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Parametric sensitivity analyses for FEA of hot steel forging

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Abstract

This paper reports a system for quantifying and comparing the sensitivity of a thermomechanical finite element analysis (FEA) of forging to variations in different input parameters. The results of applying the method to analyses of simple upsetting, impression-die forging and backward extrusion of hot steel are also described.

The number of parameters in a thermomechanical FEA of forging make it impractical to investigate all of them, so the investigations were restricted to the parameters that define the flow stress of the forged steel and heat transfer and friction at the die–workpiece interface.

Theoretical forging investigations of the kind described should be compared with the results of physical forging trials. This comparison would indicate whether or not more work characterising parameters for FEA of forging were justified.

Keywords: Finite element analysis; Forging; Parametric sensitivity analysis

1. Introduction

Despite a scarcity of yield strength data for metals subjected to forging conditions finite element analysis (FEA) is a tool that can be used to improve the understanding of industrial forging. A large number of mechanical and thermal parameter values, which are used to characterise the process, are used in a thermomechanical FEA of forging. It is obvious that whereas the results of an FEA of forging will be significantly affected by variations in some of these parameter values, the effect of similar variations in other parameter values will be of little consequence. Investigations of the effect of parameter variations are important because they provide a guide to the level of uncertainty of the parameters, which is acceptable in relation to the results that they yield. The parameters that have the greater effect should be specified with greater accuracy than those whose effect is small.

Many FE analyses of industrial forging have been reported. See, e.g. [1–4]. However, investigations of the effect that variations in input parameters have on the results of FEA of forging are not widely reported; only three such investigations were found in a recent literature survey. One of these, carried out by Majerus et al. [5] for an axisymmetric analysis of hot isothermal forging looked at the effect that changing the constant-shear friction factor at the die–workpiece interface from 0.085 to 0.225 had on an FE deformation grid. Ou and Balendra [6] examined the effect that changing the Coulomb friction coefficient had on a plain-strain isothermal FEA of forging an aerofoil blade. Increasing the Coulomb friction coefficient from 0.1 to 0.2 increased the computed forging load by between 35 and 45%. In a third investigation, Saigal et al. [7] examined the influence that the initial die temperature and ram velocity had on a coupled thermomechanical plane-strain FEA of hot forging. The analysis examined was of forging a compressor blade. The response of the analysis to die temperature was that if it was increased from 300 to 700 °F the forging load decreased by 9% and the average temperature of the workpiece increased by 43 °F. Increasing the initial ram velocity from 15 to 25 in./s decreased the forging load by 25.2% and increased the average temperature of the workpiece by 36 °F.

In the first two of these investigations the analyses considered were isothermal, when in fact most hot forging does not take place under isothermal conditions, and no comparisons of the reported effects with the effect of variations in other parameters were made. In the third investigation the analysis was thermomechanical. However, the parameters investigated were the ram velocity and die temperatures, which are well-controlled and understood in

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industry. It is more useful to investigate the effects of the parameters that define the properties of the forged metal and the tool–workpiece interface since it is these that industry faces the greatest uncertainties over. This investigation is of the effects of these parameters on three thermomechanical finite element analyses of forging. The use of a full-factorial design of experiment in the investigation makes it possible to eliminate the interacting effects that varying the thermal and mechanical parameters had on the results.

2. Model overview

The input required for the analyses followed from the model used in FORGE2, a commercial package developed at CEMEF, Ecoles des Mine de Paris for FEA of hot and cold metal forging. The key phenomena of viscoplastic deformation, friction, heat transfer and thermomechanical coupling are incorporated into the FE solver. FORGE2 also features automatic remeshing, which avoids excessive element distortion, when analysing large-scale deformations. The release of the software used for this work was FORGE2v2.7.

The criterion used to determine flow conditions in FEA of metal forming is in accordance with the stress at which the metal yields under uniaxial loading. It was assumed that the uniaxial flow stress of AISI 8620H steel was governed by a development of the Norton–Hoff rule [8,9] designed to incorporate strain hardening and temperature effects:

$$\sigma_F = K\varepsilon^n \, e^{-BT} \dot{\varepsilon}^s$$

where K is a constant, ε the plastic strain, n the strain-hardening index, B the temperature term and T the absolute temperature (K), s the strain rate sensitivity index and $\dot{\varepsilon}$ the plastic strain rate.

Because it is most commonly used friction model for hot-forging analysis the constant-shear definition of friction was applied at the boundary between the tool and the workpiece. In the constant-shear friction model, the product of a friction factor and the shear define the interfacial shear stress at the tool–workpiece interface

$$\tau_f = mk$$

where m is the friction factor and k the shear yield stress of the forging.

Fourier's law governs heat conduction and an energy balance defines the relationship between heat flux, heat from metalworking and the temperature of the workpiece

$$\rho c \frac{dT}{dt} = -\nabla(k\nabla T) - \dot{w}$$

where ρ is the density, c the specific heat, k the conductivity of the workpiece and $\dot{w}$ the rate of heat dissipation from the deformation process.

The heat dissipated is a fraction of the plastic work rate

$$\dot{w} = \eta\bar{\sigma}\dot{\bar{\varepsilon}}$$

where η is the conversion efficiency ($\eta \approx 1$), $\bar{\sigma}$ the generalised stress and $\dot{\bar{\varepsilon}}$ the generalised strain rate.

The heat flux per unit area at the free surface of the forging comprises of conduction and convection

$$\dot{q} = h(T_d - T) + e\sigma(T_a^4 - T^4)$$

where $\dot{q}$ is the heat flux per unit area, h the heat transfer coefficient for the workpiece ambient interface, e the emmisivity and σ the Stephan–Boltzmann constant.

At the constrained surface of the forging heat flux per unit area comprises of conduction and heat due to friction

$$\dot{q} = h(T_d - T) + \frac{b}{b + b_d}\tau_f v$$

where h is the heat transfer coefficient for the die–workpiece interface, b the workpiece effusivity ($= \sqrt{k\rho c}$), b_d the die effusivity, τ_f the frictional shear stress and v the sliding velocity.

3. Forging cases examined

Three forging operations were examined. In all three cases the workpiece was of AISI 8620H steel pre-heated to 1350 °C.

The first operation examined was upsetting. The upsetting operation was the compression of a cylinder between two flat platens, to 40% of its original height. Before forging the diameter of the cylinder was 96.4 mm and its height was 132.9 mm. The forging plant simulated was a mechanical press with a stroke of 254 mm, a connecting rod length of 85 mm and a speed of 70 rpm. The press mechanism is presented schematically in Fig. 1 and a mesh at the start and the end of a typical analysis is illustrated in Fig. 2.

The second forging example was the manufacture of a clutch plate preform. The process was a closed die forging operation with flash: a cylindrical billet was compressed between a pair of axisymmetric dies. The dimensions of the billet and the press characteristics were the same as in the upsetting case. Fig. 3 shows a mesh at the start and the end of an analysis.

Operation examined was a case of backward extrusion. This was a preform forging for a stub-axle. In this process a cylindrical billet, height 875.6 mm and diameter 289.2 mm was placed in a container and a punch used to drive a cylindrical depression into the billet. The press used was a hydraulic press with constant forging velocity of 8 mm/s. Fig. 4 shows FE meshes for a typical analysis.

4. Parameter assignation

4.1. Constant parameter values

The parameters whose values were constant throughout the investigation and the values assigned to them are listed in