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

B.-A. Behrens[a], R. Kawalla[b], B. Awiszus[c], A. Bouguecha[a], M. Ullmann[b], M. Graf[c], C. Bonk[a], A. Chugreev[a], H. Wester[a]*

[a]*Institute of Forming Technology and Machines, An der Universität 2, 30823 Garbsen, Germany*
[b]*Institute of Metal Forming, Bernhard-von-Cotta-Str. 4, 09599 Freiberg, Germany*
[c]*Virtual Production Engineering, Reichenhainer Str. 70, 09126 Chemnitz, Germany*

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.

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

* Corresponding author. Tel.: +49-511-762-3913; fax: +49-511-762-3007
E-mail address: wester@ifum.uni-hannover.de

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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].

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

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

Equation (2). The first term HS_α describes the hardening section at the beginning of the forming and is expressed by equation (3) whereas the second term HS_β, expressed by equation (4), is used to describe the section where a balance of hardening and softening induced by recrystallisation takes place.

$$\delta_{HS} = 0.5 + \pi^{-1}\tan^{-1}[w_1\vartheta^{-w_2}(\varphi - \varphi_k\vartheta_\gamma^{w_\gamma}\dot{\varphi}^{w_4})] \quad (2)$$

$$HS_\alpha = A_a C\%^{m_{C_1}}\varphi^{m_a}e^{-m_{a1}\vartheta}\varphi^{m_{a2}\vartheta^{m_{a\varphi}}C\%^{m_{C_2}}}\dot{\varphi}^{m_{a3}} \quad (3)$$

$$HS_\beta = A_b C\%^{m_{C_3}}e^{-m_{b1}\vartheta}\varphi^{m_{b2}}\dot{\varphi}^{m_{b3}} \quad (4)$$

This flow curve model considers the effect of carbon content on the yield stress in the Hensel-Spittel approaches by the general parameter $C\%$ (weight%). Moreover, temperature ϑ, strain φ and strain rate $\dot{\varphi}$ have been taken into account. A direct relationship between dynamic softening and carbon content has not been evaluated [3]. Furthermore, it takes the initial microstructure into account with respect to the austenitising temperature ϑ_γ. A detailed description of the flow curves and the used adjustment coefficients (A, m, w) of the used model have been presented in the previous work [3]. An overview of the used material specific parameters for the steel matrix is provided in table 1 and 2 as well as for the oxide scale layer in table 3.

Table 1. Material specific parameters for the flow curve terms HS_α and HS_β

A_a	m_{C_1}	m_{a1}	m_{a2}	$m_{a\varphi}$	m_{C_2}	m_{a3}	A_b	m_{C_3}	m_{b1}	m_{b2}	m_{b3}
3275	0.03662	0.0027	0.41618	-0.0421	-0.08004	0.07959	894	-0.01367	0.00276	0.00236	0.17777

Table 2. Material specific parameters for the transition function δ_{HS}

w_1	w_2	w_4	w_γ	φ_k
1.83501	0.00015	0.13325	0.048	0.15951

Modelling flow curve for oxide scale and oxide scale growth

In addition to the model for metal matrix, a model describing the oxide scale flow behaviour is also needed for the numerical simulation. Due to the significantly different mechanical properties induced by the varying chemical composition of the oxide scale, the forming behaviour which can be described by flow curves has to be investigated, for the mono oxides as performed by Graf [8].

To define mechanical properties of the mono oxides, cylindrical samples have been sintered from powder materials with different oxygen contents. The force-displacement curves, which are needed to describe flow behaviour, have been evaluated from cylindric compression test at elevated temperatures and variable strain rates.

Based on the results of experimental tests, a flow curve model has been developed based on the Freiberger approach derived from Hensel-Spittel equation approach for each oxide. This models consider temperature as well as strain and strain rate dependence.

$$k_f = A\, e^{m_1\vartheta}\varphi^{m_2}e^{\frac{m_4}{\varphi}}(1+\varphi)^{m_5\vartheta - m_6}e^{m_7\varphi}\dot{\varphi}^{m_3+m_8\vartheta} \quad (5)$$

The flow curves of the oxides are not comparable with commonly known flow curves of metallic materials. They show neither an elastic part during loading nor the characteristic flow curve shape known from metals. Nonetheless, they have given a good description of material behaviour under the effect of compression loadings. The adjustment coefficient (A, m) were taken from Graf [8].

For the numerical simulation of oxide scale behaviour an initial layer thickness of the sample must be determined. The initial layer thickness can be calculated by means of a combined ARRHENIUS-approach, presented in the previous work [3], which considers furnace temperature, oxidation time as well as carbon content.

Numerical model

As already mentioned, the oxide scale influences the entire forging process as well as the end product quality, thus a numerical prediction of oxide scale forming behaviour in a forging process is of particular interest. Oxide scale thickness with regard to the basis material dimensions is very small and the oxide scale itself can consist of three different components possessing different mechanical properties. These facts lead to an increased complexity for modelling of oxide scale in a forging process. This paper presents an insight into modelling of intermediate layers or coatings by using the oxide scale phenomena as an example. It provides a numerical model which takes the material properties as well as interaction with metal matrix of an intermediate layer into account by using a multi-material approach. The numerical model with consideration of oxide scale was created in the commercial FE-software simufact.forming 13.3.1. A schematic representation of the created numerical model is given in fig. 1. Due to significant difference in the forming behaviour of metal matrix and oxide scale, a multi-material approach

has been used.

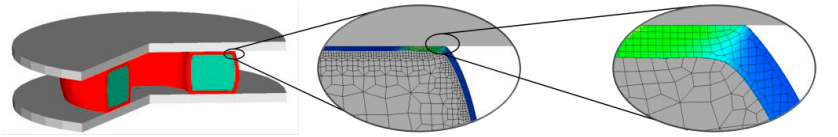


Fig. 1. Schematic representation numerical model and regarding dimensions

Thus, it was possible to create various user defined material models for the workpiece. Moreover, fig. 1 shows the different dimensions of the metal matrix and the oxide scale which requires appropriate meshes in order to get accurate results for material behaviour in the oxide scale layer as well as adequate computation times.

The user defined material models are based on the above described flow curve models. As an initial approach, the oxide scale is assumed to be a smeared continuum. This allows the description of a material with non-uniform properties as a homogeneous continuum. Thus the three layers wuestite ($Fe_{1-\gamma}O$), magnetite (Fe_3O_4) and haematite (Fe_2O_3) are considered as a mono material layer with weighted mechanical properties depending on the current individual mass fractions.

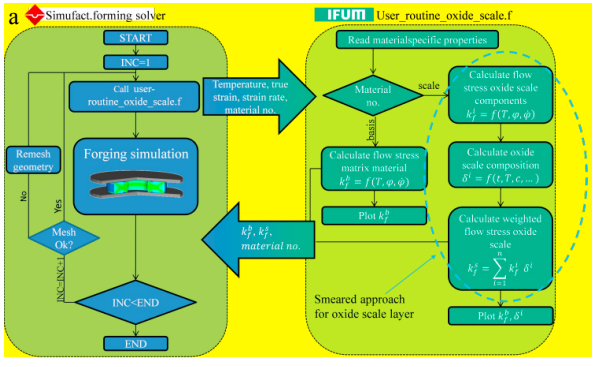
The assignment of the actual yield stress depending on material as well as actual temperature, strain, strain rate and material-specific parameters takes place with the help of in Fortran coded user subroutines created during this research. A schematic representation of the dataflow within the developed user subroutine and interactions with the solver is given in fig. 2. In order to calculate the actual yield stress the routine is executed by the solver in every iteration for all integration points of each element. The solver submits the current data for the temperature, true strain, strain rate, a specific material id number as well as material-specific parameters like carbon content or oxide scale composition. Within the user-subroutine the elements are characterized by the specific material id number to assign the correct yield stress, depending on whether the element material is steel or oxide scale.

The generally observed oxide scale layer on steels consists of three different components namely wuestite, martensite and haematite. Therefore, the use of a smeared approach is appropriate which requires calculation of flow stress for each of the components separately. For this purpose, three different material models parameterized with the findings of oxide scale characterization are implemented as functions into the user subroutine. Each function calculates the flow stress for one of the three oxide scale parts depending on the current temperature, true strain, strain rate as well as material specific parameters. Based on the assumption of a smeared continuum, a weighting of the individual flow stresses is required in order to calculate a homogenous flow stress for the oxide scale layer. The weighted oxide scale flow stress is calculated depending on the oxide scale composition and the function is in the form

$$k_f^s = k_f^w\,\delta^w + k_f^m\delta^m + k_f^h(1-\delta^w-\delta^m) \tag{6}$$

whereby k_f^s represents the global oxide scale flow stress, k_f^w, k_f^m and k_f^h are the flow stress of the constituent oxide scale components. The terms δ^w and δ^h are the mass fractions of wuestite and magnetite respectively. All numerical results of the oxide scale layer presented in this paper have been calculated based on the smeared approach described above. In general, the mass fractions depend on temperature, time and carbon content of the matrix material.

a



b

Parameter	Wuestite	Magnetite	Haematite
A	1524800	34050.3	243658
m_1	-0.00835641	-0.00055586	-0.00207265
m_2	0.894583	1.15844	2
m_4	0.00178116	0.000893842	0.00124089
m_5	0.00195354	-0.0853523	0.00388508
m_7	-6.83988	51.0793	-25.662
m_8	0.00013633	0.000105641	-5.7308E-05

Fig. 2. a) Schematic representation of the user-subroutine and the interaction between user-subroutine and simufact.forming solver, b) Material specific parameters used in this project for the individual flow stress calculation of oxide scale components wuestite ($Fe_{1-\gamma}O$) , magnetite (Fe_3O_4), haematite (Fe_2O_3)

The developed user-subroutine has been integrated into the simufact GUI, thus key parameters like carbon content of used steel material and oxide scale composition can be easily adjusted by the user. Furthermore, the modular structure of the user-subroutine allows a simple extension to take other phenomena like the growth of oxide scale during the forging process or the separation of oxide scale parts into consideration.

Validation and results

A validation of the numerical model has been carried out by comparing numerical results with experimental data of a performed ring compression test. The samples (d_a=9 mm x d_i=4.5 mm x h=3 mm) has been heated to defined temperatures of 1000 °C and 900 °C with an oxidation time of 30 s in order to create a specific oxide scale layer and compressed with a stroke of up to 60% of its initial height. Tool temperature has been equivalent to Workpiece temperature. The time-stroke relationship has been calculated based on the experimental data and the average calculated press speed has been 3.2 mms^{-1}. After heating an initial scale layer thickness of 50 µm (1000 °C) and 30 µm (900 °C) has been measured and used as initial condition for FE-simulation. During the simulation constant thickness ratios for wuestite:magnetite:haematite (95:4:1) have been assumed [20]. The used friction factor (m) has been determined as 0.65 by evaluation of experimental ring compression tests. The numerically calculated and experimentally measured force-displacement curves presented in fig. 3a shows a good qualitative agreement, thus it can be concluded that the used numerical boundary conditions are applicable. In the current research project, experimental data for heat transfer coefficients have not been measured. Literature predicts a heat transfer coefficient for non-fractured oxide scale which is 10-15 times lower than that of steel [21,22]. Therefore, the heat transfer coefficient for numerical simulation has been assumed as 1400 $W/(m^2K)$. The upper and lower dies have been modelled as heat-conducting rigid bodies. The force-displacement curves for both numerical and experimental are presented in fig. 3a for steel grade C15 at 1000 °C with a layer thickness of 50 µm as well as at 900 °C with a layer thickness of 30 µm and show a good qualitative correlation.

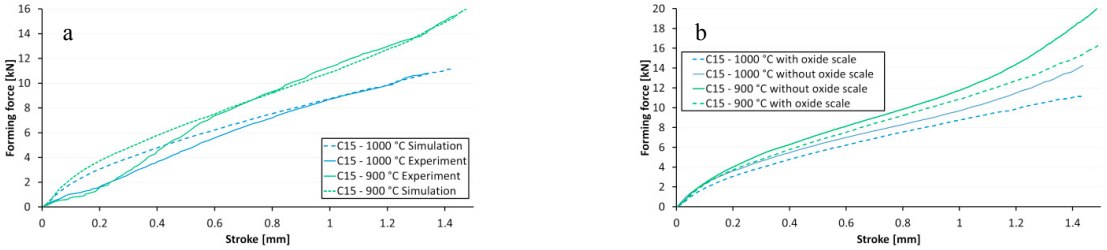


Fig. 3. a) Numerical and experimental force-displacement curves for ring compression test at 900 °C (30 µm oxide scale layer thickness) and 1000 °C (50 µm oxide scale layer thickness), b) Numerically calculated force-displacement curves for ring compression test with and without oxide scale for steel C15 at 900 °C and 1000 °C

Particularly at the beginning of forging process, there is an offset between measured and calculated force. This can be caused either by the machine stiffness in the experimental tests or due to the used oxide scale flow curve model. On the basis of complex oxide scale material behaviour the material characterisation has been limited to specific temperatures, strains and strain rates. Therefore the implemented flow curve model needs to be extrapolated for higher strains as well as a wider temperature range. Moreover, in complex hot forging processes the oxide scale can detach or rupture caused by its brittleness, thus influencing the friction conditions as well as the material flow. For the next project period it is planned to extend the user-subroutine in order to take the oxide scale damage behaviour induced by rupture or detachment into consideration.

The numerically calculated force displacement curves for both with and without scale are presented in fig. 3b. The process without oxide scale shows a higher forming force throughout the whole stroke. The difference increases particularly at the end of process. This is caused on one hand by the smaller flow stress of oxide scale layer compared with the metal matrix and on the other hand the oxide scale layer can influence friction conditions as well as material flow. Furthermore, the oxide scale layer has an isolating effect which decelerates the cooling of the metal matrix and results in lower flow stress. Further numerical and experimental investigations are planned to investigate the effects of oxide scale on forming behaviour.

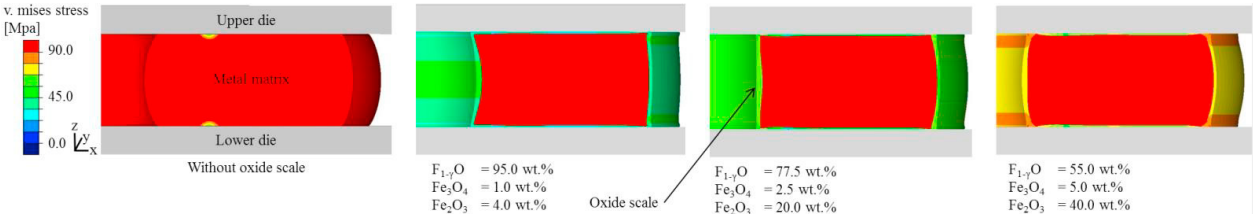


Fig. 4. Numerically calculated results for ring compression test samples without oxide scale and with a 50 µm oxide scale layer with varying composition using the presented smeared approach

Some initial exemplary results of a sensitivity analysis are presented in fig. 4. It shows the cross section and von Mises stress after compression. All simulations have been carried out with identical initial conditions for friction, temperature and press velocity. In the simulations with oxide scale the composition of the components which influence mechanical properties has been variated as described in fig. 4. The figure shows a significant influence of oxide scale as well as its composition on the forming behaviour of the metal matrix. The von Mises stress inside the oxide scale layer is observed to be significantly lower than the stress in the metal matrix thus the oxide scale is squeezed out of the region between die and metal matrix and flows to the sides.

The von Mises stress inside the oxide scale layer depends on composition and increases with an increasing proportion of haematite and martensite and decreasing proportion of wuestite which shows significant lower flow stress. Moreover, the scaled samples show a concave or straight shape at the inner diameter in contrast to the unscaled sample which has a convex shape. The shape is also influenced by the scale composition and the deviation increases with increasing proportion of wuestite. This difference in shape can be induced by changes in material flow caused by strongly different flow stress for oxide scale and metal matrix as well as changing friction conditions depending on oxide scale composition. This influence on the finished component's shape clarifies the requirement of taking the oxide scale into account accurately predict the end shape with the FE-simulation.

Summary

Based on a multi-material approach, an FE-model to describe the oxide scale material behaviour in hot forging has been developed. Four different material models for both oxide scale and steel have been implemented by means of user subroutines. This enables an accurate description of the oxide scale material flow behaviour depending on temperature, strain as well as strain rate. Furthermore, the implemented model for general steel grades takes into account the influence of varying carbon content as well as the initial microstructure. The developed numerical model has been validated by comparing the results of the performed ring compression tests and the numerical simulation. First results have shown a significant influence of oxide scale on the finished component shape. In future the dependency of scale formation and friction conditions will be investigated and coupled with the presented FE-model. A coupling between the model for calculating oxide scale growth and the presented numerical model is planned as well. In addition, further investigations on the adhesion interface between oxide scale and metal matrix as well as oxide scale rupture will be carried out in order to examine its behaviour during hot forging process.

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