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Numerical and experimental analysis of twist channel angular pressing (TCAP) as a SPD process

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ABSTRACT

The article brings detailed information about the deformation behavior of copper during twist channel angular pressing (TCAP) obtained via 3D numerical analysis based on the finite element method (FEM). It was proved that the geometric parameters of the die, as well as the used deformation parameters, significantly affect the size and homogeneity of the effective strain, temperature or stability of the plastic flow of material. It may be stated that the largest effect on the size of the deformation was due to the twist rotation angle. The largest homogeneity of strain was detected at a higher friction coefficient. On the other hand, the distance between the twist and bend does not significantly affect the value of the strain. At higher extrusion speeds, the temperature of the extruded billet and the size of the dead zone both grow significantly. A comparison between the FEM and experimental results of the required loads and the homogeneity of the effective strain distribution showed good agreement. The homogeneity of the distribution of the deformation was confirmed by micro-hardness testing, whereas a relative growth of 80% was documented after the first pass.

1. Introduction

Among the methods based on the application of severe plastic deformations (SPD), the ECAP process designed by Segal [1] continues to hold a significant place. For its relative simplicity, this procedure is used very frequently to increase, among others, the mechanical properties of metal materials. The main properties characterizing an ECAP process are the possibility of relatively keeping the original shape of the sample, as well as simple shear, as the main deformation mechanism at the point of intersection between both channel parts [2]. This process is currently under commercialization efforts. The goal is the possibility of the continuous processing of long products. Concrete results include dissimilar channel angular pressing (DCAP) [3], ECAP-Conform [4] or equal channel angular pressing with partial back pressure (ECAP–PBP) [5]. However, to obtain well-defined and stable microstructures, it is generally necessary to perform a large number of passes. Increasing process efficiency, in the sense of imposing larger strain during individual passes to reduce the number of passes, is thus one of the desired goals. The first solution variants was the application of a rotary die that allowed multiple extrusions without removing the sample from the die [6,7], or the use of ECAP with parallel channels [8]. Certain results can be seen, for example, in the manner of proposing more efficient deformation paths. A concrete example is, for example, the work [9] of using a newly designed deformation route (BcUdII) to obtain the desired state after a lower number of passes. Another method is based on non-equal channel angular pressing (NECAP) technology, where protrusion occurs through a die with differing channels [10]. This method can lead to an increase of shear deformation by 25%, at a 50% reduction of the cross-section of the output channel in one direction. The relatively promising solution variants also include the recently proposed twist channel angular pressing (TCAP) process [11,12]. The process is based on the assumption that the bend of the channel is preceded by a twist situated in the vertical part of the channel. As the first partial results documented, this method can lead to higher homogeneity, as well as higher values of the imposed strain for each pass.

Numerical simulations based on the finite element method (FEM) have long been used to predict the deformation behavior of materials during plastic deformation for a long time now. A similar case also applies for SPD techniques. The large number of published results in this area confirms the applicability of this approach in various fields. Djavanroodi et al. [13] used 3D simulation to study the effects of channel angle, friction and backward pressure for the ECAP process when processing copper.

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Similarly, Kocich et al. carried out a 3D study of the ECAP process under temperature when considering Mg alloys based on Mg–Al–Zn [14]. Wang et al. used numerical analysis to evaluate geometric adjustments of the die to lower friction in the internal curving of the channel [15].

The purpose of this article is to provide a more detailed mapping of the TCAP process in the sense of ascertaining the influence of the variability of selected factors, especially the size of effective strain (ES). A more detailed description of this process with respect to the influences of geometry (die parameters, i.e., position of twist, angle of twist or angle between individual parts of channel) or deformation parameters (e.g., velocity of extrusion) has never been carried out. The subsequent experimental application of this process can then represent a partial verification of the predicted results (e.g., required pressing force).

2. Experimental

The goal of the experiment was to provide a more detailed description of the TCAP technology with respect to various influences of die parameters and selected deformation parameters on the resulting temperature, ES, in-homogeneity of strain at the cross-section of the sample, or pressing force needed for extrusion. The other monitored characteristics also included material flow. The TCAP process principle is illustrated in Fig. 1a.

The first part of the paper contains a numerical analysis of various variants of this process. The influence of the extrusion speed was monitored here, whereas the behavior of the material at extrusion speeds $v=3$ mm/s and $v=6$ mm/s were investigated. Other monitored factors included applied friction, which was represented in the simulation by two selected values of Coulomb friction ($\mu=0.02$, $\mu=0.05$). The discussed values of friction coefficient were chosen considering experiments carried out before, of which mutual comparison of values predicted with numerical simulations was successful with the help of measurement of punch loading. The influence of the geometry of the used die was also monitored. Specifically, this was carried out by simulating the influence of angle φ (angle between individual parts of the channel), angle β (twist slope angle), and angle ω (angle of the twist rotation) (Fig. 1a). The ECAP process was also analyzed to compare the efficiency of the TCAP process.

The second part of the experiment was based on the practical realization of the TCAP process. This part was focused on verification of the model used in FEM. The selected material was commercially pure Cu (99.97%) with a chemical composition of 0.0074Ni, 0.0058Sn, 0.0031Fe, 0.0030Zn, 0.0023Si (in wt%). The extruded samples were defined to match the numerical simulation, i.e., they had a square 12 mm × 12 mm × 130 mm cross-section. The experiment itself followed the copper being annealed at 650 °C/h. To objectively evaluate the results of numerical prediction, the die used in the experiment was defined by φ angle of 90°, ψ angle (outer corner) of 20°, β angle of 40°, and ω angle of 90°. Extrusion was carried out at room temperature (25 °C) on a hydraulic press at a rate of extrusion of 3 mm/s and MoS_2 was used as lubricant.

During the practical experiment, the temperature of the extruded material was also monitored. This was done via two thermocouples located at a distance of 1 mm from both primary deformation areas (the twist and bend). Simultaneously, the force load of the extruder during TCAP was also monitored. These parameters were subsequently verified with the results obtained from the numerical

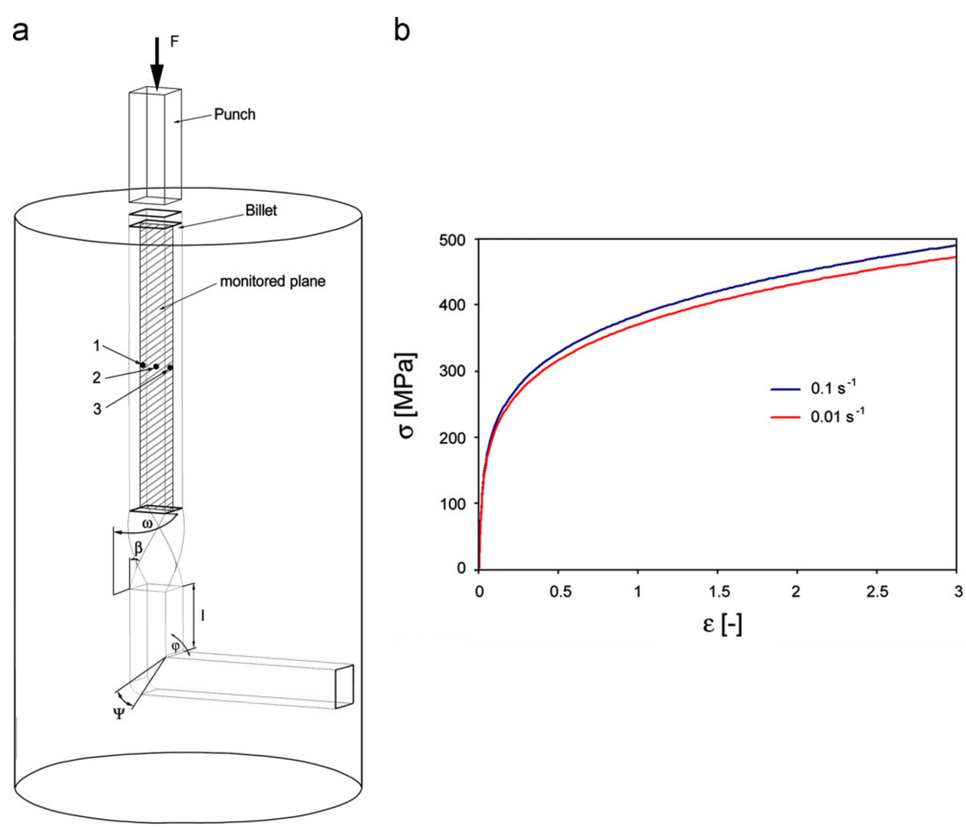

Fig. 1. Diagram of the TCAP process including monitoring points located on the "dividing" plane. 1, 2, 3—monitored places, ω—angle of twist rotation, β—twist slope angle, l—distance between the end of twist part of the channel and the bend of channel, φ—channel angle, ψ—angle associated with the arc of curvature where the two parts of the channel intersect, F—force (a) Stress–strain curves of Cu used in FEM (b).