HOT PLASTIC DEFORMATION BEHAVIOR OF NEW-DEVELOPED MULTI-PHASE STEEL

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Abstract

The paper presents the results of the effect of deformation parameters on the hot-deformation behavior of the newly developed multi-phase steel assigned for production of forged machine parts. Continuous and interrupted compression tests of the samples after the given deformation were carried out with the use of the Gleeble 3800 thermomechanical simulator. The samples were tested in the temperature range from 900°C to 1100°C at the rate of $0.1s^{-1}$ and $1s^{-1}$. Basing on the analysis of the form and the course of curves obtained in the compression test, it was found that in the studied range of parameters of hot plastic deformation, the decrease of strain hardening of studied steel is caused by the process of dynamic recrystallization. This is also confirmed by calculation results of activation energy of plastic deformation process. Executed hot compression tests will contribute to establishing conditions of forging of newly developed multi-phase steel with the method of thermo-mechanical treatment.

Keywords: Multi-phase steel, hot plastic deformation, dynamic recrystallization, thermo-mechanical treatment

1. INTRODUCTION

Modern construction materials should combine high strength, ductility, resistance to cracking and often show high fatigue strength. In the case of steels intended for forgings, it is also very important to ensure adequate hardenability and machinability by machining, with at the same time reduced production costs, significantly dependent on the concentration of alloy additions introduced into the steel [1-4].

In recent years, there has been a continuous increase in interest in multiphase steels with potential application for die forgings for the automotive industry [5-8]. The forgings made of multiphase steels, in addition to high strength, should be resistant to cracking, also under impact loads, high fatigue strength and reduced weight with minimal technological allowances [9,10]. A special feature of these steels is the presence of plastic retained austenite, which enables the simultaneous increase in strength and ductility of multiphase steels.

Despite the research conducted, mainly by Japanese and German units [11-13], the optimal conditions for hot deformation and cooling profiles enabling the combination of all the aforementioned mechanical, technological and operational properties have not been developed so far. One of the main problems is the lack of homogeneity of the austenitic phase, in particular the uncontrolled martensitic transformation of block grains of this phase into martensite under mechanical load conditions, which may be the cause of crack initiation and propagation during the next load cycle [14].

Obtaining the desired multi-phase structure with the correct proportions of individual components requires the knowledge of the diagrams of austenite phase transformations. The authors published the results of these studies in earlier works [15,16]. The aim of this work is to investigate the influence of temperature and deformation rate on hot-deformation behavior of the newly developed multi-phase steel.

2. EXPERIMENTAL PROCEDURE

The chemical composition of the analyzed steel is summarized in **Table 1**. The metallic charge in the form of Armco iron sheets, carburizer in the form of synthetic graphite, FeSi75A ferroalloy and pure Mn was melted in the VEM I20 electric induction furnace. The pouring temperature of the molten steel was measured using a Pt-PtRh10 thermocouple. The pouring temperature was 1672°C. The chemical composition of ingots with a diameter of 30 mm and a length of 400 mm was determined using the LECO GDS500A Glow Discharge Emission Spectrometer.

Table 1 Chemical composition of the tested steel [wt%]

C	Mn	Si	P	S	Cr
0.165	2.03	1.11	0.014	0.02	0.028

In order to determine the influence of temperature and deformation rate on changes in yield stress and steel structure, plastometric tests were carried out with the use of the Gleeble 3800 simulator. Axial symmetric samples with a diameter of 10 mm and a length of 15 mm were used for the tests. In order to determine the σ-ε curves and the activation energy of the plastic deformation process, continuous compression tests of the samples to a deformation of 0.69 were carried out, with using graphite-tantalum foils reducing the friction between the faces of the samples and the anvil surface. The samples were resistance heated in a vacuum at the rate of 3°C/s to the austenitizing temperature of 1150°C, annealed in it for 30 s and then cooled to the programmed plastic deformation temperature, which was 1100°C, 1050°C, 1000°C, 950°C and 900°C. Compression of the samples was performed with the deformation rates of $0.1s^{-1}$ and $1s^{-1}$. Additionally, the samples after the given deformation of 0.2 and 0.69 were quenched in water. The activation energy of the plastic deformation process Q was calculated on the basis of the obtained results, using the ENERGY 4.0 software based on the dependence [17]:

$$\dot{\varepsilon} = A[\sinh(\alpha\sigma)]^n \exp\left(-\frac{Q}{RT}\right) \quad (1)$$

where:

A, α, n – constants,

$\dot{\varepsilon}$ – deformation rate,

σ – stress value corresponding to the maximum yield stress,

T – deformation temperature,

R = 8.314 $J \cdot mol^{-1} \cdot K^{-1}$ – gas constant.

Next, performed the metallographic tests of samples that were immediately cooled water after plastic deformation. The specimens were made in the plane consistent with the sample axis, at a distance of 1/3 from the center of the sample. The metallographic specimens were etched in 5% nitrile and then examined using the Zeiss Observer.Z1m light microscope.

3. RESULTS AND DISCUSSION

The conducted tests of continuous compression of samples in the temperature range from 900°C to 1100°C allowed to determine the influence of deformation parameters on the course of the strengthening curves σ–ε (**Figure 1**). In the initial phase of compression, in the strain hardening range ε<0.025 (**Figure 1a**), the σ–ε curves showed an increase in yield stresses due to the increasing density of dislocations generated in this process. In the next phase of compression, with an increase in the strain from approx. 0.025 to ε_m, which corresponds to the maximum stress value, a milder increase in stress occured. This indicates that simultaneously with the generation of new dislocations by the sources during plastic deformation, thermally activated processes take place, causing a partial disappearance of the emitted dislocations. For the

deformation $\varepsilon_m<\varepsilon<\varepsilon=0.69$, the strengthening curves are characterized by a mild decrease of yield stresses to the value of the equilibrium state between the strengthening processes and its decrease due to the course of thermally activated processes. The shape and course of the curves obtained in the compression test with a rate of $0.1s^{-1}$ (**Figure 1a**) indicate that the decrease in strain hardening in the temperature range used is the result of a continuous dynamic recrystallization process. The hardening curves of the tested steel obtained after compression with the rate of $1s^{-1}$ are shown in **Figure 1b**. In this case, dynamic recrystallization is a process that controls the course of plastic deformation in the temperature range from 1000°C to 1100°C. However, at the temperature of 900°C and 950°C, this process is dynamic recovery.

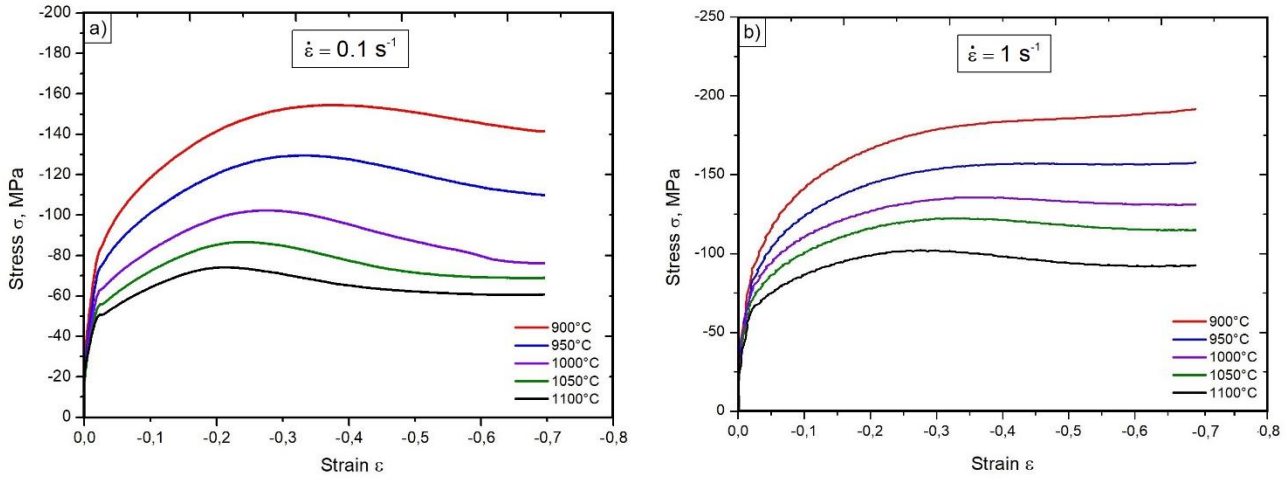

Figure 1 Influence of temperature and deformation rate on the course of σ-ε curves

Detailed results of plastometric tests are presented in **Table 2**. The data presented in this table and in **Figure 2** show that the value of deformation ε_m decreases with increasing test temperature and decreasing the rate of deformation.

Table 2 Parameters of continuous compression of samples

L.p.	Temperature of deformation [°C]	Rate of deformation $\dot{\varepsilon}$ $[s^{-1}]$	Maximum deformation ε_m	Maximum yield stress σ_m [MPa]
1.	900	0.1	0.433	154.4
2.	950	0.1	0.312	130.7
3.	1000	0.1	0.299	102.1
4.	1050	0.1	0.256	87.1
5.	1100	0.1	0.186	74.3
6.	900	1	0.568	188.3
7.	950	1	0.454	159.5
8.	1000	1	0.389	138.1
9.	1050	1	0.331	124.9
10.	1100	1	0.251	107.4

For a deformation rate of $0.1s^{-1}$, the reduction of the plastic deformation temperature from 1100°C to 900°C causes an increase in the maximum yield stress σ_m from approx. 74 MPa to approx. 154 MPa and the strain ε_m from approx. 0.19 to approx. 0.43. Lowering the deformation temperature in the same range of compression

temperature at the rate of $1s^{-1}$ influences the increase of σ_m from approx. 107 MPa to approx. 188 MPa, with a simultaneous increase of ε_m from approx. 0.25 to approx. 0.57.

The performed calculations of the plastic deformation activation energy confirm that for the applied conditions, the dominant mechanism controlling the course of deformation is dynamic recrystallization. The activation energy of plastic deformation of the tested steel is Q = 375 $kJ \cdot mol^{-1}$, while the constant values in equation (1) for the stresses corresponding to the deformations ε_m are: $A = 3.02 \cdot 10^{12}$, α=0.016, n=3.9. The obtained value of the plastic deformation activation energy is much higher than the self-diffusion activation energy, when the process controlling the course of plastic deformation is dislocation climbing and subgrain formation.

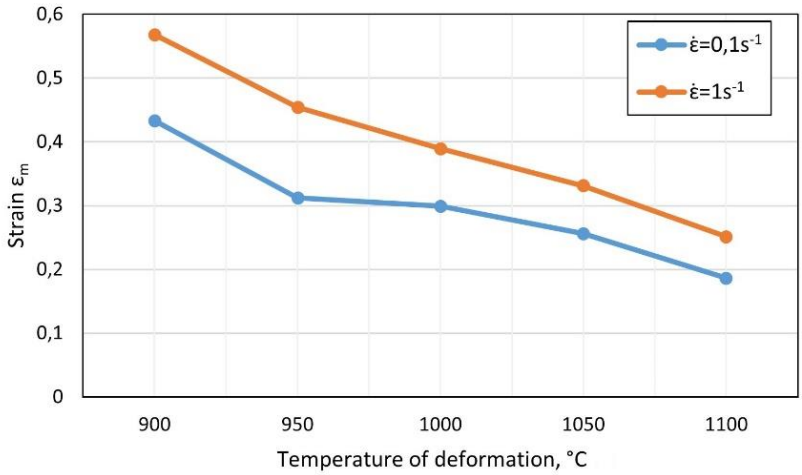

Figure 2 Influence of temperature and rate of deformation on the values of deformation ε_m

The conducted metallographic tests allowed to determine the influence of plastic deformation parameters on the structure of the analyzed steel. For example, **Figure 3** shows the structures of the tested steel revealed after the samples were compressed at the temperature of 1100°C at the rate of $1s^{-1}$. The samples of the tested steel, hardened in water after obtaining the deformation of 0.2 and 0.69, show a martensitic structure with a small share of retained austenite (**Figure 4**).

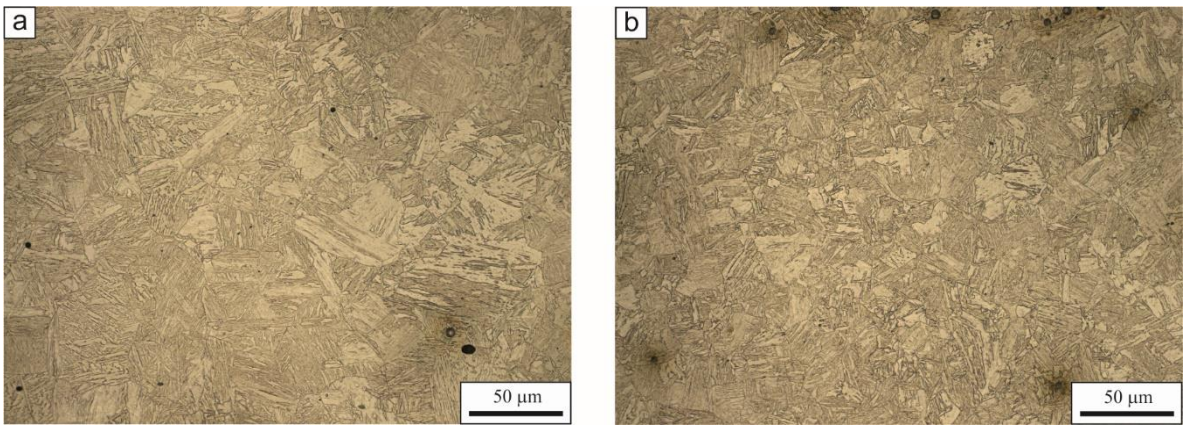

Figure 3 Martensitic structure with a small share of retained austenite of steel hardened in water after a given deformation: a) 0.2, b) 0.69; plastic deformation temperature:1100°C

Retained austenite was revealed by etching the sample with Klemm's reagent staining it white. The presence of this phase was confirmed by the authors in [16,18]. As expected, the deformed samples with a higher degree of deformation show greater fragmentation of the structure.

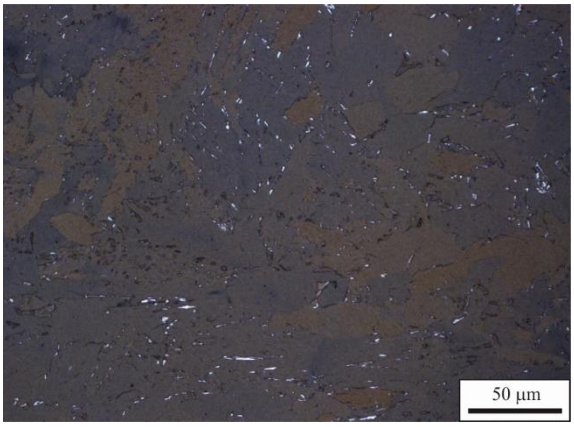

Figure 4 Martensitic structure with a small proportion of retained austenite (white colored) of steel hardened in water after deformation 0.69; plastic deformation temperature:1100°C

4. CONCLUSION

The analysis of the shape and course of the strengthening curves obtained in the compression test shows that in the tested range of deformation parameters, dynamic recrystallization is the main thermally activated mechanism controlling the process of plastic deformation. This is also confirmed by the results of calculating the activation energy of the plastic deformation process. The obtained value ($Q=375$ kJ·mol^{-1}) – clearly higher than the activation energy of self-diffusion - is similar to the Q values obtained in the works [19,20].

Samples cooled in water directly from the plastic deformation temperature - regardless of the deformation rate used, show a martensitic structure with a small share of retained austenite.

The next stage of the research will be interrupted compression tests for a given deformation with isothermal strength of the samples between successive stages of deformation. They will allow to determine the kinetics of plastically deformed austenite recrystallization. Such a comprehensive approach will make it possible to develop a technology for the production of forgings from the tested steel using the thermo-plastic treatment method.

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