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An analytical approach for simple shear extrusion process with a linear die profile

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ABSTRACT

In the present work, for the first time, an analytical approach based on upper-bound theorem is proposed to analyze the simple shear extrusion process. In this regard new die parameter named maximum inclination angle is introduced. By this model, the power dissipated on all frictional and velocity discontinuity surfaces is determined and the total power is optimized for two types of die, fixed and movable inlet channel die. To check the validation of the upper-bound model, the process is simulated by the commercial finite element code, Deform-3D. To compare the theoretical results with experiments, a fixed inlet channel die and two dies with movable inlet channel are used to determine the processing force for different cross sections. The developed model predicts that the relative extrusion pressure increases with increasing the constant friction factor; also, for a given value of the constant friction factor and the maximum distortion angle, there is an optimized maximum inclination angle which minimizes the power. Comparing the fixed inlet channel die with the movable inlet channel one, it is seen that the optimized maximum inclination angle is higher in the FIC die.

1. Introduction

Severe plastic deformation (SPD) is considered as a promising method for producing bulk polycrystalline materials with the grain sizes typically in the range of nanometer and sub-micrometer. In this regard, many techniques are used to refine the microstructure of materials by applying large shear strain by high hydrostatic pressure. Equal channel angular pressing (ECAP) [1], high pressure torsion (HPT) [2], accumulative roll bonding (ARB) [3], multi-directional forging (MDF) [4], twist extrusion (TE) [5], constraint groove pressing (CGP) [6], simple shear extrusion (SSE) [7] and cyclic expansion–extrusion (CEE) [8] are some of the most-used SPD techniques.

Simple shear extrusion (SSE), invented in 2009 by Pardis and Ebrahimi [7] is one of the most-recent SPD techniques which is based on pressing material through a specially designed direct extrusion channel. The distribution of strain is more symmetrical through the cross-section of the workpiece, which is a great advantage [7,9]. Furthermore, SSE is beneficial due to the low amount of waste material [7,10]. The strain in SSE is imposed gradually which made it a good candidate to severely deform hard to work materials like twining induced plasticity (TWIP) steel [10,11] and Magnesium alloys [12]. The strain reversal during SSE is reported in the processing of TWIP steel during SSE [11]; the dislocation density increased up from start to the middle of the deformation channel and reduced in the second half of the channel due to the annihilation of the dislocation substructure result from the reversal straining nature of SSE process.

Recently, the present authors proposed new die profiles for SSE technique [13]. In that work, three deferent curvatures for deformation channel based on linear, quadratic and sinus form of equations were introduced. It was shown that the most homogeneous distribution of strain is obtained in the linear die profile while the shape of the profile did not have a significant effect on the deformation force and the required back-pressure for filling the channel. For all the profiles, the strain is increased gradually by increasing the distance. The rate of increasing the strain for the quadratic profiles decreases at the start, middle and the end of the channel while for the sinus profile it decreases only at the middle; whereas for the linear profile the rate of increasing the strain remains constant through the entire channel. The study states that the linear die profile is the best candidate for SSE because of the simplicity of the die design, the homogeneity of the strain and its constant strain rate.

During metal forming operations, prediction of the force of the plastic deformation and the size of the plastic deformation zone is

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Nomenclature

a	side length of square cross section
J^*	actual externally supplied power
k	shear yield stress of the material
L	length of deformation channel
L_0	length of inlet channel
L_f	length of outlet channel
m	constant friction factor
p_{ext}	extrusion pressure
s_f	area of frictional surface
s_v	area of velocity discontinuity surface
s_t	area of the surfaces that the traction may occur on
T_i	tractions
Δv	amount of velocity discontinuity
V_0	entrance velocity
$\dot{U}_x, \dot{U}_y, \dot{U}_z$	velocity components
$\dot{w}_f$	power dissipated on frictional surfaces
$\dot{w}_i$	power dissipated on deformation zone
$\dot{w}_s$	power dissipated on velocity discontinuity surfaces
$\dot{w}_{total}$	total power of the process
x, y, z	cartesian coordinates

Greek symbols

α	distortion angle
$\alpha_{\max}$	maximum distortion angle
β	inclination angle
$\beta_{\max}$	maximum inclination angle
$\beta_{\max}^{opt}$	optimized maximum inclination angle
$\dot{\varepsilon}_{ij}$	strain rate tensor
σ_f	mean flow stress of the material

Abbreviations

ARB	accumulative roll bonding
CEE	cyclic expansion–extrusion
CGP	constraint groove pressing
ECAP	Equal channel angular pressing
FEM	finite element method
FIC	fixed inlet channel
HPT	High pressure torsion
MDF	multi-directional forging
MIC	movable inlet channel
SPD	severe plastic deformation
SSE	simple shear extrusion
TE	twist extrusion
TWIP	twining induced plasticity

an important task, because it can help in the design of tools. Plastic deformation of materials during SPD has been studied by many researchers. These studies are widely used finite element methods (FEM). Some of the processes which were analyzed by FEM are ECAP [13,14], HPT [15], TE [16], ARB [17], CGP [18] and CEE [8]. In addition to finite element methods, there are only a few studies that analyzed the SPD processes by the upper-bound approach most of them are investigated the ECAP technique [19,20].

Recently, an upper-bound solution was proposed to predict the extrusion power and the optimum working conditions of TE process [21]. Effect of die geometry and process condition on deformation pattern and extrusion power of TE process was investigated by an upper-bound model based on two kinematically admissible velocity fields. Moreover, a minimum critical value for the die length was found.

Using the finite element method, deformation behavior in SSE, different processing routes for deformation via this Technique [9] and effect of geometric parameters on the deformation behavior of SSE [13]was studied. In these FEM studies, the strain distribution and the force of the process during SSE processing of commercially pure aluminum (AA1050) by different die profiles and different processing routes was investigated. In 2010, Pardis and Ebrahimi [9] introduced four different processing routes (A–D) for deformation via simple shear extrusion process. They concluded that the variation of shear strain was the same in routes B and C while the homogeneity was improved in route C due to 90° rotation of the sample about its main axis.

In the present paper, for the first time, an upper-bound approach according to Avitzur and Pachla [22,23] is used to predict the total power of the process and the relative extrusion process of SSE technique with linear profile by fixed and movable inlet channel dies (FIC and MIC dies). For this reason new die parameter named maximum inclination angle, $\beta_{\max}$, is introduced. The effect of the constant friction factor, the maximum distortion angle, the maximum inclination angle and the type of the die on the model is investigated. To check the validation of the analytical upper-bound model, the process is simulated by the commercial finite element code, Deform-3D. Finally, the force needed for SSE was predicted and compared with the experimental value.

2. Method

2.1. Deformation during SSE

During SSE, the sample is pressed through a direct channel with a specific shape [13]. As the specimen with a square cross section passes through the channel, it deforms gradually while its cross-section area remains constant. Fig. 1 shows that passing through the extrusion channel, the material undergoes shear deformation by changing the shape of cross-section from a square at the entrance of the channel to a parallelogram with the

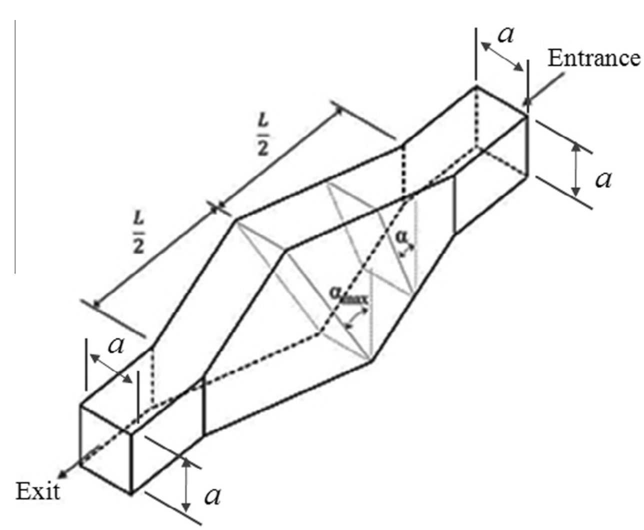

Fig. 1. Schematic presentation of the geometry of deformation channel of simple shear extrusion process (linear die profile).