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Numerical Investigation of the Oxide Scale Deformation Behaviour with Consideration of Carbon Content during Hot Forging

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Abstract

Due to increasing product requirements the numerical simulation has become a powerful tool for the effective and efficient design of individual process steps as well as entire process chains. In order to model hot forging processes with finite element based numerical methods realistic models are required which consider the detailed mathematical description of the material behaviour during the forging process, the surface phenomena at die and workpiece as well as machine kinematics. Although this data exist for several steel grades, yet general mathematical models for steel groups based on alloying elements like carbon content are not available. In hot forging the surface properties are strongly affected by the growth of oxide scale, which influences material flow, friction as well as product quality of the finished components. The influence of different carbon contents on oxide scale growth and material behaviour is investigated by considering three different steel grades (C15, C45 and C60). For a general description of the material behaviour, an empirical approach is used to implement mathematical functions so as to express the relationship between flow stress and dominant influence variables like alloying elements, initial microstructure and reheating mode. The oxide scale consists of three different components namely wuestite, magnetite and haematite. In order to take the oxide scale into account, additional models are required to describe the growth kinematic and flow behaviour of the oxide scale components. The mathematical relationship between oxidation time, temperature, carbon content and oxide scale height is based on Arrhenius approach. The deformation behaviour of oxide scale is separately modelled for each component with parameterized flow curves. This paper gives first approaches on the numerical modelling of plastic deformation of oxide scale in a hot forging process. The main focus lies on the involvement of the different materials as well as the calculation and assignment of material properties in dependence of current process parameters by using subroutines. The numerical model and subroutines will be implemented in the FE-Software simufact.forming. A validation of the numerical model will be carried out by comparison of numerical results with experimental data.

Keywords: hot forging, fem, oxide scale, multi-material modelling

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Nomenclature

δ_{HS}	transition function
δ	mass fractions
φ	strain
$\dot{\varphi}$	strain rate
ϑ	temperature
ϑ_{γ}	austenitising temperature
A, m, w	adjustment coefficients for flow curve models
HS_{α}, HS_{β}	first and second term of metal matrix flow curve model
k_f	flow stress

Introduction

Hot forging process is widely used to manufacture industrial components. Advantages are the significantly decrease of required forming forces as well as higher achievable degree of deformation by a pre-heating of semi-finished goods to temperatures above 800 °C. However, the hot temperatures lead to oxidation at the surfaces resulting in a change of surface properties as well as the formation of oxide scale. During the oxidation process, different iron oxides (wuestite, haematite and magnetite) occur depending on the steel matrix properties like carbon content as well as temperature and oxidation time. The oxide scale has to be removed leading to material losses up to 3 % by weight. In addition, the oxide scale particularly influences friction as well as material flow and can lead to an increase of die wear [1]. This paper focuses on numerical modelling of the oxide scale behaviour during a hot forging process and provides an overview of the used flow curve models to describe the material behaviour of scale components and the steel matrix with regard to carbon content, temperature, strain rate as well as grain size.

The influence of alloying elements on the oxidation behaviour of steel has been described in [2]. The Si-steel has shown a delayed oxidation behaviour at lower temperatures and a significantly increased oxidation rate for temperatures higher than 1100 °C as compared to the IF-steel and S355-steel due to the alloying elements Si and P. Previous research works have presented a relationship between temperature, carbon content and growth of oxide scale and it has been shown that, at temperatures higher than 700 °C an increasing carbon content leads to a decrease in oxide scaler layer thickness [3,4,5,6]. Experimental investigations at elevated temperatures within a range between 900 °C and 1200 °C have shown different material-specific forming behaviours depending on the considered oxide scale component. The highest bearable strain was observed for wuestite whereas its yield stress has been found to be lower as compared to haematite and magnetite. Haematite has been observed to posess the maximum yield stress. Moreover, it has also been found to be the hardest oxide scale component at room temperature with a Vickers hardness of 1000 HV10 as compared to magnetite (600 HV10) and wuestite (400 HV10). Furthermore, the investigations have shown a significant influence of the strain rate on the forming behaviour [7,8].

The presence of oxide scale in metal forming processes has a significant influence on the friction, but until now only analytical and phenomenological approaches for mono materials have been published. Friction with regard to different scale conditions, which were induced by defined furnace temperature and holding times in variable atmospheres haven been investigated by various research groups. They showed that a thin oxide layer has a positive influence on the friction coefficient µ in contrast to thicker ones, which are harder and brittle [9,10,11,12]. Furthermore, there have also been experimental investigations indicating a decrease of friction coefficient with increasing scale layer thickness [13,14,15].

In addition to the oxide scale of the workpiece, the forming behaviour, which is described by material laws in the FEM, is significantly influenced by the metal matrix. Parameters with a significant effect on the flow stress are the process specific parameters (e.g. strain rate and temperature) as well as material-specific parameters (e.g. alloying concept, microstructure and previous production processes) [17]. Experimental investigations have shown a significant influence of total carbon content on material flow behaviour. Increasing carbon content has led to a reduction of the yield stress, particularly at high temperatures [3,18,19]. In [3] the authors have presented a Hensel-Spittel based flow curve model which takes initial grain size, temperature, strain rate as well as carbon content into account.

Modelling flow curve for general steels

As mentioned above, an accurate flow curve model with consideration of dynamic hardening and softening behaviour depending on material as well as process parameters needs to be evaluated. In this research work numerical simulation of forming behaviour of the metal matrix is based on a model presented by Korpalla as shown in Equation (1). This model provides a general description of yield stress with regard to the carbon content [3].

$$k_f = (1 - \delta_{HS})\, HS_{\alpha} + \delta_{HS}\, HS_{\beta} \quad (1)$$

The flow curve model is based on two Hensel-Spittel approaches modified by the transition function δ_{HS} as provided in