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Analytical model to estimate force of constrained groove pressing process

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ABSTRACT

Purpose of the present study was to estimate force of constrained groove pressing process using elastic-plastic relationships and some relations have been provided to calculate force of the process. In this research, behavior of sheet was examined and constrained groove pressing process was classified into three bending, stretching and forging steps. Then, the force of process was estimated using plasticity relationships and the results were compared to experimental data and finite element simulation. To investigate the effect of parameters of material and geometry, three different materials and two different geometries of die and sheet were compared together. According to the obtained results, presented relationships can predict the force during constrained groove pressing process for each material and geometry of sheet and die. Also, Von-Mises and Tresca yield criterion were examined and found that Von-Mises criterion can better estimate force of the process.

1. Introduction

Production of materials with ultrafine grains (UFG) and Nanostructure is very important because of specific properties. One of the methods to produce materials with ultrafine grains is severe plastic deformation (SPD) [1,2]. There are various processes for severe plastic deformation and production of materials with ultrafine grains microstructure that can be mentioned to equal channel angular pressing (ECAP), equal channel angular rolling (ECAR), accumulative roll-bonding (ARB), high pressure torsion (HPT), repetitive corrugation and straightening (RCS), cyclic extrusion compression (CEC), torsion extrusion (TE), Constrained Groove Pressing (CGP) and Continuous High Pressure Torsion (CHPT) processes [3,4].

Among the existing processes, only ECAR, ARB, RCS and CGP can be used on metal sheets. CGP is a relatively new method in severe plastic deformation. This process was introduced in 2002 by Shin et al. [5] to produce ultrafine grains aluminum sheets. To date, several experimental studies have been carried out to investigate the effect of CGP process on mechanical properties and ultrafine grains of different alloys such as aluminum [6–8], copper [9,10], steel [11,12], Mg [14,15], Ni [16,17] and brass [18,19]. Study the effect of CGP process on mechanical properties and grains size shown using CGP process could reduce grain size and produce ultrafine grain materials also CGP process increases yield strength, ultimate strength and hardness that is because of increased dislocations, work hardening and ultrafine grains microstructures [8–17].

In a research by Peng et al. [20], first equation was presented to estimate the maximum force in CGP process. Eq. (1) is the presented relation which was not validated.

$$F_{\max} = k\frac{\sigma_{UT} L h^2}{t} \tag{1}$$

In this equation, σ_{UT} is ultimate strength, L and h are length and thickness of sample, t is groove width and k is a constant coefficient between 0.33–2.6 dependent to the die geometry. Hosseini et al. [21] in an analytical study presented a relation to calculate the flow stress at any pass of CGP according to dislocations theory and validated by experimental results. Eq. (2) shows the presented relation. In this equation σ_{mises} is Von-Mises stress, M is Taylor factor and τ^r is shear stress of structure.

$$\sigma_{mises} = M\tau^r \tag{2}$$

Peng et al. [22], by investigating CGP process, provided a relationship to estimate the minimum radius of die in CGP process. The formability and anisotropy behavior in CGPed aluminum sheets by Niranjan and Chakkingal [23] were studied. Hosseini and Kazemynezhad [24] with an analytical and finite element study provided relationships to determine homogeneity of structure based on hardness in copper CGPed sheets. They optimized the geometry of the die to achieve desired plastic deformation in

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Nomenclature

$d\varepsilon_i^p$	Plastic strain in *i* direction
$d\ \varepsilon_p$	Equivalent plastic strain
σ_i	Stress in *i* direction
σ_e	Effective stress
Y	Distance between two die in vertical direction
Y_c	Distance between two die in vertical direction at the moment of changing deformation pattern
y	Displacement of die in vertical direction
y_c	Displacement of die in vertical direction at the moment of changing deformation pattern
d	Perpendicular distance between two die on shear region
θ	Die angle
γ	Instantaneous angle of sheet
t_0	Initial thickness of sheet
t	Instantaneous thickness of sheet
x_0	Initial length of sheet on inclined planes
r	Instantaneous length of sheet on shear region
w	Sheet width
N	Number of shear region
n	Power of work hardening
k	Work hardening factor
μ	Friction coefficient
F	Force
p	Pressure
C	Calibration coefficient
K	Shear stress
A	Effective area

another study [25]. Dong et al. [26] by using regression relations obtained from experimental data and finite element model investigated grain recovery in CGPed aluminium sheet. Khakbaz and Kazeminejad [27] determined the effect of CGP on the work hardening and mechanical properties of aluminum sheets and provided a relationship to estimate the amount of dislocation production by cold working. They investigated strain rate sensitivity and fracture in another study and provided relationships for angle and stress of fracture [28]. Khodabakhshi et al. [29,30] proposed a new model for CGP process. They investigated feasibility and microstructure in new model and calculate the effective strain. In another study they examined the relationship between strength and hardness in CGP process. Wang et al. [31] experimentally evaluated mechanical properties of nickel sheets in the CGP process and demonstrated the die angle cannot be more than 60°.

Always forming force has been concerned by researchers in forming processes. Shirdel et al. [32] examined the mechanical properties of CGPed sheets and compared the force of process in experimental and simulation mode. Sateesh Kumar and Raghu [16] investigated hardness and tensile behavior based on different criteria in CGPed nickel sheets. Sajadi et al. [33] studied mechanical properties of CGPed aluminum sheets. They compared force of the process with finite element simulation in the plane stress, plane strain and three-dimensional stress-strain modes. Solhjuei et al. [34] studied force of CGP process in different passes as experimental and finite element and compared the CGP and RCS processes. Wang et al. [31] investigated the effect of groove width and die angle on the force of CGP process using finite element simulation and by regression method presented a relationship to estimate the maximum force of CGP for Ni sheets in terms of groove width and shear regions.

According to the literature, an analytical relationship based on the elastic-plastic relations has not been provided to estimate force in CGP process. In this study, the force of CGP process is estimated by using plasticity relations and the results based on the different yield criteria are compared with experimental results and finite element simulation. Also, the effect of material parameters and geometry of the die and sheet on presented model is investigated.

2. Analytical model of constrained groove pressing

Based on the principle of CGP, a material is alternate pressed using groove die and flat die to apply repetitive shear deformation under plastic strain deformation conditions [5,6]. Fig. 1 illustrates CGP process and shear regions on a CGPed sheet. Each groove has two shear regions which is repeated throughout the sheet. To modeling the force of CGP process, all computations have been done on one of the shear regions and then are extended throughout the sheet.

2.1. State of stresses in CGP process

Review of CGP process is shown, during the upper die moves down, sheet length in the shear region increases and so thickness of the sheet in this area reduces but sheet width remains constant. If the die movement be controlled, always sheet width in CGP process and Semi-CGP is constant and would not be changed. So, according to explanation state in plastic deformation, Eq. (3) is established. In this equation, $d\varepsilon_i^p$ represents the plastic strain in *i* direction.

$$d\varepsilon_x^p = d\varepsilon_y^p \neq 0, \quad d\varepsilon_z^p = 0$$
$$d\varepsilon_x^p + d\varepsilon_y^p + d\varepsilon_z^p = 0 \quad \rightarrow \quad d\varepsilon_x^p = -d\varepsilon_y^p \tag{3}$$

With assuming pure shear in CGP process [3,5,21] and considering to Eq. (3) and Prandtl-Reuss [35] relation can be revealed:

$$\frac{d\varepsilon_x^p}{\sigma_x - \sigma_m} = \frac{d\varepsilon_y^p}{\sigma_y - \sigma_m} = d\lambda \quad \rightarrow \quad \sigma_x = -\sigma_y \tag{4}$$

In Eq. (4) σ_x and σ_y is stress in X and Y directions and σ_m is mean stress. Also in Z direction, according to Eq. (3) and using the plastic strain relation [35], can be written:

$$d\varepsilon_z^p = \frac{d\varepsilon_p}{\sigma_e}\left[\sigma_z - \frac{1}{2}(\sigma_x + \sigma_y)\right] = 0 \quad \rightarrow \sigma_z = \frac{1}{2}(\sigma_x + \sigma_y) \tag{5}$$

In this equation, $d\varepsilon_p$ and σ_e are equivalent plastic strain and effective stress. Considering to Eqs. (4) and (5) could find, summation of the stresses in three axes is equal to zero $(\sigma_x + \sigma_y + \sigma_z = 0)$ that shows the stress condition in the CGP process is as pure shear and confirm initial assumption.

2.2. Investigation of CGP process based on the sheet deformation

By accurate reviewing CGP process, it can be concluded that CGP process is done in three steps of bending, stretching and forging. In the first step, two small bends occur on the edge of dies that are the first contact points with the sheet in shear region. In fact, these two points show the start and end of deformation area (or shear region). Fig. 2 shows three steps of deformation in the CGP process.

In the second step, because at start of the process, distance of the two dies is more than the sheet thickness, the sheet is only stretched and has no contact with slop surface of the die. This step causes the sheet length increases on the slope surfaces and sheet thickness reduces. At this step, sheet between two points of primary bending is restrained and nature of the process is as stretching process. Not change thickness of the sheet on the flat areas is proof of this claim.

The third step of the process begins when thickness of the sheet on the slope surface to be equal with distance of two dies. In this step, the sheet completely is in contact with the dies and nature of the process is as forging process. Eq. (6) shows if the die angle is