DETERMINATION OF THE HOT DEFORMATION ACTIVATION ENERGY AND FLOW STRESS COURSE OF THE AISI 4140 STEEL

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https://doi.org/10.37904/metal.2019.817

Abstract

The paper deals with the possibilities of the determination of the hot deformation activation energy and the flow stress course at hot forming conditions. By means of the Gleeble 3800 plastometer, the set of uniaxial compression tests has been carried out for the AISI 4140 steel. The tests were carried out within the temperature range of 850 - 1 250 °C and the strain rate range of 0.1 - 50 s^{-1} when the strain reached up to 1.0. From the obtained stress - strain curves the values of peak stress were determined and subsequently used to determine the value of the activation energy at hot forming according to the classical equation of the hyperbolic-sine type. Enumeration of its coefficients allow at the same time to predict the maximum flow-stress values of the investigated steel in dependence on the temperature and strain rate. The value of the activation energy has been used to assembly the mathematical models which allow to describe the flow stress course and the kinetics of the dynamic recrystallization of this steel at hot-forming conditions. By this way obtained results have been compared with the previously examined steel of the grade of AISI 4130.

Keywords: Stress - strain curves, hot deformation activation energy, AISI 4140 steel, uniaxial compression test

1. INTRODUCTION

The stress-strain curves serve for description of evolution of the flow stress in dependence on the strain, temperature and strain rate. It is very important to predict the material natural flow stress during hot forming, for example, for choosing the right tool for material forming. Such a prediction can be, however, complicated in the case of big strains where it is complicated by dynamic softening processes. A whole range of equations exists dealing with the mathematical description of stress curves [1,2]. The issue is phenomenologically addressed, for example, by the modified Fields and Backofen [3] model, or the complicated model designed by Hensel and Spittel [4], incorporated together with the relevant material database, into, for example, the popular FORGE simulation software. The mathematical models with a physical basis are mostly based on the description of the peak-stress coordinates, possibly also the coordinates of the point corresponding to the beginning of the steady-state flow - see for example [5,6]. Many authors approach to separate descriptions of different parts of the stress-strain curve by separate equations - see for example [7,8]. Activation energy is an important material constant for hot forming, which depends on the chemical composition and material microstructure. It is used, for example for prediction of the stress peak point, i.e. of the maximum flow stress and the beginning of the dynamic recrystallization of material formed under the given thermo-mechanical conditions. These tests will then provide the appropriate data for calculating the activation energy, which is calculated from the relationship (1) derived from the Garofalo's equation [9].

$$\dot{e} = C \cdot \exp\left(\frac{-Q}{R \cdot T}\right) \cdot [\sinh(\alpha \cdot \sigma_{max})]^n \qquad (1)$$

where $\dot{e}$ - strain rate (s^{-1}), Q- activation energy ($J \cdot mol^{-1}$), R - specific gas constant 8.314 ($J \cdot mol^{-1} \cdot K^{-1}$), T- temperature (K), σ_{max} - natural flow stress in the peak (MPa), C - material constant (s^{-1}), α - material constant (MPa^{-1}), n - material constant (-)

The coordinates of the characteristic points of the flow curves (peak point, steady-state origin, etc.) are determined by subtracting from the experimental flow curves compiled for specific combinations of temperatures and strain rates. C. Zener and J. H. Hollomon have proposed a parameter that allows combining the effect of temperature and strain rate on the flow stress level. This parameter thus represents the so-called temperature-compensated strain rate. The Zener-Hollomon parameter Z (s^{-1}) is then expressed by the following relationship [10]:

$$Z = \dot{e} \cdot \exp\left(\frac{Q}{R \cdot T}\right) \tag{2}$$

where $\dot{e}$ (s^{-1}) is the strain rate and T (K) is the thermodynamic temperature of the deformation. R (8.314 $J \cdot K^{-1} \cdot mol^{-1}$) represents the universal gas constant and Q ($J \cdot mol^{-1}$) represents the so-called activation energy at hot forming. Thanks to the knowledge of Zener-Hollomon parameter it is possible to determine the coordinates of the peak point of flow curves (e_p a σ_{max}) and thus the beginning of dynamic recrystallization can be predicted. The maximum flow stress value σ_{max} (MPa) can be calculated according to the following relation (3) and the peak strain e_p according to (4):

$$\sigma_{max} = \frac{1}{\alpha} \cdot \operatorname{arc\,sinh} \sqrt[n]{\frac{Z}{C}} \tag{3}$$

$$e_p = U \cdot Z^W \tag{4}$$

where U (s) and W (-) are material constants.

The main objective was to determine the value of the hot activation energy of AISI 4140 steel and to compare it to AISI 4130 steel. Simple equations were derived allowing rapid prediction of both peak point coordinates in dependence on temperature-compensated strain rate, i.e. the maximum natural flow stress and strain corresponding to the onset of dynamic recrystallization. The next goal was to describe the stress-strain curves of AISI 4140 by two uniform models - with a complex phenomenological and a simpler one with a physical basis. Both equations reflect the effect of dynamic recrystallization and allow prediction of the natural flow stress up to strain 1, in the temperature range of 850 °C to 1250 °C and the strain rate range of 0.1 s^{-1} to min. 50 s^{-1}.

2. DESCRIPTION OF EXPERIMENT

The experiment was performed on samples from AISI 4140 steel obtained from Třinecké železárny a.s. in a post-hot-rolling state. The chemical composition can be seen in **Table 1**. Samples of ø10 x 15 mm were resistively heated and deformed by uniaxial compression to the strain of 1 on the Hydrawedge II simulator module of the Gleeble 3800 plastometer. Heating at the rate of 5 °C/s was applied directly at the deformation temperature (850 - 960 - 1090 - 1250 °C), with the dwell-time of 300 s, followed by forming at nominal strain rates (0.1 - 0.8 - 6 - 50 s^{-1}). The recorded stress-strain curves in a raw state, that is, without preliminary smoothing - were used for the subsequent mathematical processing. Both coordinates of the peak point were localized for each curve. The σ_{max} values were used to determine the constants in the relationship (1) through the proven interactive ENERGY 4.0 software. The curve courses for selected temperatures are shown in **Figures 1 - 2.**

Table 1 Chemical composition of AISI 4140 steel and comparison with AISI 4130 in mass %.

	C	Si	Mn	Cr	Mo	Ni	P	S
AISI 4140	0.36 - 0.44	0.1 - 0.4	0.65 - 1.1	0.9 - 1.2	0.15 - 0.35	0 - 0.3	0 - 0.04	0 - 0.04
AISI 4130	0.28 - 0.33	0.1 - 0.35	0.4 - 0.6	0.7 - 1.1	0.15 - 0.35	0 - 0.25	0 - 0.035	0 - 0.04

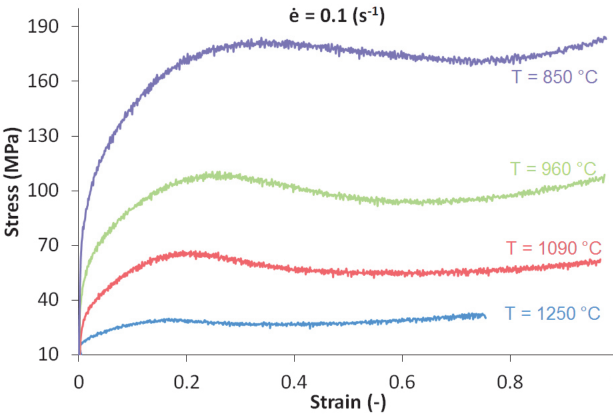

Figure 1 Stress-strain curves at selected deformation temperatures

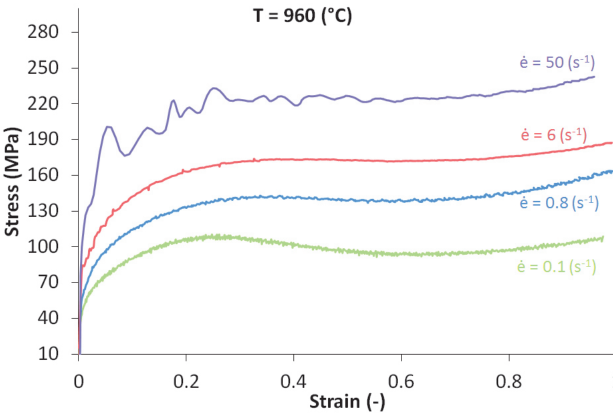

Figure 2 Stress-strain curves at selected strain rate

3. CALCULATION OF THE ACTIVATION ENERGY

A special software "ENERGY" was developed for calculation of activation energy at hot forming and for description of kinetics of dynamic recrystallization. This software ENERGY in the version of 4.0 works in two modes (manual and automatic). The manual mode evaluates the data on the basis of linear regressions. The automatic mode refines more precisely the results obtained in the manual mode using the method of least squares on the basis of non-linear regressions. The values of the maximum flow stress σ_{max} and the strain rate values at a given temperature serve as input data for calculating the activation energy.

The results of activation energy calculation and the corresponding constants can be seen in **Table 2**. The activation energy of AISI 4140 is slightly higher than that of AISI 4130 [11]. The higher activation energy is due to a greater proportion of carbon and manganese. We must, however, take into account, that the AISI 4130 steel has not been tested under the same temperature conditions.

Table 2 *Q*-value comparison between the selected steels

	AISI 4130	AISI 4140
Q (J·mol^{-1})	383	392
n (-)	4.7	5.62
α (MPa^{-1})	0.012	0.0087
C (s^{-1})	2.2E+14	2.05E+15
U (s)	0.018	0.189
W (-)	0.08	0.016

In **Figure 3**, the experimental values of σ_{max} and e_p of the AISI 4140 steel are compared with the values which were calculated using the equations (2), (3) and (4) and the obtained coefficients. The accuracy of peak stress localization on the specific experimental stress-strain curve is always higher than the determination of e_p strain, and therefore the better match of predicted and experimental data in the case of σ_{max} is not surprising. The correlation coefficient for σ_{max} is $R = 0.997$ and $e_p = 0.669$.

Using the results of regression analysis in the automatic mode of the ENERGY 4.0 program, 3D graphs were created, which are shown in **Figures 4** and **5. Figure 4** confirms that with increasing temperature and decreasing strain rate, the stress decreases.

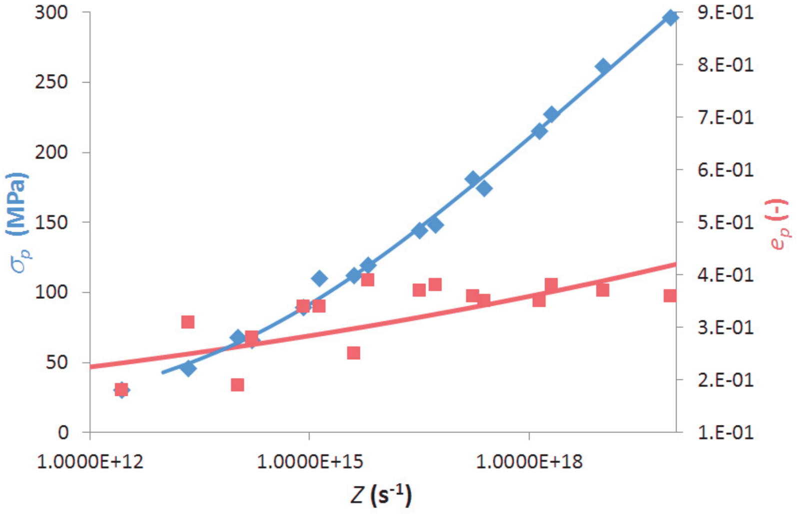

Figure 3 Dependence of peak point coordinates on the Zener-Hollomon parameter (points - experiment; lines -calculations)

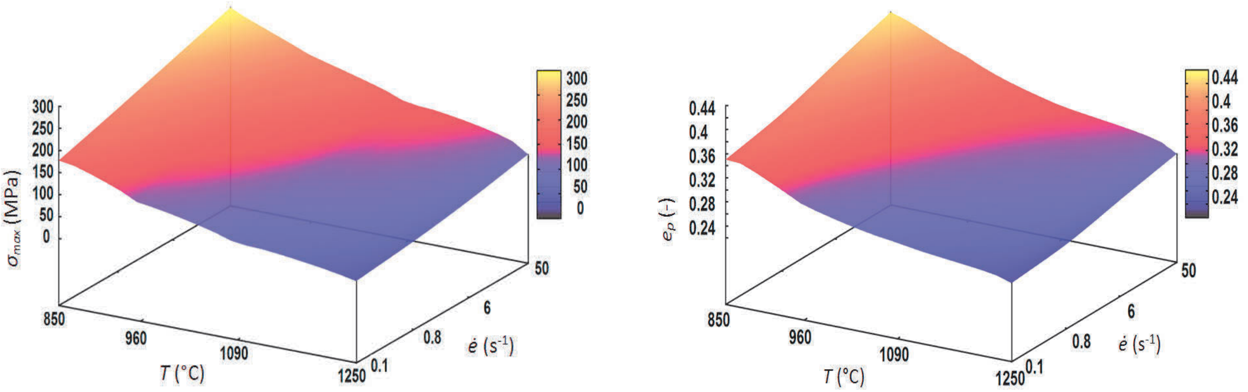

Figure 4 Spatial dependence of the calculated maximum stress on the temperature and nominal strain rate

Figure 5 Spatial dependence of the calculated peak strain on the temperature and nominal strain rate

4. MATHEMATICAL DESCRIPTION OF THE NATURAL FLOW STRESS

To describe the flow curves, two models were selected with the ability to describe flow curves over the entire range of strains. The first model to predict flow stress is the model of A. Hensel and T. Spittel (H-S), which is implemented in FEM simulation software FORGE®. Its form for the prediction of hot flow stress is as follows [4]:

$$\sigma = K_1 \cdot e^n \cdot \exp\left(\frac{K_2}{e}\right) \cdot (1+e)^{K_3 \cdot t} \cdot \exp(K_4 \cdot e) \cdot \exp\,(P \cdot t)\ \cdot t^p \cdot \dot{e}^{M_1} \cdot \dot{e}^{M_2 \cdot t} \tag{5}$$

Obviously, the model (5) is quite complicated. It includes a total of four strain components (two power and two exponential), ensuring the desired shape change of the flow curve with the strain e (-). In addition, it includes two terms (power and exponential), reflecting the influence of the deformation temperature t (°C) on the flow stress σ (MPa) and also two power terms reflecting the influence of the strain rate $\dot{e}$ (s^{-1}). The main advantage of the model (5) is its ability to describe a set of flow curves uniformly over almost the entire range of strains through a single functional prescription and one set of material constants. The prediction option is limited only in the region of very low strains (for *e* <0.04). Its main drawback is that it does not include any of the characteristic points of flow curves.

The I. Schindler, J. Kliber and J. Bořuta (S-K-B) model was chosen as the second model. The model reliably describes the flow curves in the area of strains up to the peak e_p and partly also in the area of predominant softening up to the value of the so-called inflection point e_i (-) (which is located between the peak strain e_p and the beginning of the steady-state flow e_{ss} (-)) and has the following form [12]:

$$\sigma = K \cdot e^n \cdot \exp\left(-n \cdot \frac{e}{e_p}\right) \cdot \dot{e}^{\left(M_1 - \frac{M_2}{T}\right)} \cdot \exp(-P \cdot T) \qquad (6)$$

The model (6) has two strain components. The first one, e^n, provides an increase of flow stress up to the peak e_p (-) and the second one, $\exp(-\,n \cdot (e\,/\,e_p))$, mediating the exponential decrease of the flow stress beyond the peak-point value, thus reflecting the consequences of the dynamic recrystallization process.

Using of demanding nonlinear regression analysis in UNISTAT 6.5 statistical software, material constants of the above-mentioned models were been obtained for the examined AISI 4140 steel in order to calculate flow stress in dependence on strain, strain rate and temperature. The calculated constants for both equations are shown in **Table 3.**

Table 3 Calculation of constant for equations (5) and (6)

H-S (5)	K_1 (MPa·s^2·°C^{-1})	K_2 (-)	K_3 (°C^{-1})	K_4 (-)	M_1 (-)	M_2 (°C^{-1})	n (-)	P (°C^{-1})	p (-)
	1722.84	-0.0125	-0.0002	-0.1456	-0.2163	0.0003	0.1069	-0.0041	0.2484
S-K-B (6)	K (MPa·s)	M_1 (-)	M_2 (K)	n (-)	P (K^{-1})				
	16,996.99	0.5328	520.3416	0.2031	0.0035				

As shown in the graphs in **Figures 6-7**, the real accuracy of the derived equations (5) and (6) is more or less the same. The simpler physically-based S-K-B model responds better to changes in e_p size with varying *Z*-value and is applicable even for very small deformations. From the values of the determination coefficients (0.989 and 0.994 for the model S-K-B and H-S, respectively), somewhat higher accuracy of the H-S model could be derived.

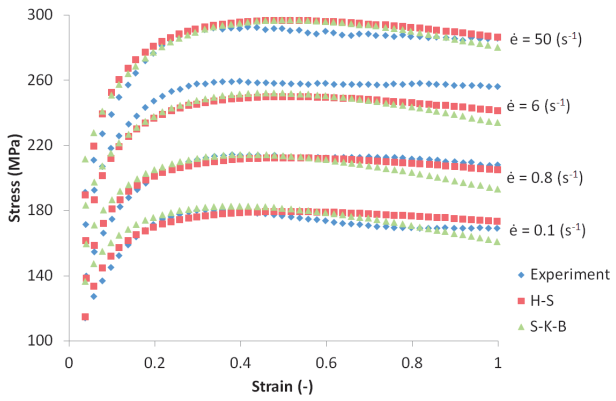

Figure 6 Comparison of accuracy of the H-S (5) and S-K-B (6) model with experimental data (T=850 °C)

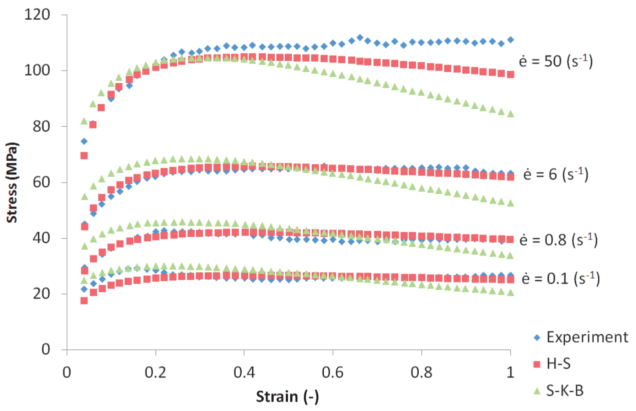

Figure 7 Comparison of accuracy of the H-S (5) and S-K-B (6) model with experimental data (T=1250 °C)

5. CONCLUSION

Based on the analysis of experimental data, the value of the activation energy for hot forming 392 kJ·mol^{-1} was determined for AISI 4140 steel, which is a higher value than the comparative activation energy of 383 kJ·mol^{-1} for AISI 4130 steel with a lower carbon and manganese content.

Simple equations were derived, enabling fast prediction of both peak point coordinates in the case of AISI 4140 steel, depending on the temperature-compensated strain rate, i.e. the maximum natural flow stress and strain corresponding to the onset of dynamic recrystallization.

The stress-strain curves of AISI 4140 steel have been described with good accuracy by two uniform models - a complex phenomenological and a simpler one with a physical basis. Both equations reflect the influence of dynamic recrystallization and allow prediction of natural flow stress in the temperature range of 850 to 1250 °C and strain rates of 0.1 to 50 s^{-1}, respectively.

ACKNOWLEDGEMENTS

The paper was created thanks to the project No. CZ.02.1.01/0.0/0.0/17_049/0008399 from the EU and CR financial funds provided by the Operational Programme Research, Development and Education, Call 02_17_049 Long-Term Intersectoral Cooperation for ITI (Managing Authority: Czech Republic - Ministry of Education, Youth and Sports), as well as the student grant projects SP2019/86 and SP2019/43 (VŠB-TU Ostrava).

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