

HOT DEFORMATION BEHAVIOUR OF STEEL C45 AT HIGH STRAINS

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Abstract

High-grade medium-carbon steel C45 with content of carbon 0.42 - 0.50 % and manganese 0.50 - 0.80 %, intended for hardening and tempering, has been often used for production of die forgings and the less exposed machine components. The hot stress-strain curves of this steel were investigated by uniaxial compression tests using the Hot Deformation Simulator HDS-20 within a wide strain range (up to 1.0). The testing temperatures were 1000 - 1100 - 1200 °C and nominal strain rates were 0.1 - 1.0 - 10 - 100 s⁻¹. The unique computing method was developed which enabled to correct the shape of the experimentally obtained stress-strain curves, influenced by the samples' spreading at high strains. The value of the activation energy at hot forming was calculated (290 kJ·mol⁻¹) using the peak stress values and the dynamic recrystallization kinetics was described. The mathematical model was developed which considered the predicted peak strains and described mathematically the influence of strain, strain rate and temperature on the flow stress. Reliability of this model was verified in comparison with the experimental data and compared with the stress-strain curves calculated according to the software FORGE material database. Thanks to its physical fundamentals the developed model is more accurate than the FORGE-based calculations, at the highest strain rates in particular.

Keywords: Medium-carbon steel, hot compression test, stress-strain curves, mathematical models

1. INTRODUCTION

The C45 ranks among unalloyed steel intended for example to production of die forgings and hot rolled products like bars, sheets, strips and wires. Products from this steel are mainly used for less exposed machine components in automotive industry and for railway wagons. An optimal mechanical values including toughness are achieved by quenching and the following tempering when, with respect to products with complex shape, it is better to use oil quenching. Further, this steel is suitable for surface quenching by flame and even induction [1, 2].

If we want to process materials like steels etc., we have to master the deformation behaviour during their forming. To investigate the hot deformation behaviour we commonly use the plastometric tests in order to obtain the flow stress curves for the following mathematical analysis and predictions of the force parameters. To apply wide range of deformation conditions, the thermo-mechanical simulators (for instance HDS-20 -which is essentially Gleeble 3800 plastometer) are generally used [3].

The main aim of this investigation was to develop the suitable phenomenological model describing the hot flow stress of the medium-carbon steel C45 at high strains with sufficient precision. This model should take in account combined effect of temperature, strain and strain rate. Moreover, the new model should offer the more accurate prediction of the stress-strain curves in comparison with the calculations based on the FEM software FORGE material database.

There are many various mathematical models describing the hot flow stress. Difference among these models consists in their mathematical structure and in the strain extent for which the flow stress can be predicted. With regard to extent of the applied strain, there are three types of models. The first one is capable of describing the flow stress up to the peak strain, the second one is intended for description the flow stress beyond the peak stress. As for a third group, this is able to describe the whole flow curves - which means in large extent of strains including a steady-state [4]. For our needs the third group of models describing the whole flow curves is especially important. The most widely used model for hot flow stress description within wide strain range is the Sellars model based on hyperbolic sine function, usually written as [5]:

$$\sigma = \frac{1}{\alpha} \cdot \ln \left[\left(\frac{Z}{A} \right)^{1/n} + \sqrt{\left(\frac{Z}{A} \right)^{2/n} + 1} \right] \quad (1)$$

where Z [s⁻¹] is Zener-Hollomon parameter and A [s⁻¹], n [-] and α [MPa⁻¹] are materials constants. However, this model exhibits some disadvantages. It doesn't take into account the deformation history, which is problem when softening processes take place significantly. This model also loses the accuracy when significant peak stress appears [5, 6]. One of the most sophisticated is the Hensel-Spittel model widely used for hot flow stress prediction in FORGE software [7]:

$$\sigma = p_1 \cdot \exp(p_2 \cdot t) \cdot t^{p_3} \cdot e^{p_4} \cdot \exp\left(\frac{p_5}{e}\right) \cdot (1+e)^{p_6} \cdot t \cdot \exp(p_7 \cdot e) \cdot \dot{\epsilon}^{p_8} \cdot \dot{\epsilon}^{p_9} \cdot t \quad (2)$$

where e [-] is strain, $\dot{\epsilon}$ [s⁻¹] is strain rate, t [°C] is temperature and $p_1 - p_9$ are material constants. This model is intended for universal description of whole stress-strain curve but irrespective of the dynamic recrystallization processes. Another model - Schindler et al., however, is capable of to describe hot flow stress based on the peak strain values which are generally coupled with the onset of dynamic recrystallization [8]:

$$\sigma = p_1 \cdot e^{p_2} \cdot \exp\left(-p_2 \cdot \frac{e}{e_p}\right) \cdot \dot{\epsilon}^{\left(p_3 - \frac{p_4}{T}\right)} \cdot \exp(-p_5 \cdot T) \quad (3)$$

As in the previous case, e [-] is strain, $\dot{\epsilon}$ [s⁻¹] is strain rate, T [K] is temperature and $p_1 - p_5$ are material constants. Moreover, there is the e_p [-] value as strain to peak. There are two deformation members in model (3). The first one is a power law function reflecting strengthening and the second one based on exponential function takes into account dynamic softening. Technically, the Eq. (3) can not describe the steady-state phase of the flow stress curve. Finally, there is a modified model Hensel-Spittel which incorporates a part of Garofalo model [9]:

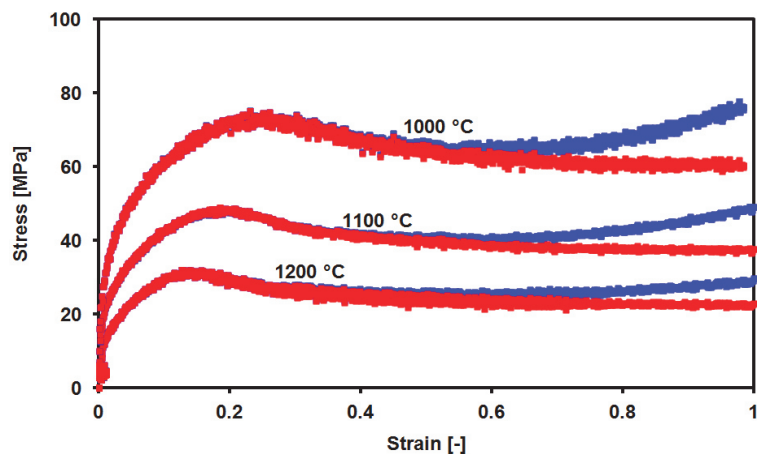
$$\sinh(\alpha \cdot \sigma) = p_1 \cdot \exp(p_2 \cdot T) \cdot e^{p_3} \cdot \dot{\epsilon}^{p_4} \cdot \exp\left(\frac{p_5}{e}\right) \cdot (1+e)^{p_6 \cdot T} \cdot \exp(p_7 \cdot e) \quad (4)$$

The stress value was replaced by hyperbolic sine function from Garofalo model, where α [MPa⁻¹] is material constants, T [K] is temperature and other symbols have the same meaning as in Eq. (2). It was found that this model succeeded in the excellent description of the hot flow stress of AA6005 aluminum alloy.

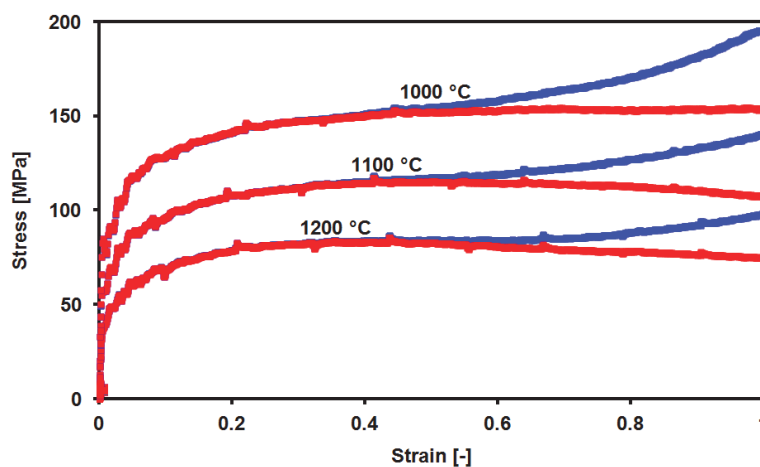
2. EXPERIMENT

The experimental data from uniaxial hot compression tests, acquired by the Hydrawedge II of the Hot Deformation Simulator HDS-20 at VSB-TUO Ostrava, were used to create a suitable mathematical model for description of the hot flow stress of the C45 steel (with content of carbon 0.42 - 0.50 % and manganese 0.50 - 0.80 %) at wide range of strains. The cylindrical test specimens with diameter 10 mm and height 15 mm were prepared from a hot-rolled bar. Combination of three deformation temperatures (1200; 1100 and 1000 °C) and four nominal strain rates (0.1; 1; 10 and 100 s⁻¹) were sequentially used whereas each sample was first pre-heated to temperature 1200 °C per 30 s.

In case of the uniaxial hot compression test is obvious, at high strains, shape of the stress-strain curves is strongly influenced by varying friction and uneven spreading. The standard calculation algorithm is then leading to illogical stress growing at strains above ca 0.6 - see [10] for example. This issue can be solved by the complicated mathematical methods [10, 11]. For our needs, we developed a simple method when from the knowledge of curve shape with a significant steady-state, for given material, was derived mathematical function compensating the appropriate flow stress curves in this area. Then, there is possible to obtain significantly more reliable results when we apply this concrete function on a whole set of curves corresponding to the given material - see Fig. 1 for example.



a) 0.1 s⁻¹



b) 10 s⁻¹

Fig. 1 Stress-strain curves of the steel C45 obtained by uniaxial compression tests (blue) and after following shape correction (red) - for strain rates 0.1 and 10 s⁻¹

3. RESULTS AND DISCUSSION

3.1 Activation energy at hot forming and peak coordinates

After the necessary corrections, it was possible to determine both peak coordinates from the stress-strain curves. The traditional hyperbolic sine equation was used to determine the activation energy at hot forming Q [J.mol⁻¹] [12]:

$$\dot{\epsilon} = C \cdot \exp\left(-\frac{Q}{R \cdot T}\right) \cdot \left[\sinh\left(\alpha \cdot \sigma_{\max}\right)\right]^n \quad (5)$$

where $\dot{\epsilon}$ [s⁻¹] is strain rate, R [J.K⁻¹.mol⁻¹] is universal gas constant, T [K] is deformation temperature, σ_{\max} is the peak stress, C [s⁻¹], n [-] and α [MPa⁻¹] are material constants. We employed special interactive software ENERGY 4.0 [13], working on the principle of partial linear regressions, to work out the constants in equation (5) as well as the value of the activation energy $Q = 290$ kJ.mol⁻¹. It can be noted that for the achieved Q -value and for the following calculations were used not nominal, but real mean values of strain rate. The values of strain to peak could be than described by relationship of type [12]:

$$e_p = 0.00163 \cdot Z^{0.206} \quad (6)$$

where Z is the Zener-Hollomon parameter [14]:

$$Z = \dot{\epsilon} \cdot \exp\left(\frac{Q}{R \cdot T}\right) \quad (7)$$

3.2 Hot flow stress models

Two different models were applied to predict the hot flow stress of the C45 steel under various thermo-mechanical conditions. At first, the Hensel-Spittel model (2) was chosen with material constants which are incorporated in the simulation software FORGE database. Four constants (i.e. p_3 , p_6 , p_7 and p_9) take zero values in this way simplified model which affected negatively its precision - see comparison of the experimental (black) and according to this model calculated (green) flow stress values in **Fig. 2**. The observed inaccuracy is very important mainly for low temperature and high strain rate values.

The better curve of the complex Hensel-Spittel model was obtained after the multiple nonlinear regression analysis of the experimental data (with the coefficient of the determination 0.9895) in the statistical software UNISTAT 5.6. Material constants $p_1 - p_9$ are displayed in **Table 1**. The corresponding red stress-strain curves are plotted in **Fig. 2**. It can be seen that these curves much better describe hot deformation behaviour of steel C45 but still can not clearly describe the steady-state area.

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

Constant	p_1	p_2	p_3	p_4	p_5	p_6	p_7	p_8	p_9
Value	1393	-0.0038	0.23	0.20	-0.0042	-0.00061	0.044	0.067	0.00012

Based on experiences with the previous mathematical modeling, the Schindler et al. model (3) was chosen as the second one. The material constants of this model were determined as in previous case through the nonlinear regression analysis - see **Table 2**. Plotted blue flow stress curves in **Fig. 2** show the best fit with experimental data and prove advantages of this model. The coefficient of the determination of these constants was calculated to be 0.9902.

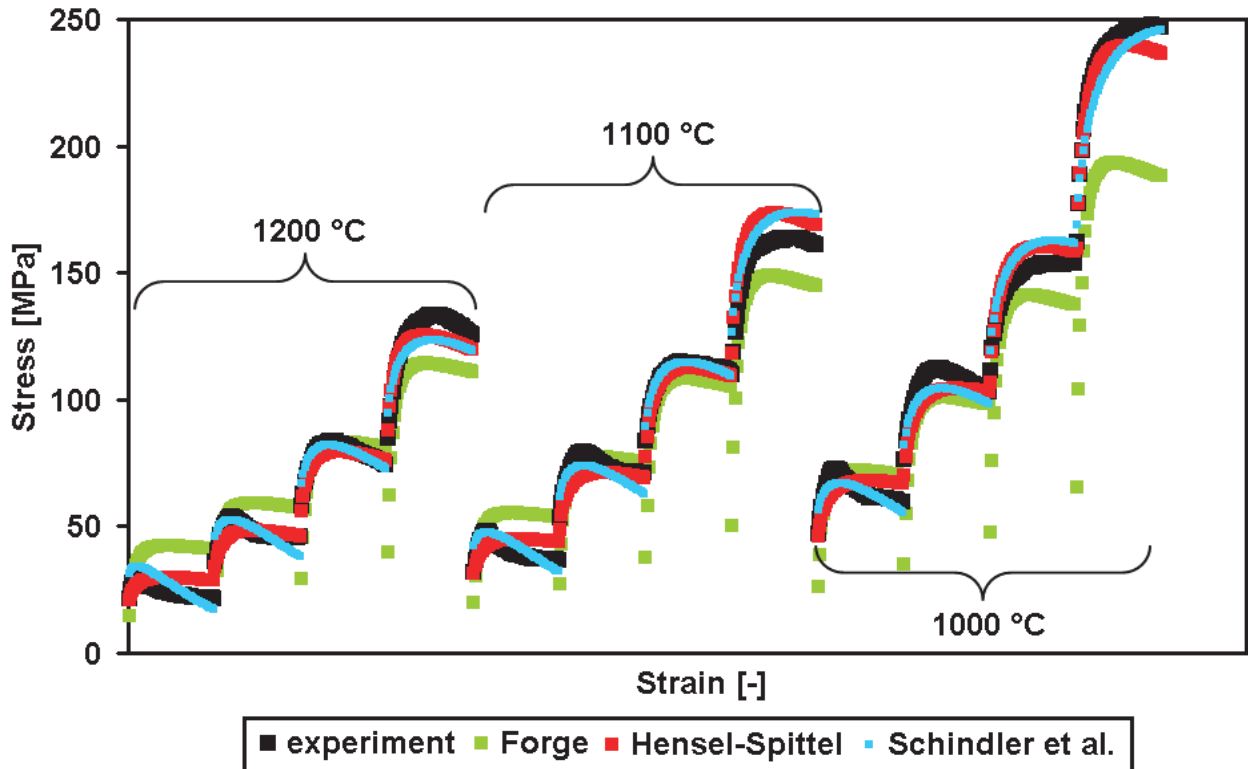


Fig. 2 Comparison of experimental data and calculated flow stress curves (four stepwise increasing strain-rate values for all three temperature levels)

Table 2 Constants of the Schindler at al. model after nonlinear regression analysis of the experimental data in UNISTAT 5.6

Constant	p_1	p_2	p_3	p_4	p_5
Value	5139	0.16	0.13	-34.2	0.0029

It is demonstrated by **Fig. 2** that the Hensel-Spittel model is not able to describe the steady-state phase of hot flow stress curves so correctly as the relatively simple model Schindler et al., what seems to be quite surprising. In addition, the Hensel-Spittel model does not take into account the peak strain values so there is not possible to correctly describe the dynamic recrystallization onset. It can be said that the Schindler et al. model is more suitable for prediction of the hot flow stress of the C45 steel owing to its better physical basis. The Hensel-Spittel model, however, must be in this case used for the FEM-based simulations of the hot deformation processes since only this model is incorporated in the software FORGE and there is not possible to put into this software the Schindler et al. model. However, the results of this investigation show that it is still much better to apply the Hensel-Spittel model with constants originally calculated from the own experimental results. Use of the constants from the FORGE material database (which are probably more or less based on chemical composition mainly, not on plastometric data) results in the much worse results of prediction, mainly at very high strain rates connected e.g. with some die forging processes.

CONCLUSIONS

Results of the uniaxial compression tests of the steel C45, carried out in temperature range 1000 - 1200 °C and strain rate range 0.1 - 100 s⁻¹, were processed by the multiple nonlinear regression analysis methods to achieve the hot flow stress models. A simple mathematical process was developed for high strain area,

allowing to modify a stress-strain curve shape which is influenced during compression test by changing friction and spreading. Developed Schindler et al. model reflects the influence of dynamic recrystallization and describes experimental data most accurately thanks to its physical base. For the SEM-based forming processes simulations in the FORGE software, however, the Hensel-Spittel model is used exclusively. The material constants listed in database of this software do not allow sufficiently the accurate prediction of the steel C45 flow stress, especially at high strain rates. Thus it is beneficial to obtain these material constants by the methods of multiple nonlinear regression analysis of the own experimental data.

ACKNOWLEDGEMENT

The research was supported by the grant projects TA02010390 (TA ČR), LO1203 (MŠMT ČR) and SP2014/100 (MŠMT ČR).

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