INFLUENCE OF INITIAL STRUCTURE ON STRESS-STRAIN CURVES OF MEDIUM-CARBON STEEL

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Abstract

In this paper, influence of initial structure of C45 medium-carbon steel on the value of its flow stress was examined. The research was based on comparison of experimental stress-strain curves acquired using uniaxial compression tests of two initial structural states. Experimental labors were performed in the range of deformation temperatures of 900 °C - 1250 °C and strain rate range of 0.05 s^{-1} - 20 s^{-1}. The values of the true (logarithmic) strain reached up to 1.0. The values of the hot deformation activation energy of both initial structure states were calculated and compared. The impact of the initial structure on the flow stresses of the surveyed carbon steel was confirmed.

Keywords: Uniaxial compression test, flow stress, activation energy

1. INTRODUCTION

The stress-strain curves serve for description of evolution of the flow stress in dependence on the deformation, 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 deformations where it is complicated by dynamic healing processes. A whole range of equations exists dealing with the mathematical description of stress curves [1-3].

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. Plastometric tests (torsion test and compression test) are used in particular its the determination of [4, 5]. These tests will then provide the appropriate data for calculating the activation energy, which is calculated from the relationship (1) derived from the Sellars and Tegart equation [6].

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

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 relation (1) was originally developed for a mathematical description of the strain rate corresponding to the stress in the steady state area σ_{ss}. In principle, it is possible to use for calculation of activation energy both σ_{max} and σ_{ss}. However, the maximum stress σ_{max} is used more often since the σ_{ss} values are available only with difficulties for wide ranges of strain rates and temperatures.

2. DESCRIPTION OF EXPERIMENT

The main objective of the experiment was to determine the effect of the initial structure on the stress-strain curves on C45 medium-carbon steel. Two types of initial structures, namely cast structure (CS) and deformed structure (DS), were examined. Another objective of the work consisted in determination of the activation energy of both structures.

Steel C45, which is according to ČSN standard, referred to as steel grade 12 050, is the most used high-grade carbon steel. Its carbon content of 0.42-0.50 % classifies this steel as a sub-eutectoid steel. Other chemical elements include silicon, chromium and nickel, all three of which have an identical weight content of max. 0.4 %. Another element is manganese, the content of varies within the range from 0.50 to 0.80 %. The maximum content of noxious elements, such as phosphorus and sulphur, is max. 0.035 %. The molybdenum content is max. 0.1 %. It is appropriate to apply moreover heat treatment to this steel, such as refining or surface hardening.

3. METALLOGRAPHIC ANALYSES

In the first part of the experiment, the samples were subjected to metallographic analysis, where they were etched to the original austenitic grain. The results of the microstructures are presented in **Figures 1 - 5**. All the samples were heated to the respective quenching temperature, with a dwell of 7 minutes at this temperature, and then quenched in water. They were then tempered at 350 °C for 30 minutes.

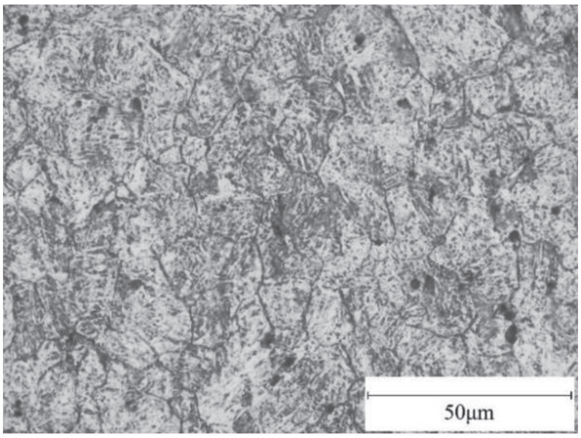

Figure 1 Deformed state - quenching temperature 900 °C

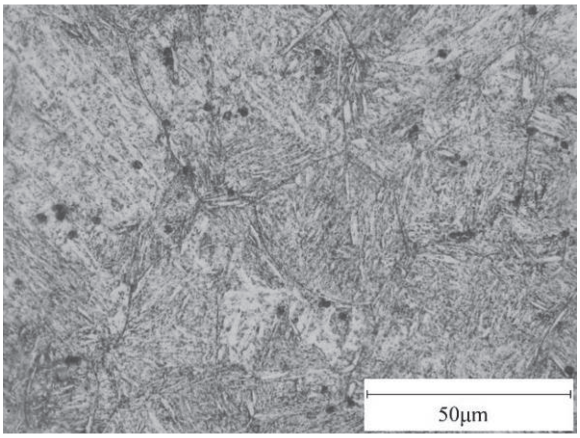

Figure 2 Deformed state - quenching temperature 1000 °C

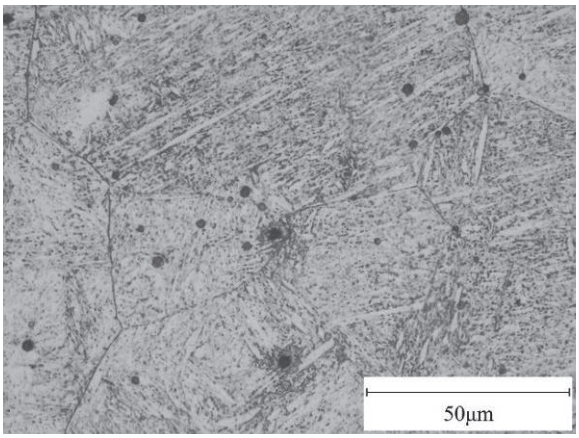

Figure 3 Deformed state - quenching temperature 1120 °C

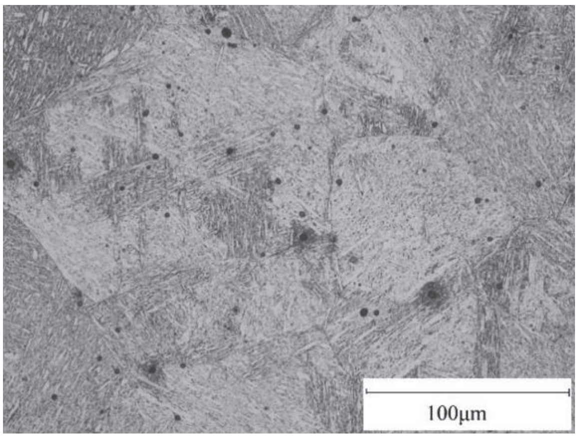

Figure 4 Deformed state - quenching temperature 1250 °C

Figures 1 - 4 represent an initial deformed structure (DS) heated to the appropriate investigated temperature; **Figure 5** shows the initial casting structure (CS) heated to 1250 °C. The size of the original austenitic grain was determined from the selected structures by the straight line method [7]. The results of grain size determination are shown in **Table 1**. Metallographic analysis proved that the size of the original austenitic grain increased with the increasing temperature. At high temperature, the size of the original austenitic grain in the cast and deformed structure was almost identical.

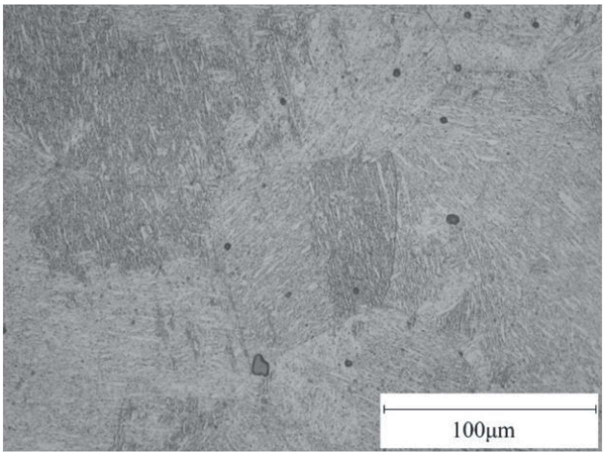

Figure 5 Cast state - quenching temperature 1200 °C

Table 1 Determination of the size of austenitic grain

Sample	Average grain size [µm]
DS- 900 °C	8.15
DS-1000 °C	17.04
DS-1120 °C	38.85
DS-1250 °C	95.25
CS-1250 °C	98.06

4. STRESS-STRAIN CURVES

Compression tests were performed to determine the stress curves. The tests were run on the Gleeble 3800 plastometer using the Hydrawedge II module. The test specimens was a cylinder with a height of 15 mm and a diameter of 10 mm. Samples of the C45 steel were taken from two types of initial structure, cast and deformed one. Test specimens of cast steel were prepared from continuously cast blanks (CCB), while test specimens of steel with deformed structure were made from rolled bars. Thermocouples were welded onto the test samples, which measured temperature during the test. We used strain rates of 0.05 s^{-1}, 1 s^{-1}, and 20 s^{-1} and a deformation temperatures of 900, 1000, 1120 and 1250 °C. The test specimens taken from the cast structure were preheated to 1250 °C with a dwell of 60 seconds before the deformation itself. The specimens were then cooled down to the appropriate deformation temperature or they were even immediately deformed. The specimens taken form the deformed structure were heated to the appropriate deformation temperature with a dwell of 60 seconds. After completion of the individual tests, the measured data necessary for evaluation of the plastometric tests were recorded and automatically stored. The curve evolutions for all the investigated temperatures are shown in **Figures 6 - 9**.

Evolutions of the both initial structures at 900 °C can be seen in **Figure 6**. The cast state is represented by a solid line, the deformed state is represented by a dashed line. At the strain rate é = 0.05 s^{-1}, the peak of the curve for the sample with the deformed structure is shifted to a lower value of deformation as compared to the peak for sample with the cast structure. At the strain rate é = 1 s^{-1}, the peak of the curve for the sample with the deformed structure is also shifted to a lower value of deformation. At the highest investigated strain rate é = 20 s^{-1}, the peak of the sample with deformed structure reached higher values of stress. In all the curves related to the initial deformed structure, a drop in the stress curve after the peak is evident till the value of the stabilised state of plastic flow rate. The drop of stress for samples with the initial cast structure is not to noticeable.

The stress curves for both structures at a temperature of 1000 °C can be seen in **Figure 7**. At the strain rate of 0.05 s^{-1} no such significant shift of the stress peak to greater deformations can be observed, as it was observed at 900 °C. In the case of strain rate of 1 s^{-1} it is possible to observe for the initial cast structure a significant shift of the stress peak to greater deformations, as well as less significant drop of stress.

When comparing the diagrams for temperatures of 1120 °C and 1250 °C (**Figures 8 and 9**) no more significant shift of the curve can be observed anymore. Only the curve for the initial deformed structure that was deformed at the strain rate of 1 s^{-1} and at a temperature of 1120 °C, shows higher values of stress in the steady state area.

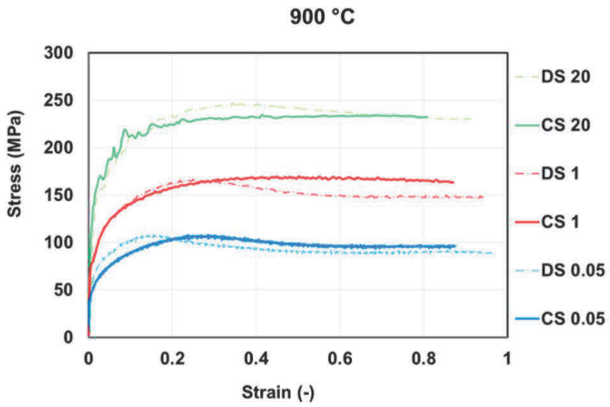

Figure 6 Influence of strain rate on the stress curves of both structures at a temperature of 900 °C

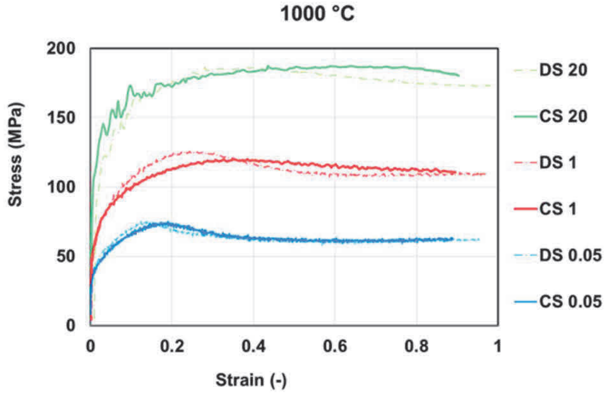

Figure 7 Influence of strain rate on the stress curves of both structures at a temperature of 1000 °C

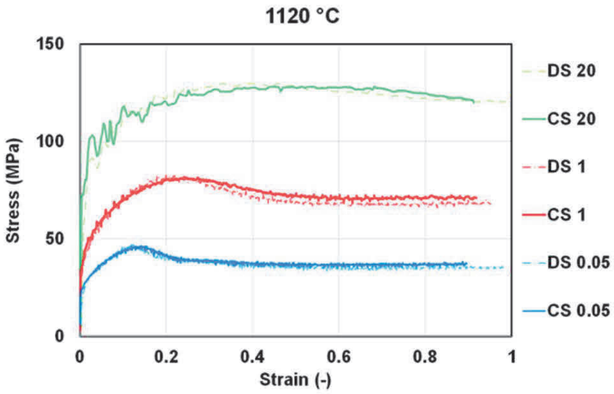

Figure 8 Influence of strain rate on the stress curves of both structures at a temperature of 1120 °C

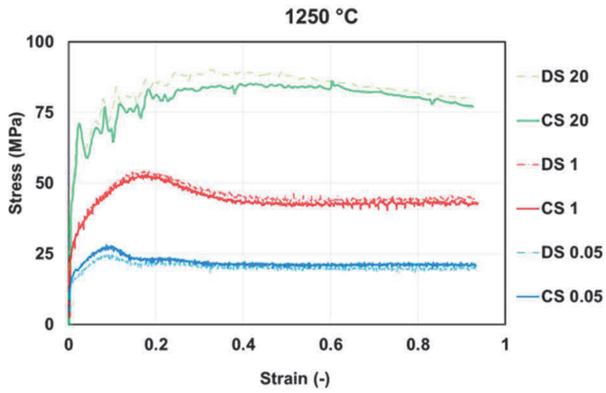

Figure 9 Influence of strain rate on the stress curves of both structures at a temperature of 1250 °C

5. 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 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 [8].

The program ENERGY 4.0 makes it possible during manual calculation to remove at any step of calculation the points that are rather remote and might negatively affect the calculation. In this case, this feature was not used and all the points were used for the calculation, since no point was found to be too remote. The final step consists in automatic calculation of the activation energy and of all other constants, using the method of least squares, for more precise determination of the values that were calculated in the manual mode. In this step a graphical comparison of the measured and calculated values of stress is also created. It is generally assumed that the values obtained by the automatic mode are more accurate than those determined in the manual mode. Therefore, we can say that the activation energy of the investigated steel for the cast state is 312 kJ/mol and for the deformed state it is 300 kJ/mol. The results of the activation energy and of the individual constants for the initial cast and deformed structures are given in **Table 2** and **Table 3**.

On the basis of the calculated values of the activation energy and of other material constants of the investigated steel, it is possible to predict with good accuracy its maximum natural flow stress and the deformation necessary for the initiation of dynamic recrystallization (approximately e_p (2)) in dependence on the strain rate compensated by temperature, i.e. on the Zener-Hollomon parameter Z (3) involving the material factor exactly by specific value of the activation energy.

$$e_p = U \cdot Z^W \tag{2}$$

$$Z = \dot{e} \cdot exp\left(\frac{Q}{R \cdot T}\right) \tag{3}$$

Table 2 Values of activation energy and of individual constants for the initial cast structure

	Q [kJ/mol]	n (1250 °C)	α (900 °C) [MPa^{-1}]	C [s^{-1}]	U	W
Manual calculation	345.92	5.4100	0.00868	$5.03 \cdot 10^{13}$	0.01063	0.100
Automatic calculation	312.01	5.1039	0.00790	$4.19 \cdot 10^{12}$	0.01157	0.108

Table 3 Values of activation energy and of individual constants for the initial deformed structure

	Q [kJ/mol]	n (1250 °C)	α (900 °C) [MPa^{-1}]	C [s^{-1}]	U	W
Manual calculation	308.13	4.5400	0.00948	$8.45 \cdot 10^{11}$	0.01081	0.106
Automatic calculation	299.42	5.0654	0.00720	$2.12 \cdot 10^{12}$	0.01100	0.109

6. CONCLUSIONS

The paper presents the results of uniaxial compression tests carried out on the plastometer Gleeble 3800 using a Hydrawedge module and metallographic analyses. The tests were performed on the cast and deformed structure of medium carbon steel grade C45. Compression tests were conducted over a wide range of temperatures, i.e. 900 - 1250 °C, as well as that of deformation rates of 0.05-20 s $^{-1}$.

It is evident from comparison of the deformation curves that the curves of both structures differ. The difference in curves is most noticeable at lower temperatures. The curves of the deformed structure achieve the maximum values of stress at lower values of deformation than the curves characterising the cast structure. It can be said, therefore, that the fine-grained structure shifts the beginning of dynamic recrystallization to lower values of deformation. At high temperatures, the stress curves of both structures are almost identical.

Using the program “Origin”, the peak values of the individual curves necessary for calculation of the activation energy were read. After that the values of the activation energy values of cast and deformed structures were calculated with the use of program “Energy 4.0”. The value of the automatically calculated activation energy of the cast structure was 312.01 kJ/mol, while for the deformed structures it was 299.42 kJ/ mol. Metallographic analysis showed that the size of the original austenitic grain increased with the increasing temperature. At high temperature, the size of the original austenitic grain in the cast and deformed structures was almost identical. This fact explained the similarity of the deformation curves - stress at high temperatures.

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