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Optimum groove pressing die design to achieve desirable severely plastic deformed sheets

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ABSTRACT

In this paper, considering the problems of common finite element (FE) codes that consider simple constitutive equations, a developed FE code that considers a new constitutive model is used to simulate the behavior of copper sheets under severe plastic deformation (SPD). The new proposed constitutive model, that considers dislocation densities in cell interiors and cell walls of material as true internal state variables, can investigate all stages of flow stress evolution of material during large plastic deformations and also can explain the effects of strain rate magnitude on the mechanical response of material, during room temperature SPD. The proposed FE analysis is used to investigate the effects of die design on the property of SPDed sheets by groove pressing (GP) processes. To do so, the GP processes through existent designations of dies are simulated and a good agreement between the modeling results and experimental data is obtained. In addition, a new die design is proposed that can eliminate the problems of the existent designations of dies and can produce the sheets with higher strength and more uniform hardness.

1. Introduction

The production of high quality products in a short time and at a low cost without or with little waste material is an ultimate goal in metal-forming processes of manufacturing companies. In addition, in recent years, there has been a growing need in the metal-forming industry to improve not only the described parameters, but also the quality of products. All above parameters force the manufacturers to reform their attention to metal-forming designs and get the processes designing more important than before. The metal-forming process design consists of many decision-making stages and is a very expensive and time-consuming process. Currently in industry, the decisions are made based on trial and error without the fundamental understanding of the complicated deformation mechanisms.

Therefore, to avoid trial and error procedure in metal-forming simulations, there has been a considerable interest in numerical modeling of metal-forming processes. One of the most usable and prosper approaches of numerical simulation is finite element (FE) modeling. Many research groups are still developing and improving the FE codes for analyzing the die design. In these analyses, a metal-forming process is characterized by various process parameters including the shape of work piece and product, forming sequences, shapes of the tools or dies, friction, temperature, forming speed, and the material property. Within them, designation of the dies is the most important factor. It is well known, that unsuitable dies can lead to poor production rates and product defects. Therefore, the aim of large amount of manufacturing investigations is related to the die design analysis. Many researches are carried out on the conventional metal-forming processes. For example Lee et al. [1] investigated the effect of extrusion die design on the extrusion load and flow of material in the chamber during the extrusion process. They used FE analysis and proposed an extrusion die design that leads to an optimum material property and loading force. However, recently the importance of severe plastic deformation (SPD) has been increasingly recognized due to the excellent physical and mechanical properties in various ultrafine grained and nanostructure materials that are producible via SPD processes. For example in the automobile industry, lightweight problems are very important in respects of reducing fuel and protecting the environments, hence using the nanostructured materials with high specific strength, can be a suitable method in these aspects. Two major kinds of nanomaterials are producible by the SPD approaches; bulk materials by processes such as equal channel angular pressing (ECAP) and sheet materials by processes such as accumulative roll banding (ARB) and groove pressing (GP). However, there are not many researches on the die design effects for these processes. The only researches in these subjects are carried out on the bulk material processes and the case of sheet material processes has not yet been investigated. For example, Yoon et al. [2] studied the effects of die parameters on the homogeneity of ECAPed metals.

As mentioned, two major sheet SPD processes are ARB and GP. The ARB process that is invented in 1998 by Saito et al. [3] involves

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Nomenclature

b_i	body force density
t_i	surface traction
V	volume
S	surface area
$\dot{u}$	velocity vector
$\ddot{u}$	nodal acceleration vector
σ	stress tensor
ρ	mass density
M	lumped mass matrix
F	internal force vector
P	body force and surface traction vector
n	solution step
t	time
L_e	characteristic length of solid element
c	sound speed in the material
μ	shear modulus
v	Poisson's ratio
S^{overall}	over all strength
S^{cell}	cell interiors strength
S^{wall}	cell walls strength
f	volume fraction of cell walls
f_0	initial cell walls volume fraction
f_{sat}	saturated cell walls volume fraction
ε	strain
λ	numerical constant
S_d^j	partial dislocation interactions strength
M	Taylor factor
α	numerical constant
b	magnitude of Burgers vector
ρ^j	partial dislocation density
α^*	probability constant
β^*	probability constant
$\dot{\varepsilon}$	strain rate
T	absolute temperature
v_0	frequency of annihilation attempt
w	length of a potential site for annihilation of screw dislocations
$Q_{\mathrm{cross\text{-}slip}}$	activation enthalpy of cross-slip
D_L	lattice diffusivity coefficient
K_b	Boltzmann's constant
χ^*	numerical constant
δ^*	numerical constant
K	proportional constant
d	cell size
K_0	initially value of K
K_∞	saturated value of K
η	numerical constant

repetitive bonding of heavily rolled sheets. This method can effectively refine the structure and produce high strength nanomaterials. However, recent investigations showed that problems such as bonding defects and edge cracking through this process, which cause to material waste and low mechanical properties, limit the application of this process [4]. Therefore, the second approach, that eliminates the described problems, seems to be more useful. The principle of GP process is subjecting a sheet metal to a large amount of shear plastic deformation with grooved and flat dies in a plane strain condition, alternatively. This large amount of deformation that is imposed to the sheet, causes to improve the strength and hardness and also refine the microstructure of sheets [4–9]. Previous experimental works [4–6] reported a strength improvement about three times and a microstructure refinement over than 100 times during this process. This process includes a couple of dies (see Fig. 1); grooving die and flattening die, that are alternatively used in stages of process. Each pass of GP process is consisted of four stages: (1) The flat sheet becomes grooved by first die; (2) The flattening die flattens the grooved sheet; (3) and (4) The produced flat sheet in previous section, is rotated 180° around the axis perpendicular to the plane of the sheet and then the stages (1) and (2) are repeated. At the end of fourth stage, the sheet undergoes relatively uniform strain magnitude of about 1.15.

As shown in Fig. 1, two modes of dies are usually used in this process (see Fig. 2).

In first mode, both grooving and flattening dies are consisted of a cave that the sheet is placed in it during the process and so the sheet is not free to elongate during the process in any direction. This mode of dies is called constrained dies and the process that is carried out by these dies is called constrained groove pressing (CGP). However, in second mode of dies, there is a rake (rail) that the sheet is placed in it. So, in this approach that is called repetitive corrugating and stretching (RCS), the sheet can elongate in one direction (length of sheet).

The mechanical properties and especially the uniformity of these properties in the processed sheets by these approaches are different [4–6,8]. Also, by observing a large amount of inconsistency between the reported properties of the processed sheets in prior works that are claimed to be on same materials [4,6], it is found that experimental works can not determine the efficiency of each process. However, it seems that simulations can be a more accurate tool for detecting the better die design. It should be noted that after proposing the designs of the described modes of GP processes, there is not any effort to find better dies for producing better and more uniform sheets. Thus, a perfect simulation like proper FE model can be useful in this object.

A number of simplified methods have been developed to investigate the effects of die design in the last 10 years [10]. By considering the important effects of constitutive equations on the behavior of materials during deformation, especially in large magnitude of strain, using the simple constitutive equations in FE analysis is not acceptable [11–13]. For example, strain rate has a clear effect on the mechanical response of materials during cold large deformation [14]; however, none of the presented simple constitutive equations considers this fact. Therefore, some developments should be carried out on the existent simulation approaches. An appropriate substitution for simple constitutive equations is a constitutive model that can investigate the mechanical behavior of material under deformation by considering true internal state variables.

In this study, the FE analysis is developed by coupling with a new true internal state variables model to investigate the effects of die design on the properties and also the uniformity of these properties on severely plastic deformed copper sheets. As a consequent, a new die design called Modified RCS (MRCS) die is proposed that can produce better and more uniform mechanical properties in the sheets comparing with the existent dies designations.

In this paper, first, the new design of GP dies is introduced and in next couple of sections, reviews of FE analysis and true internal state variables model are presented. Then the properties of produced sheet by CGP, RCS and the MRCS are compared. At last, the main findings are presented in Section 6.