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Sensitivity analysis of a finite element model for the simulation of stainless steel tube extrusion

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ABSTRACT

In this work, a sensitivity analysis has been performed on a finite element model of glass-lubricated extrusion of stainless steel tubes. Fifteen model parameters, including ram speed, billet and tool temperatures, friction coefficients and heat transfer coefficients, were considered. The aim of the study was to determine the parameters that are most important for the response of the extrusion force. The relationship between the model parameters and the responses was analyzed by a calculation of two different regression models: one linear polynomial model and one model that includes interaction terms. Additional simulations were then carried out to validate the regression models. The results show that the initial billet temperature is the factor that has the strongest impact on the extrusion force within the parameter ranges studied in this work. The goodness of prediction and goodness of fit are very good for both regression models.

1. Introduction

Seamless stainless steel tubes can be manufactured by extrusion using glass as lubrication. The process is performed at high temperature and is associated with large deformations and high strain rates. Finite element (FE) simulation has become an important tool in the design and development of extrusion and other manufacturing processes. Most of the simulation work involves aluminum extrusion, but some work on steel and titanium extrusion has also been reported, for example, by Damodaran and Shivpuri (2004) and Hansson (2006). A large number of input parameters are used in a FE analysis of extrusion. These parameters include boundary conditions, initial conditions and parameters that describe the mechanical and thermal properties of the material. The accuracy of the extrusion simulation depends, to a large extent, on the accuracy of these parameters. In addition, many of these are often impossible to measure during the extrusion process itself or in tests under similar conditions. Among the simulation work that is reported on extrusion, only few authors include investigations on how changes in input parameters affect the computed results. Flitta and Sheppard (2005) studied the effect of the variation of initial billet temperature and ram speed on FEM predictions of temperature evolution during aluminum extrusion. The simulation was compared with data obtained from experiments. Sivaprasad et al. (2004) studied the effect of ram speed on the distribution of strains, strain rates and temperature in glass-lubricated extrusion of 304 L stainless steel rods. The results were compared with processing maps by Venugopal et al. (1992) and used to identify the best ram speed for obtaining the desired microstructure. A more systematic approach to sensitivity analysis was performed by Snape et al. (2002), who investigated the sensitivity to variations in different input parameters of three axisymmetric FE models: compression, impression-die forging and backward extrusion. A full factorial design of experiments (DOE) was used. The analysis was restricted to the parameters that define the flow stress of the material and heat transfer and friction at the die–workpiece interface. The maximum strain, maximum load, forging work and final die fill were considered as response variables. In this paper, no physical forging trials were used for comparison.

Compared to aluminum extrusion, steel extrusion is carried out at higher speed, at higher temperature and with larger temperature gradients between the billet and the tools. The billet–container, billet–mandrel and billet–die contact areas in glass-lubricated steel extrusion are all lubricated in different ways. It could, therefore, be expected that the friction and heat transfer conditions are somewhat different, and it is of interest to investigate the effects of changes in friction, temperature and heat transfer on each one of these contact areas separately.In the present study, a sensitivity analysis is carried out on an axisymmetric FE model of the extrusion of tubes. The material that is extruded is Sandvik Sanicro 28

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(UNS: N08028), an austenitic stainless steel designed for service in highly corrosive conditions. The extrusion model is similar to a model developed in Hansson (2010). In Hansson (2010), the initial billet temperature was calculated using simulations of the process steps preceding extrusion. Forces from the extrusion model are compared with data obtained from an experimental extrusion press for validation.

The aim of the sensitivity analysis is to study the influence of certain process parameters on the resulting extrusion force. The parameters that affect the force and ones that do not have any significant impact will be determined. This knowledge will be valuable for further work on extrusion simulation, where more effort can be put into giving accurate values to the parameters that have a greater effect. Another important objective is to evaluate whether it is possible to find empirical models for the extrusion force that show the importance of the process parameters and their interactions. Such models could have a practical use in the process development of extrusion.

Fifteen different process parameters, such as initial temperature, ram speed, friction and heat transfer coefficients between the billet and the tools, are included in the sensitivity study. The initial peak force and the extrusion forces at 300, 475 and 650 mm ram displacement are considered as responses. The relationship between the parameters and the responses is established according to two different regression models; one linear polynomial model and one model that includes interactions. Additional simulations are then carried out to verify the regression models. The DOEs for the numerical experiments are created by fractional factorial design using MODDE, a commercial software for DOE and optimization. In total, 107 extrusion simulations are carried out within this study. All simulations are performed in the commercial FE software MSC.Marc 2008r1.

2. Process description

The stainless steel billet is heated to the extrusion temperature in an induction furnace. During the transfer to the extrusion chamber, the billet is coated with a thin layer of powdered glass. Glass powder is also applied in the bore to assure good lubrication between the billet and the mandrel. Lubrication through the die is provided by a thick disc of compacted glass, the glass-pad, which is positioned between the billet and the die in the extrusion press. During extrusion, the glass-pad is pressed against the die by the hot metal. The glass-pad will deform with the billet and melt progressively to surround the extrusion with a lubricating glass film. The glass film provides very low friction and acts as a thermal barrier to prevent excessive heating of the tools and rapid cooling of the billet. The use of molten glass as lubricant for extrusion of steel was first introduced by Sejournet and the process is often referred to as the Ugine–Sejournet process. A detailed description of the process and the glass lubrication can be found in Sejournet and Delcroix (1955).

As the ram starts to move, the billet upsets along the container walls and the mandrel. A peak in the force that corresponds to the upsetting of the billet, and simultaneously, the entry of metal into the die orifice, can be observed. After the initial peak, the material flow behavior is, more or less, steady-state. When the billet has been extruded almost completely, the resistance to radial flow of the billet material towards the center is high, and the load will, therefore, increase heavily. The extrusion stroke is stopped at this point, and an unextruded discard is left behind.The total extrusion force is a sum of the force necessary to make the material flow through the die and the force required to overcome the friction between the billet surface and the tools. The detailed extrusion force curve is difficult to predict. It depends on complex interactions between different process variables and the mechanical and thermal properties of the material. The major effects of the extrusion variables on the extrusion force arise from their effect on the temperature of the billet and, hence, the flow stress of the material. This is concluded in Hughes et al. (1974) which reports measurements of temperature gradients during glass-lubricated steel extrusion. Some temperature-related factors that have to be taken into account for calculations of the extrusion force are:

- heat loss to the tools;
- heat gain that results from deformation;
- heat generation due to friction between the billet and the tools;
- heat conduction inside the billet and between the billet and the extrudate.

Table 1
Billet and tube dimensions used in the simulation of Sandvik Sanicro 28 tube extrusion.

Billet	Outer diameter	[mm]	240
	Inner diameter	[mm]	112
	Length	[mm]	888
Extruded tube	Outer diameter	[mm]	142
	Wall thickness	[mm]	22.0

3. Finite element model

A finite element (FE) model for the extrusion of Sandvik Sanicro 28 tubes was developed in the commercial FE software MSC.Marc 2008r1. The model shares many boundary conditions and initial conditions with the extrusion model presented in Hansson (2010). In Hansson (2010), the entire manufacturing chain, including induction heating, expansion, extrusion and cooling at the intermediate transports, was simulated using FEM. The temperature field in the billet before extrusion in this model is thus calculated based on the temperature evolution in the preceding process steps. Billet and tube geometries used in the simulation are given in Table 1. The container diameter is 250 mm, and die and mandrel geometries are chosen in accordance with the final tube dimensions.

The FE model is axisymmetric and consists of four node quadrilateral elements. The volumetric strain in the element is assumed to be constant for von Mises plasticity to overcome volumetric locking. The extrusion is performed in a coupled thermo-mechanical analysis, using the Lagrangian approach. Since the deformations in the process are large, the elements get distorted, and continuous remeshing is needed throughout the analysis. The material is extruded using a constant ram speed of with the mandrel moving at the same speed as the ram. Generation of heat due to plastic deformation in the material is taken into account, as well as the heat generation due to friction. 95% of the plastic and 95% of the frictional work is assumed to be converted into thermal energy.All tools are assumed to be rigid bodies with a constant temperature of 400 °C. Melting of the glass-pad is not taken into account in the model. The shape of the glass-pad die profile is constant and based on an earlier experiment where cross-sections of stickers were studied, see Hansson (2006).

The FE model at the initial stage of the analysis is shown in Fig. 1. In this figure, the different tools and contact areas can be identified.

The lubricating glass film provides low friction and acts as a thermal barrier to prevent excessive heating of the tools and rapid cooling of the billet. A contact heat transfer coefficient of 1500 W/(m^2 K) and a Coulomb friction coefficient of 0.023 is used at all glass-lubricated contact areas in this context. The friction coefficient and contact heat transfer coefficient between the billet