R. KAWULOK, S. RUSZ, T. PETREK

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HOT FLOW STRESS MODELS OF THE STEEL C45

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Flows stress of the steel C45 were predicted on the basis of experimentally obtained flow stress curves, using uniaxial hot compression tests on the plastometer HDS-20, by two completely different types of mathematical models, moreover with comparison to a model comprised in the FEM database of the FORGE software. The tests were carried out within the temperature range from 900 to 1 280 °C, at the strain rate from 0,1 to 100 s^{-1} and deformations up to 1,0. It follows from the results of flow stress prediction that models designed on the basis of experimental measurements have much better information capability than the generated model implemented into the database of the FORGE software, however, their extrapolation for larger deformations is limited.

Key words: medium-carbon steel, uniaxial hot compression test, flow stress curves, hot flow stress model

INTRODUCTION

In order to subject materials, such as investigated steel C45, to plastic deformation while maintaining their integrity, it is necessary to know their deformation behaviour during forming processes. Commonly used plastometric experiments serve this purpose, when on the basis of the experimentally obtained flow stress curves it is possible to determine natural flow stress of the given alloy, and thus select the forming equipment with suitable energy and force parameters. For application of the greatest possible range of deformation conditions it is appropriate to use thermo-mechanical simulators, such as HDS-20 [1], which is based on the concept of the plastometer Gleeble 3 800 [2 - 3].

The main objective of this work was to calculate on the basis of experimental flow stress curves from uniaxial hot compression testing for the steel C45 the material constants of the Hensel-Spittel model [4] allowing prediction of hot flow stress in the widest possible range of strain.

It is expected that thus obtained material constants will enable better prediction of flow stress in comparison with the constants, which are for this steel and for this type of model given in the material database of the FEM simulation software FORGE.

In recent years numerous mathematical models were developed, which allow prediction of flow stress based on experimentally obtained flow stress curves. These models essentially differ by their mathematical structure and by extent of strains, which they can describe [1]. The frequently used model Sellars, based on the sine-hyperbolic function [5], belongs to the models that allow description of flow stress in a wide range of strain. Models Estrin, Mecking and Bergstrom also find their application [6, 7]. However, all these models have in comparison with the above-mentioned Hensel-Spittel model [4] one major drawback in our case – they cannot be implemented without modifications of the program code into the simulation software FORGE, who works with the model [4].

EXPERIMENTAL PROCEDURE

From a series of uniaxial hot compression tests performed with use the test module Hydrawedge II on the Hot Deformation Simulator HDS - 20 at the VŠB - Technical University of Ostrava we obtained experimental data for creation of a flow stress model for the given steel.

Cylindrical test specimens with diameter of 10 mm and height of 15 mm were made by cutting and turning from a hot rolled bar from a medium carbon steel C45, with the indicative chemical composition (see Table 1).

Table 1 **Indicative chemical composition of given steel**

C / wt. %	Mn / wt. %
0,42 – 0,50	0,50 – 0,80

The experiment was carried out at the temperatures of 900 °C – 1 000 °C – 1 100 °C – 1 200 °C – 1 280 °C and at nominal strain rates of 0,1 s^{-1} to 1 s^{-1} - 10 s^{-1} - 100 s^{-1}. The samples were preheated to 1 200 °C with a duration of dwell of 30 seconds, only the samples tested at 1 280 °C were for operational reasons heated directly to this temperature. Next process and evaluation of tests

P. Opěla, I. Schindler, P. Kawulok, R. Kawulok, S. Rusz, T. Petrek - VŠB – Technical University of Ostrava, Faculty of Metallurgy and Materials Engineering, Czech Republic
F. Vančura – Kovárna VIVA SpA, Czech Republic

showed that this procedure did not affect the initial structure in such an extent as to inhibit description of the deformation behaviour of the investigated steel by uniform equations.

It is possible to see in Figure 1 that the experimentally obtained flow stress curves show from the theoretical viewpoint an incorrect increase of flow stress at strains higher than 0,6. This causes problems at subsequent construction of flow stress models. It is probably caused by the increasing friction on the contact surfaces of the sample with anvils, leading to the formation of undesirable barrel shape. Solution can be found in application of complicated methods described e.g. in [8, 9].

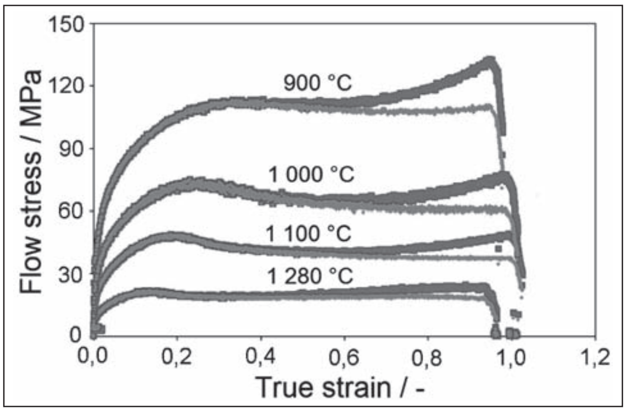

Figure 1 Flow stress curves of the steel C45 after experiment (dark) and after the following shape correction (light) – for the strain rate of 0,1 s^{-1}

For solution of this issue we applied in our case a simple correction method of the flow stress curves shape for strains greater than 0,6, based on the shape of the curve with distinct areas of steady-state.

On this basis we then derived mathematical function, which compensates the shape of the curves in this area. This function was applied to the entire set of experimentally obtained curves corresponding to the given material - see, e.g. Figure 1 (corrected curves before their smoothing). It is an originally developed proprietary and undisclosed know-how, which replaces the complicated calculations using an inverse method.

HOT FLOW STRESS MODELS

For the reasons given above we chose for the flow stress prediction the Hensel-Spittel model [4]:

$$\sigma = p_1 \cdot \exp(p_2 \cdot t) \cdot t^{p_3} \cdot e^{p_4} \cdot \exp\left(\frac{p_5}{e}\right) \cdots$$

$$\cdots (1+e)^{p_6 \cdot t} \cdot \exp(p_7 \cdot e) \cdot \dot{e}^{p_8} \cdot \dot{e}^{p_9 \cdot t} \qquad (1)$$

where e / - is strain, $\dot{e}$ / s^{-1} strain rate, t / °C is temperature and $p_1 - p_9$ / - are material constants. The model (1) enables a universal flow stress prediction in the whole range of strains, but with omission of physical essence of the impact of dynamic recrystallization. It was found for the steel C45 in the database of the simulation software FORGE, that four constants of this model (p_3, p_6, p_7 a p_9) have zero values, which probably influenced negatively the flow stress prediction, as it is demonstrated by comparison of the experimentally measured flow stress curves with those predicted by the FORGE software – see Figure 2.

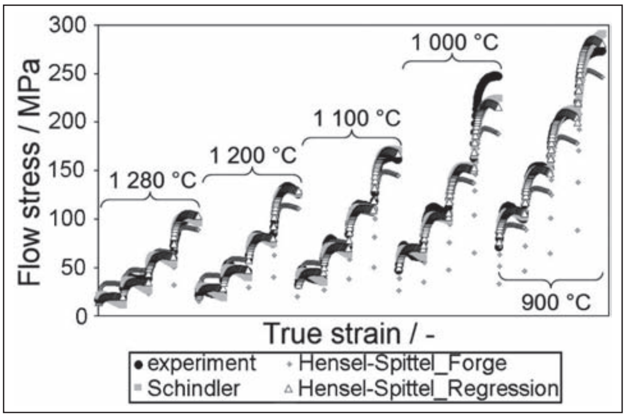

Figure 2 Comparison of the experimental and calculated flow stress curves (for every temperature four gradually increasing strain rate values)

In order to obtain more accurate flow stress prediction, we therefore calculated the material constants of the model (1) on the basis of multiple nonlinear regression analysis of experimental data using the software UNISTAT 5.6. Thus obtained and rounded constants are given in Table 2. The prediction based on thus calculated constants is expressed by triangular flow stress curves in diagram shown in Figure 2, in which it is possible to see in the whole experimental range a distinctively more accurate description of the stress-strain curves.

Table 2 **Constants of the Hensel-Spittel model (1) after nonlinear regression analysis of the experimental data in UNISTAT 5.6 software**

p_1	p_2	p_3
1 310	- 0,0040	0,25
p_4	p_5	p_6
0,12	- 0,0063	- 0,000044
p_7	p_8	p_9
- 0,19	- 0,094	0,00026

On the basis of experience with the previous modelling we then chose for comparison also the Schindler model [1], which can describe flow stress also with respect to the start of dynamic recrystallization:

$$\sigma = p_1 \cdot e^{p_2} \cdot \exp\left(-p_2 \cdot \frac{e}{e_p}\right) \cdot \dot{e}^{\left(p_3 - \frac{p_4}{T}\right)} \cdot \exp(-p_5 \cdot T) \quad (2)$$

where T / K represents temperature and $p_1 - p_5$ / - are material constants. Unlike the model (1), this model operates moreover with the peak strain values e_p / -, which reflect the influence of the start of dynamic recrystallization on the softening processes at forming. These values can then be described for the investigated combination of thermomechanical parameters by the equation [1]:

$$e_p = 0{,}00335 \cdot Z^{0{,}186} \quad (3)$$

where Z / s^{-1} is the Zener-Hollomon parameter [10]:

$$Z = \dot{e} \cdot \exp\left(\frac{Q}{R \cdot T}\right) \quad (4)$$

where $R = 8{,}314\ J \cdot K^{-1} \cdot mol^{-1}$ and $Q = 280\ kJ \cdot mol^{-1}$ is activation energy of the given steel at hot forming, determined on the basis of knowledge of peak values of stress in experimentally obtained stress-strain curves, and by regression determination of constants in the Arrhenius type equation with hyperbolic law [11].

The material constants of the model (2) were then again calculated on the basis of nonlinear regression analysis of experimentally obtained data (Table 3). Prediction of flow stress based on these constants and the model (2) is expressed by square curves in Figure 2.

Table 3 **Constants of the Schindler model (2) after nonlinear regression analysis of the experimental data in UNISTAT 5.6 software**

p_1	p_2	p_3	p_4	p_5
8 180	0,13	0,43	358	0,0033

DISCUSSION OF RESULTS

Both used models provide the possibility of getting quite accurate flow stress prediction in a wide range of deformation conditions, if their constants were calculated by regression analysis of experimental data (Figure 2). Certain problem arises in both models at description of the flow stress for the combination of 1 000 °C and 100 s^{-1}, which may be caused by the variability of the experimental results.

The Hensel-Spittel model is distinctly phenomenological, and unlike the Schindler model, it lacks deeper physical basis. At the highest temperatures the stress-strain curves of the given steel passed very quickly into the steady-state area, which even a complex model (1) cannot describe with sufficient accuracy (see Figure 2).

A disadvantage of the Schindler model (2) consists in the fact, that its implementation into the FORGE simulation program would require some intervention of a programmer, while the FORGE software works with the Hensel-Spittel model in a standard manner.

At an attempt to extrapolate the flow stress to higher strains (up to the value of 2) (Figure 3) both models encountered problems with the description of the steady-state area. In case of the Schindler model this can be explained by the fact that it was designed exclusively for the strain before reaching the steady-state area. At extrapolation to the area of very high deformations a paradoxical situation can thus occur, when the models more accurately describing the physical nature of the experimental data can, under certain thermomechanical conditions, give less positive real results. Although the Hensel-Spittel model was designed for universal description of the flow stress curve, but without ensuring the constant evolution in the steady-state area.

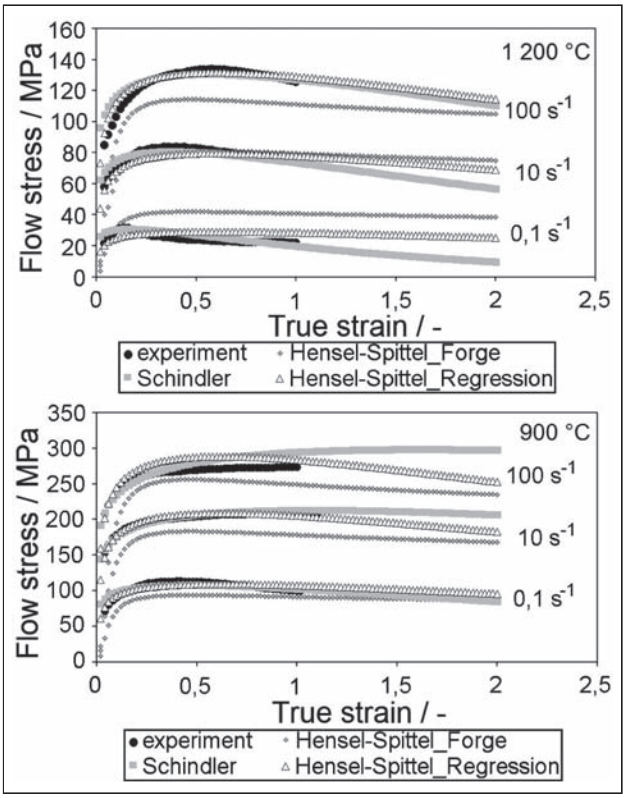

Figure 3 Flow stress curves extrapolation into higher strains

SUMMARY

On the basis of experimental flow stress curves obtained by uniaxial hot compression tests on the samples made of the steel C45 we predicted with use of multiple nonlinear regression a hot flow stress in the temperature range from 900 to 1 280 °C, at the strain rates from 0,1 to 100 s^{-1}, and for deformation up to the value of 1,0.

The developed Schindler model takes into account the effect of the start of dynamic recrystallization on the softening processes, and thanks to its physical basis it can accurately describe the given experimental data, with the exception of the steady-state area.

Prediction of constants for the Hensel-Spittel model based on nonlinear regression of experimental data appears to be more appropriate than use of constants from the FEM software FORGE. The newly determined constants provide a better match with the experimentally obtained stress-strain curves, although for the area of very high deformation the extrapolation is made somewhat uncertain by evolution of the dynamic healing, especially in the steady-state area.

The developed model of flow stress of the steel C45 is used for mathematical simulations of the processes of die forging, associated with a high degree of partial deformations.

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Note: The translator responsible for English language is B. Škandera, Dobrá, Czech Republic