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Hot extrusion process modeling using a coupled upper bound-finite element method

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ABSTRACT

A thermo-mechanical model has been developed for modeling of hot extrusion processes. Accordingly, an admissible velocity field was first proposed by means of stream function method and then, extrusion pressure as well as temperature variations within the metal and the die were predicted employing a combined upper bound and Petrov–Galerkin finite element analysis. In order to evaluate the model predictions, hot extrusion of AA6061-10%SiC_p was considered under both isothermal and non-isothermal conditions and the predicted force–displacement diagrams under various extrusion conditions were compared with the experimental ones and reasonable consistency was found between the two sets of results.

1. Introduction

Prediction of required energy and temperature variations during extrusion operations are of importance in order to control metal flow and metallurgical events during and after hot deformation. Accordingly, thermal responses and flow pattern during extrusion has extensively been studied for decades, while various techniques including analytical and numerical methods were proposed to study different aspects of the process. Although, simplified analytical approaches were utilized to estimate the required pressure [1]. However, in order to accurately predict material responses under practical deformation conditions, it needs to utilize more sophisticated analytical and/or numerical techniques. For instance; Yang et al. [2] have introduced a generalized velocity field based on high order polynomial functions to determine an admissible velocity field and the upper bound pressure of axi-symmetric extrusion. This velocity field is also capable of considering the effects of lubrication and material properties. Altan et al. [3] have employed a numerical approach based on spherical velocity field together with the finite difference method to estimate temperature distribution and required energy in hot extrusion operations. Sheu and Lee [4] have proposed a combined thermal-mechanical model to predict temperature distribution and required pressure in hot rod extrusion process. The model was then used to achieve a homogeneous temperature distribution during extrusion by means a proper combination of the process variables. Reddy et al. [5] have developed a combined finite element analysis and upper bound technique for optimal die design in axi-symmetric hot extrusion processes. In another work, Kim et al. [6] have optimized the die design for axi-symmetric hot extrusion of metal matrix composites employing finite element analysis in which an optimization algorithm was developed to obtain a die profile with the minimum redundant work. Fietier et al. [7] have developed a software based on upper bound-finite element method for designing hot extrusion dies with complicated shapes while they reported a significant reduction in computational time as well as an acceptable accuracy of the results. Gouveiaa et al. [8] also investigated the limitations of incremental updated-Lagrangian schemes for analyzing the frictional conditions in forward extrusion of rods. Chen et al. [9] have utilized a mathematical model performed on a commercial finite element package, DEFORM, to evaluate deformation behavior of AA6061/Al_2O_3 composite under hot extrusion conditions. In addition, upper bound solutions and finite element schemes have been utilized to predict metal flow pattern, temperature distribution, and required power in extrusion operations in three-dimensions and/or under plane strain conditions [10–12].

Regarding the published works, it can be found that modeling of hot extrusion operations needs computational costs as well as it includes difficulties in the finite element analysis owing to nonlinearity associated with the governing equations as well as severe mesh distortion in regions close to dead metal zone. Coupled finite element-upper bound models have been introduced as a substitute

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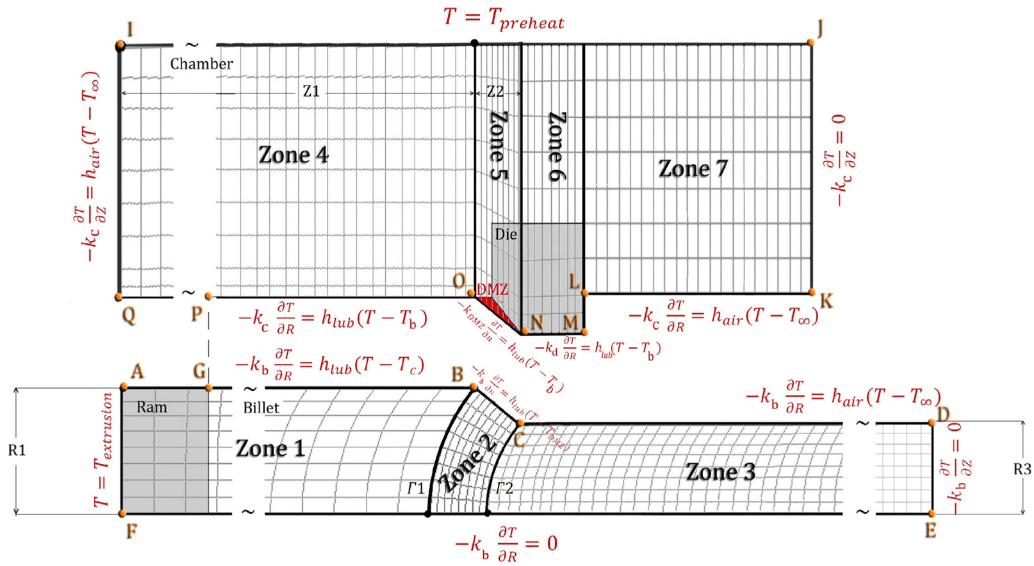

Fig. 1. Mesh system and utilized boundary conditions.

technique to estimate the temperature distributions and required power during hot extrusion operations [7,12,13] in which the mesh distortion and high computation costs can be avoided. In this work, an upper bound-finite element solution is proposed to assess extrusion pressure and temperature variations in the deforming metal, the container, and the dies under isothermal and non-isothermal conditions. The model is based on the work previously presented by the authors for the wire drawing processes [13] and it has been improved to be applicable under hot extrusion conditions. In this model, a stream function is first proposed to assess a generalized admissible velocity field and then the power function calculated based on the admissible velocity field is minimized to define the optimum velocity field. While in the mechanical part, the effect of temperature changes due to heat of deformation and/or heat transfer to the container and the die are taken into account at the same time, a neural network model is also employed to estimate the flow stress of deforming metal at high temperatures as function of temperature and strain rate. The model can simultaneously consider the effects of various process parameters such as initial billet temperature, ram velocity, and die geometry on the extrusion pressure and temperature distributions of the billet and the die. Finally, In order to examine the predictions, hot extrusion experiments are carried out and the experimentally force–displacement diagrams are compared with the predicted results.

2. Mathematical model

The modeling of hot extrusion process can be performed by simultaneously determining thermal and mechanical responses of the material being deformed. In the thermal analysis, the heat conduction problems in the metal, container and the die should be solved while in the mechanical part an admissible velocity field is first defined and then, the corresponding power function is minimized to achieve the optimum velocity field and required power regarding the upper bound theorem. Also, the employed model only considers the geometrically steady-state stage.

2.1. Thermal model

The governing conduction/convection equation for the rod with radius of "R" being extruded along its axis, i.e. Z direction, can be expressed as follows [14,15]:

$$\frac{\partial}{\partial Z}\left(k\frac{\partial T}{\partial Z}\right)+\frac{1}{R}\frac{\partial}{\partial R}\left(Rk\frac{\partial T}{\partial R}\right)+\dot{q}=\rho c\frac{\partial T}{\partial t}+\rho cu\frac{\partial T}{\partial Z} \tag{1}$$

where 'k' is thermal conductivity of the metal, '$\dot{q}$' is the rate of heat of deformation, 'c' is the specific heat, 'ρ' is the material density and 'u' is the velocity along the extrusion direction. Note that under thermally steady-state extrusion conditions, i.e. isothermal

Table 1
The boundary conditions implemented on each surface in the model.

		Boundary surfaces	Energy balance
Natural boundary conditions	Within the billet and ram	GB	$-k_b\frac{\partial T}{\partial R}=h_{lub}(T-T_c)$
		BC	$-k_b\frac{\partial T}{\partial n}=h_{lub}(T-T_{DMZ})$
		CD	$-k_b\frac{\partial T}{\partial R}=h_{air}(T-T_\infty)$
		DE	$-k_b\frac{\partial T}{\partial Z}=0$
		EF	$-k_b\frac{\partial T}{\partial R}=0$
		AG	$-k_b\frac{\partial T}{\partial R}=0$
	Within the chamber & die	JK, LM	$-k_c\frac{\partial T}{\partial Z}=0$
		KL	$-k_c\frac{\partial T}{\partial R}=h_{air}(T-T_\infty)$
		MN	$-k_d\frac{\partial T}{\partial R}=h_{lub}(T-T_b)$
		NO	$-k_{DMZ}\frac{\partial T}{\partial n}=h_{lub}(T-T_b)$
		OP	$-k_c\frac{\partial T}{\partial R}=h_{lub}(T-T_b)$
		PQ	$-k_c\frac{\partial T}{\partial R}=0$
		QI	$-k_c\frac{\partial T}{\partial Z}=h_{air}(T-T_\infty)$
Geometrical boundary conditions	Within the billet & ram	FA	$T=T_{Extrusion}$
	Within the chamber and die	IJ	$T=T_{Chamber\ Preheat\ Furnace}$