK3 tool steel and the aluminum samples were coated with a thin film of a lubricant based on molybdenum disulfide (Sumico Moly Assembly Oil containing 5 wt% MoS_2). In Frint et al. (2012), we recently used large scale ECAP to investigate the role of backpressure during processing of the commercial aluminum alloy 6060 (AlMgSi0.5). We used a 90° ECAP die with a friction reduced design with sliding walls, and a lubricant containing a large fraction of molybdenum disulfide as well as graphite. While molybdenum disulfide is in principle well established in the SPD community, it is also recognized that it does not adhere well to aluminum and thus is not specifically adapted for a contact of steel and aluminum. The selection of a suitable lubricant remains a crucial engineering factor for successful ECAP, even if dies with a design-based reduction of contact friction are used. While such dies, as discussed in greater detail in Frint et al. (2016), reduce friction in a large fraction of the contact area between billet and ECAP die, certain parts of the die necessarily remain static and hence are locations where friction does occur. This is especially true for the processing of large billets with high aspect ratios where the stability of the lubricant, in the interface of the rigid parts of the die and the billet, most likely tends to become critical due to the longer glide paths. There clearly is a need for a systematic screening of different lubricants, and for a detailed analysis of their effect on pressing forces and billet homogeneity after ECAP of aluminum alloys.

Several studies dealing with tribology for more common forming processes, e.g. cold forging and extrusion, have been reported. These studies often investigate the performance of lubricants and coatings using various testing methods and materials like steels and aluminum alloys. Ruan et al. (2005) introduced a tribotest method to evaluate the performance of phosphate coating-based lubricants in cold forging of different steels. Their testing facility enables heating the die as well the work piece, which allows controlling the interface temperature. They state that the lubricity of the lubricants is strongly influenced by the interface temperature and the surface expansion of the material. Ngaile et al. (2007) confirmed these findings for large sliding distances up to 1000 mm using different steels and six types of coating-based lubricants. They found that lubricants based on calcium and sodium soap are at the same performance level as conventional zinc phosphate coatings with metal soap. In a more recent study, Sawamura et al. (2014) use a method applying backward extrusion, which enables to create high pressure, large surface area expansion and a large sliding distance. By superimposing a rotation of the punch during testing, severe forming conditions are created to investigate two conversion coatings and two oil-based lubricants. In case of forging aluminum graphite-based lubricants are often investigated and commonly used. Buchner et al. (2008) studied the suitability of lubricants based on graphite (dispersions and emulsions of graphite in water and/or mineral oil) for forging of AA2618. By using a special modification of a rotational forging tribometer, friction coefficients were determined using typical forging parameters like a high sliding velocity (150 mm/s), normal stress (up to 330 MPa), temperature (450 °C specimen, 250 °C tool) and small sliding distances (up to 80 mm). Bay et al. (2011) presented a friction test setup for cold forging of aluminum (AA6082) and steels with conversion coating and a solid film lubricant. The lubricants studied in Bay et al. (2011) were selected from a group of lubricant systems typically used for cold forging. Aluminum was provided with an aluminate conversion coating and either alkali soap or molybdenum disulfide.

In addition to the experimental testing setups discussed so far, various instruments for an analysis of lubrication during forming of metallic materials have already been developed. A comparison of different testing methods can e.g. be found in a publication from Podgornik et al. (2004). They evaluate a pin-on-disc, cylinder-on-disk and a new load-scanning test method with two crossed cylinders, considering the methods' feasibility to asses galling. Another approach by Zhang et al. (2009) for a new testing method is T-shape compression, a setup that combines compression and extrusion of a cylinder between a flat punch and a V-grooved die. The setup characterizes cold forging conditions and additionally allows measuring the corresponding friction coefficients. Most of these experiments, however, were strongly simplified and the corresponding data cannot be used directly to evaluate realistic friction conditions for the ECAP process. The methods to simulate (cold) forging conditions, for instance, always lead to a pronounced surface expansion which does not take place during ECAP. Conventional test setups like pin-on-disc or cylinder-on-disk configurations (point contact and line contact, respectively) do not represent ECAP-like contact conditions. Furthermore, the used testing parameters like proportionally high sliding speeds and temperatures often do not correspond to the conditions occurring during ECAP. Especially the large sliding distances of up to 1000 mm, in combination with very low pressing speeds, during ECAP have not been addressed yet experimentally.

To further investigate frictional and lubrication effects, a tribometer was developed and custom-built in order to experimentally simulate the conditions of SPD processes. Typical characteristics of ECAP are large sliding distances in combination with high hydrostatic pressures and a very low surface expansion. Adhesion of aluminum on the steel parts of the tool that get in contact with the processed aluminum must be avoided: it leads to high pressing forces and high adhesive wear of the ECAP-tool. To solve this critical issue, an optimum lubricant system has to provide an excellent separation and a low friction coefficient between the sliding surfaces. Other important aspects are the environmental impact of the lubricants and their costs. In this study we discuss our experimental approach for the selection of an optimal lubricant for the processing of large ECAP billets with a low amount of friction and excellent surface quality.

2. Experimental

For a closer match between friction testing and the true ECAP process, a large-scale tribometer was built according to Seyfert (2014). Fig. 1 schematically shows its design and working principle: A rotating aluminum ring (2), representing the ECAP billet, is subjected to an axial force by a stationary steel ring (1), representing the die wall. In this tribological twist system, different lubricants can easily be applied and their effects on friction and wear can be investigated in detail.

The axial force F and the torque M of the tribometer can be measured using load cells. The outer diameter D of the aluminum ring is 120 mm and the inner diameter d is 100 mm. With these values, the normal pressure p and the friction stress τ can be calculated using elementary engineering mechanics from:

$$p = \frac{4F}{\pi\left(D^2 - d^2\right)} \tag{1}$$