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Streamline approach to die design and investigation of material flow during the vortex extrusion process

M. Shahbaz [a,*], R. Ebrahimi [a], H.S. Kim [b]

[a] Department of Materials Science and Engineering, School of Engineering, Shiraz University, Shiraz, Iran
[b] Department of Materials Science and Engineering, POSTECH, Pohang 790-784, Republic of Korea

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ABSTRACT

In this study, a streamline approach based on a cubic Bezier formulation is used to investigate the material flow during vortex extrusion (VE). The velocity field and upper bound terms are calculated based on the proposed mathematical model in order to estimate the process load. The VE dies designed according to the proposed mathematical model are used for finite element analyses of the VE process in order to investigate the effect of various processing parameters on the strain distribution and process load. Comparisons of the simulated results with those obtained from the upper bound analysis demonstrate that the load increases in the VE process as the twist angle increases. Furthermore, we demonstrate that reducing the twist zone length and increasing the friction improve the material twisting during the VE process.

1. Introduction

Severe plastic deformation (SPD) is a well-known metal-forming process, which can achieve extreme grain refinement to the sub-micrometer scale and sometimes the nanometer scale, because of its power in straining metallic materials [1–4]. Shahbaz et al. [5] developed vortex extrusion (VE) as a new SPD technique for the simultaneous torsion and extrusion of samples through a specially designed stationary die, as shown in Fig. 1. It has been demonstrated that the VE process can impose a large amount of strain during a single pass, which increases the process productivity and reduces the number of processing steps. Furthermore, VE dies can be replaced with conventional extrusion dies without requiring any additional equipment, thereby obtaining products with improved mechanical properties. However, more research is required to investigate the straining mechanisms during the VE process before applying it as a commercial alternative to the current forming techniques. In particular, it is necessary to understand the metal flow characteristics within the die under the conditions imposed in order to design optimal VE dies.

Various analytical and numerical techniques, including the streamline approach [6,7], upper bound theorem [8], and finite element analysis (FEA), have been proposed to investigate the material flow during forming processes. Ma et al. [9] analyzed forward extrusion through rotating conical dies using the upper bound theorem. They investigated the effects of the semi-die angle and lubrication on the processing load, as well as determining the effect of a rotating die on reducing the processing load. The mechanics of metal flow during twist extrusion (TE) were analyzed qualitatively using a constructed kinematically admissible velocity field [10] and investigated experimentally using a method based on a theoretical model of the velocity field [11]. Latypov et al. [12] used FEA to investigate the influence of process parameters such as the backward pressure and friction on the loading history, stress/strain states, and the final shape of processed workpieces during the TE process. Their research

* Corresponding author. Tel.: +821031081366.
E-mail address: Mehredads1@gmail.com (M. Shahbaz).

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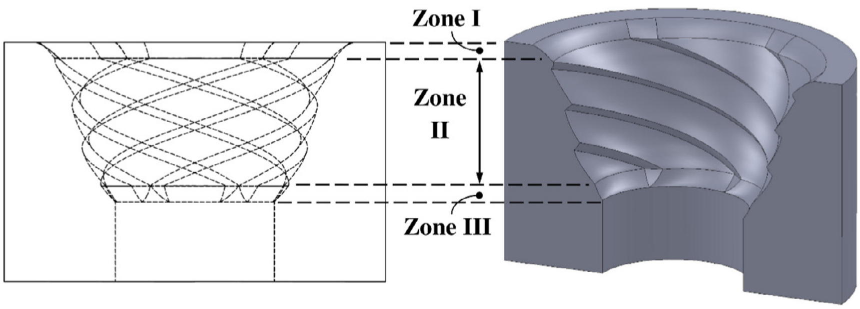

Fig. 1. Schematic of the vortex extrusion [5].

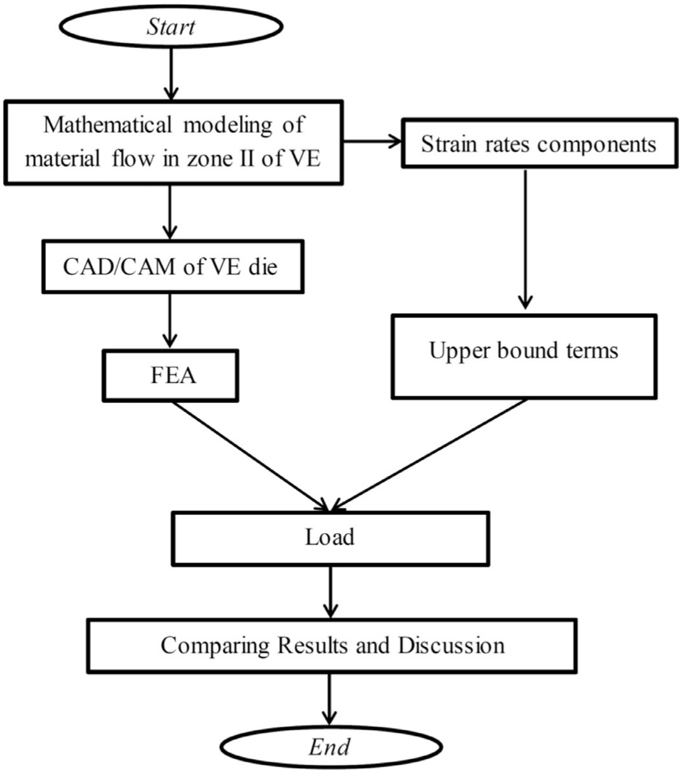

Fig. 2. Flowchart of the steps in this study.

provides a basis for making reasonable decisions regarding the processing conditions as well as for identifying the prerequisites in studies of the formability and fracture of metals subjected to TE [12]. Seyed Salehi et al. [13] performed upper bound analyses of the TE process in order to estimate the required power, deformation pattern, and optimum processing conditions, where they demonstrated that the die geometry and process parameters can significantly change the deformation pattern and extrusion power [13].

Axi-symmetric forward spiral extrusion (AFSE) was also studied using the upper bound analysis approach [14], where the results demonstrated that a reduction in friction leads to a significant decrease in the total forming force during AFSE, while still maintaining a circumferentially slippage-free flow of material during the process. Furthermore, it was demonstrated that increasing the die helix angle above a critical value could enhance the growth rate of the die reaction torque as well as increasing the extrusion load with the helix angle [14]. Chitkara and Abrinia [15] developed a generalized method based on a streamline die design to analyze the three-dimensional (3D) extrusion of arbitrarily shaped sections through straight converging dies.

In this study, a streamline approach based on the Bezier formulation is used to mathematically model the material flow in the main zone of the VE die (Zone II). The velocity fields are obtained according to the proposed mathematical model and the upper bound theorem is then used to predict the process load. The proposed mathematical model was then used as an input for the computer-aided design of VE dies, before employing the finite element method (FEM) program DEFORM-3D [16] to simulate the VE process. Fig. 2 illustrates the steps in this process.