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**Experimental and theoretical analysis of stress state of  
plastic medium influence on structural transformations in  
low-alloy steels**

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Abstract

A method for determination of the influence of the stress-strain state of metal on the structural transformations in the low-alloy steel 10HFBTch is provided. The relation between the parameters of the stress state, thermo-mechanical processing and structural changes in the deformation zone is shown based on the solution of spatial problems of the plasticity theory, the experimental research of mechanical characteristics of the low-alloy steel, the structural state of the metal after deformation. Experimental and theoretical method can be used for the development of technological modes of rolling of the new steel grade with specified mechanical properties customized.

Key words: MATHEMATICAL MODEL, PLASTIC MEDIUM, STRESSES, STEEL 10HFBTCH, PLASTOMETER GLEEBLE-3800.

**Introduction**

When developing the technology of controlled rolling or thermo-mechanical treatment of steels and alloys it is necessary to coordinate the plastic medium stress state with the thermo-mechanical process parameters, structural changes in the deformation zone and ultimately with specified characteristics of the material. In the literature an insufficient attention is given to this issue. This is due to the fact that it is not always possible to describe the stress state of the metal for the spatial loading to adequately assess the model of the plastic medium from the thermo-mechanical characteristics of the process. Besides, the mechanism of their calculation depending on the state of stress and its determining factors is not clear.

**Formulation of the problem**

On the basis of theoretical and experimental studies to determine the integral characteristics of the stress state at a point, then considering the Huber-Mises model and to establish the mechanical characteristics of the plastic medium (flow stress), the variants

of the deformation, temperature and speed loading. From the given values of the thermo-mechanical parameters to choose from the recrystallization diagram for this steel grade those that are met the necessary structural condition. It requires not only theoretical studies, but also experimental studies that allow identifying the regularities of changes in the mechanical characteristics and the physical properties from the thermo-mechanical factors of the process and the chemical composition of steel. The effect of the thermo-mechanical parameters on the structural condition of the plastic medium for a particular grade of steel should be known.

**Problem solution**

The new low-alloy high-resistance specific steel grade 10HFBTch for the manufacture of truck wheels is considered. [1]. In [2] ... [4] a solution for the spatial problem of plasticity theory in analytical form using harmonic functions is presented. In accordance with [2] ... [4] we can write

$$\begin{aligned} \sigma_x &= -2 \cdot C_{\sigma_2} \cdot \exp \theta_2' \cdot \text{Cos} A_2 F_2 - C_{\sigma_3} \cdot \exp \theta_3' \cdot \text{Cos} A_3 F_3 + C, \\ \sigma_y &= -C_{\sigma_2} \cdot \exp \theta_2' \cdot \text{Cos} A_2 F_2 - 2 \cdot C_{\sigma_3} \cdot \exp \theta_3' \cdot \text{Cos} A_3 F_3 + C, \\ \sigma_z &= -3 \cdot C_{\sigma_2} \cdot \exp \theta_2' \cdot \text{Cos} A_2 F_2 - 3 \cdot C_{\sigma_3} \cdot \exp \theta_3' \cdot \text{Cos} A_3 F_3 + C, \\ \tau_{yz} &= C_{\sigma_2} \exp \theta_2' \cdot \text{Sin} A_2 F_2, \\ \tau_{zx} &= C_{\sigma_3} \exp \theta_3' \cdot \text{Sin} A_3 F_3. \end{aligned} \tag{1}$$

An integral characteristic of the stress state of the point the intensity of the normal stresses is selected.

$$\sigma_i = \frac{1}{\sqrt{2}} \cdot \sqrt{(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 + 6 \cdot (\tau_{yz}^2 + \tau_{zx}^2)} \tag{2}$$

Substituting (1) into (2) we obtain an expression convenient for the analysis

$$\begin{aligned} \sigma_i &= \sqrt{3} \cdot \sqrt{(C_{\sigma_2} \cdot \exp \theta_2')^2 + (C_{\sigma_3} \cdot \exp \theta_3')^2 +} \\ &+ (C_{\sigma_2} \cdot \exp \theta_2' \text{Cos} A_2 F_2)(C_{\sigma_3} \cdot \exp \theta_3' \text{Cos} A_3 F_3) \end{aligned} \tag{3}$$

The condition of plastic deformation in accordance with the hypothesis of Huber-Mises

$$\sigma_i = \sigma, \quad (4)$$

where  $\sigma$  - flow stress.

The equation (4) can be written in relative values

$$\frac{\sigma_i}{\sigma_T} = \frac{\sigma}{\sigma_T}, \quad (5)$$

where  $\sigma_T$  - flow stress in the mild condition.

On the one hand we have the characteristic of the stress state of the medium, depending on the friction coefficient, form factor and on the other hand the physical magnitude determined by the degree and rate

of deformation, temperature and chemical composition. Thus, the Huber-Mises condition of plasticity is a link that allows to set the connection of the point stress state parameters and the thermo-mechanical characteristics of the process. It is necessary to know the dependence of the thermo-mechanical parameters of this steel grade and the flow stress. For such dependence for the stainless steels 10HFBTch the experimental studies on the plastometer Gleeble-3800 (1) were carried out, manufactured by Dynamic Systems, Inc., United States, [5]. These studies were carried out in Poland in Czestochowa Polytechnic under the leadership of professor G. Dyje and with the participation of professor M. Knapinski.

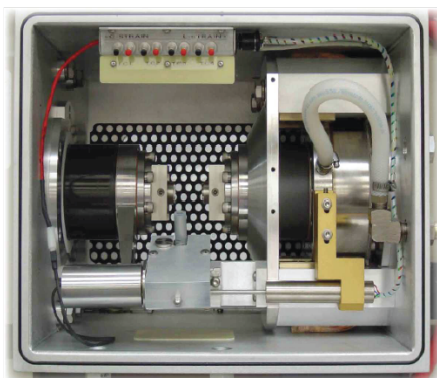


**Figure 1.** The complex Gleeble-3800.

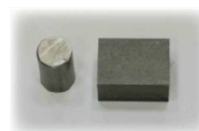
The complex Gleeble System 3800 is designed for the study of the properties of metals and alloys, and allows you to simulate the majority of metallurgical processes, including hot rolling. It should be emphasized that the high-resistance low-alloy steel of 10HFBTch grade is not investigated and its mechanical properties when hot deformation is not known. The proposed research focuses on the study of the

mechanical properties of the low-alloy steel.

Operating unit (Fig. 2) is designed to simulate the shock loading of samples (Fig. 3), with high accuracy by the degree and rate of deformation. The special design of the module allows you to perform multistage sequential loading completely reproducing modes of the deformation on almost any modern mill.

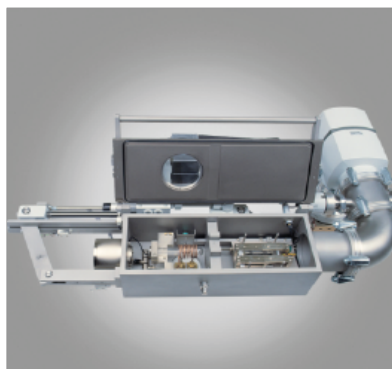


**Figure 2.** Working chamber of the Hydrawedge module.



**Figure 3.** Standard test samples

The record form is in the HDS format. This description format of test program is designed specially for work with the Hydrowedge module. This recording format provides the programming of process parameters in a format that simulates the programming operation of the rolling mill. Processing of the experiments results is carried out on the standard Origin software.



**Figure 4.** Dilatometer DIL 805A/D.

The transition temperature from one phase state to another, for the 10HFBTch grade of steel is presented in Fig. 6. From Fig. 6 it is seen that within the  $\alpha$ -phase and phase of the transition ( $\alpha + \gamma$ ) the temperature range below  $T = 724^\circ\text{C}$  is excluded. In experiment

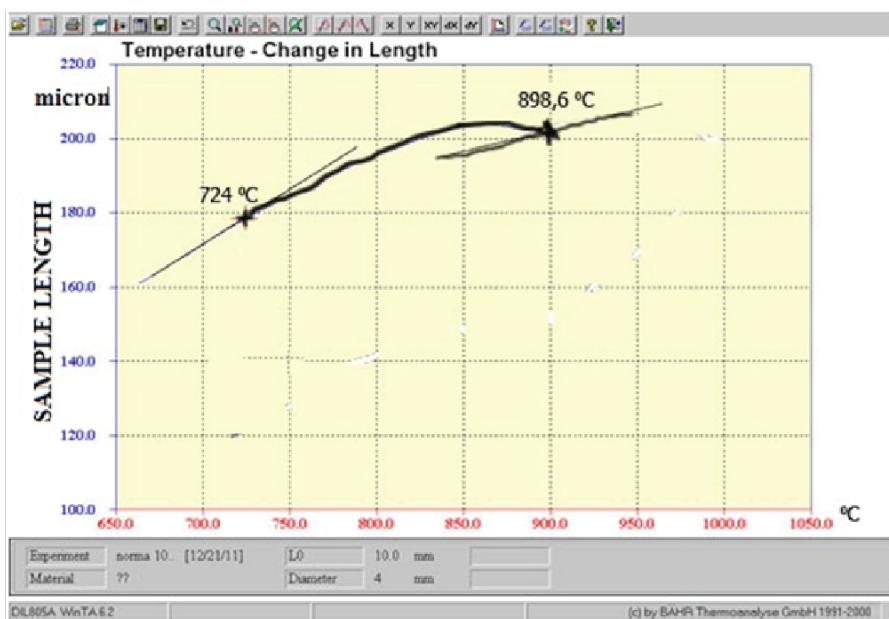
To substantiate the temperature band when studying a new grade of steel - 10HFBTch it is necessary to install the boundaries of phase transformations. For this purpose the dilatometer DIL-805A / D, Fig. 4, the Czestochowa University of Technology (Poland) was used. The test samples for research on dilatometer are shown in Fig. 5.



**Figure 5.** The test samples

21 workpiece dimensions of  $dxh = 10 \times 12$  were used.

Fig. 7...11 show the dependence of the flow stress  $\sigma$  from the deformation  $\varepsilon$  at different strain rates for each test temperature.



**Figure 6.** The boundaries of the phase transition.

The value estimating the degree of the deformation

$$\varepsilon = \ln\left(\frac{h_0}{h_1}\right)$$

Fig. 7-15 show the dependence of the flow stress  $\sigma$  from deformation  $\varepsilon$  at different temperatures for each test strain rate.

Fig. 16, 17 show ordinary dependences of the flow

stress from the percent reduction at different strain rates for  $T=700^\circ\text{C}$  and  $T=770^\circ\text{C}$ .

According to the study for the experiment the following temperatures were chosen:  $T=800^\circ\text{C}$ ,  $T=850^\circ\text{C}$ ,  $T=900^\circ\text{C}$ ,  $T=950^\circ\text{C}$ ,  $T=1200^\circ\text{C}$ , the deformation rate:  $U=1\text{s}^{-1}$ ,  $U=10\text{s}^{-1}$ ,  $U=100\text{s}^{-1}$ ,  $U=300\text{s}^{-1}$ .

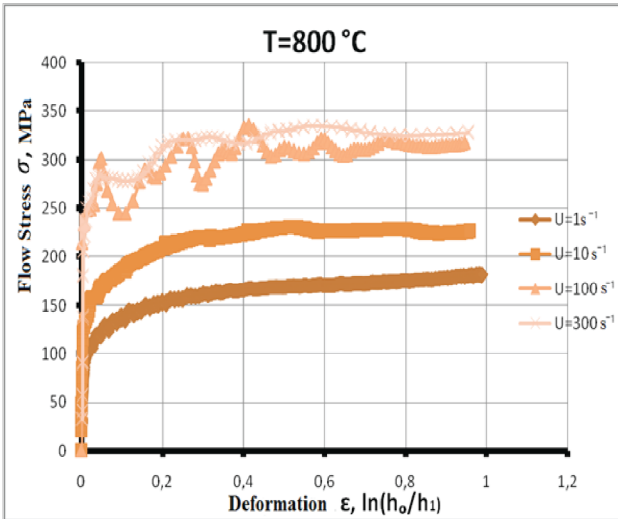


Figure 7. The dependence of the flow stress from the deformation when  $T=800^\circ\text{C}$ ,  $U=1\text{ s}^{-1}$ ,  $U=10\text{ s}^{-1}$ ,  $U=100\text{ s}^{-1}$ ,  $U=300\text{ s}^{-1}$

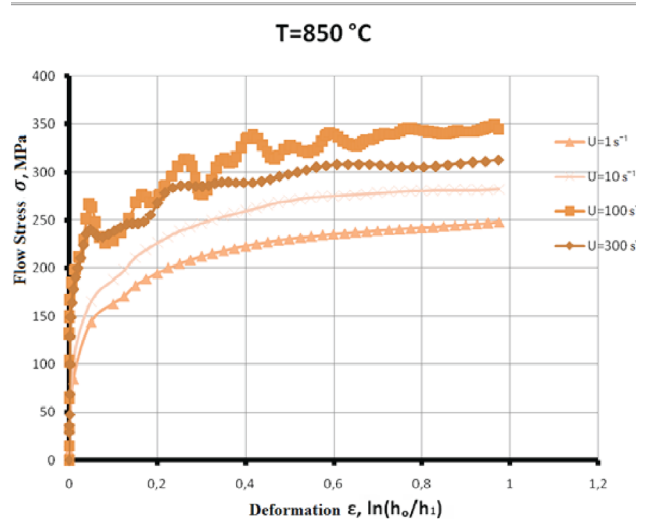


Figure 8. The dependence of the flow stress from the deformation when  $T=850^\circ\text{C}$ ,  $U=1\text{ s}^{-1}$ ,  $U=10\text{ s}^{-1}$ ,  $U=100\text{ s}^{-1}$ ,  $U=300\text{ s}^{-1}$ .

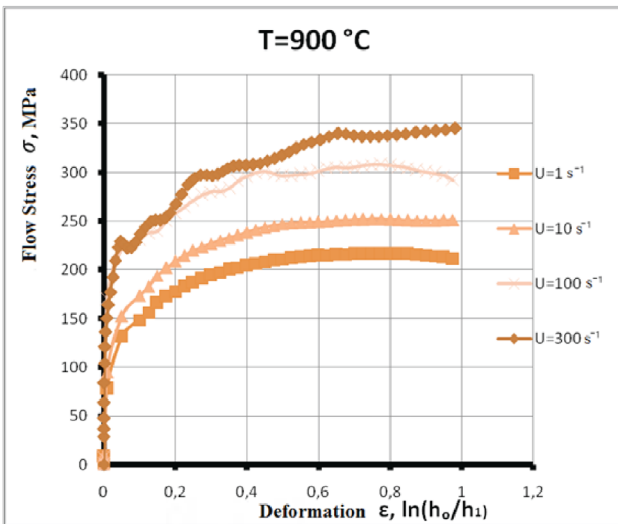


Figure 9. The dependence of the flow stress from the deformation when  $T=900^\circ\text{C}$ ,  $U=1\text{ s}^{-1}$ ,  $U=10\text{ s}^{-1}$ ,  $U=100\text{ s}^{-1}$ ,  $U=300\text{ s}^{-1}$ .

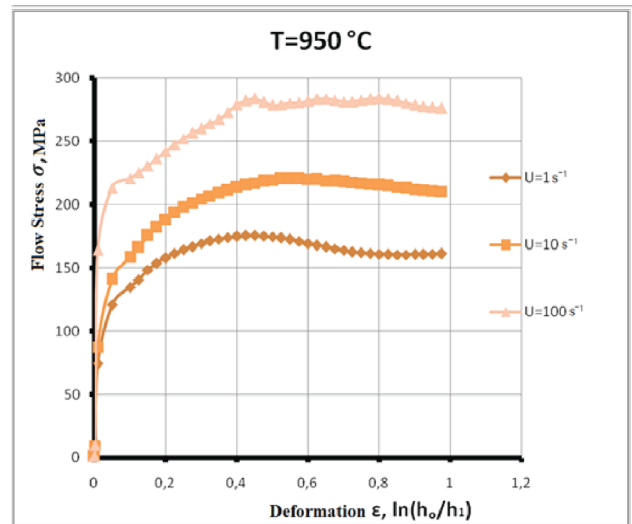


Figure 10. The dependence of the flow stress from the deformation when  $T=950^\circ\text{C}$ ,  $U=1\text{ s}^{-1}$ ,  $U=10\text{ s}^{-1}$ ,  $U=100\text{ s}^{-1}$ .

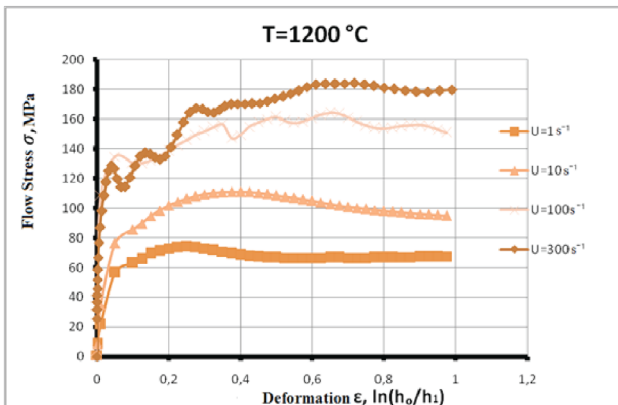


Figure 11. The dependence of the flow stress from the deformation when  $T=1200^\circ\text{C}$ ,  $U=1\text{ s}^{-1}$ ,  $U=10\text{ s}^{-1}$ ,  $U=100\text{ s}^{-1}$ ,  $U=300\text{ s}^{-1}$ .

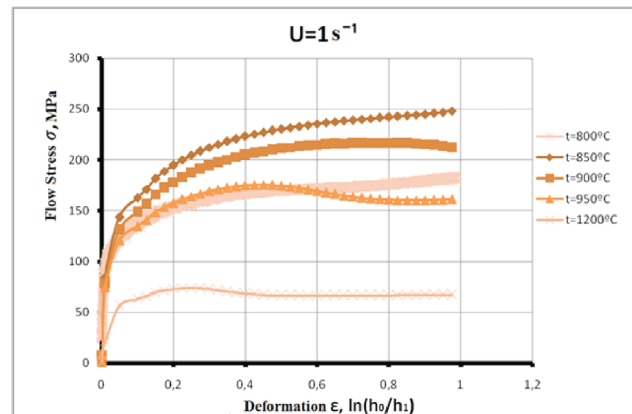


Figure 12. The dependence of the flow stress from the deformation when  $U=1\text{ s}^{-1}$ ,  $T=800^\circ\text{C}$ ,  $T=850^\circ\text{C}$ ,  $T=900^\circ\text{C}$ ,  $T=950^\circ\text{C}$ ,  $T=1200^\circ\text{C}$ .

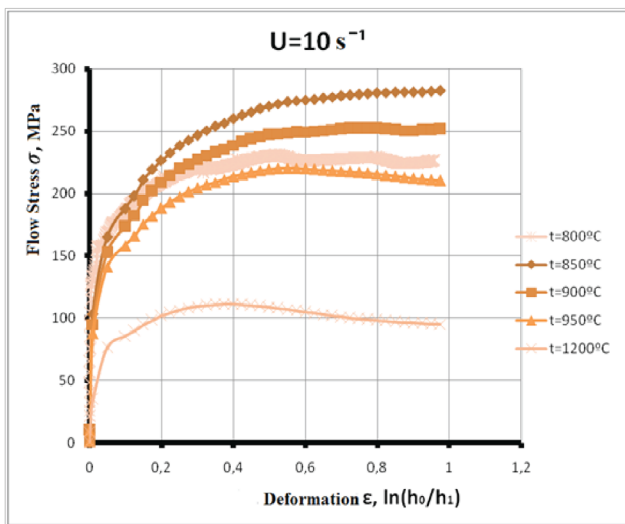


Figure 13. The dependence of the flow stress from the deformation when  $U=10s^{-1}$ ,  $T=800^{\circ}C$ ,  $T=850^{\circ}C$ ,  $T=900^{\circ}C$ ,  $T=950^{\circ}C$ ,  $T=1200^{\circ}C$ .

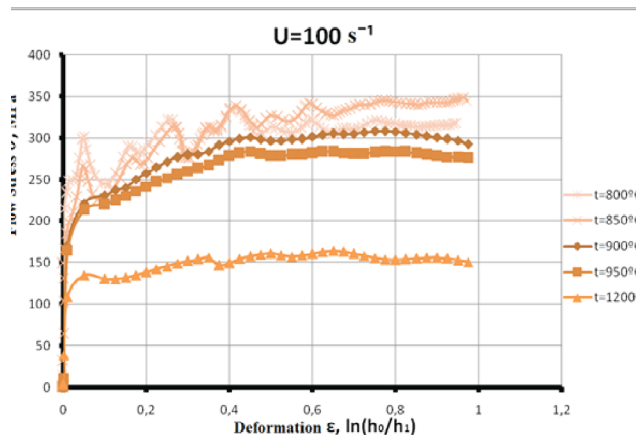


Figure 14. The dependence of the flow stress from the deformation when  $U=100s^{-1}$ ,  $T=800^{\circ}C$ ,  $T=850^{\circ}C$ ,  $T=900^{\circ}C$ ,  $T=950^{\circ}C$ ,  $T=1200^{\circ}C$ .

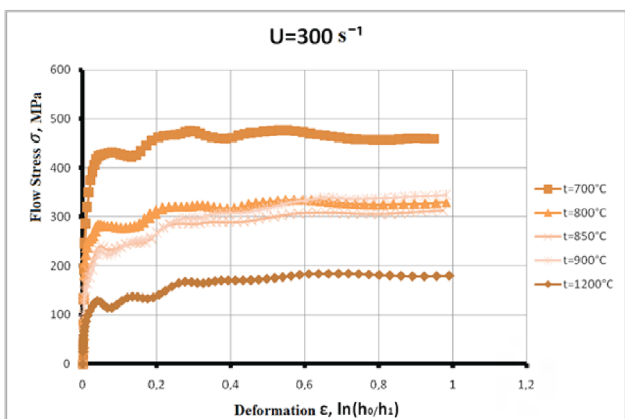


Figure 15. The dependence of the flow stress from the deformation when  $U=300s^{-1}$ ,  $T=700^{\circ}C$ ,  $T=800^{\circ}C$ ,  $T=850^{\circ}C$ ,  $T=900^{\circ}C$ ,  $T=1200^{\circ}C$ .

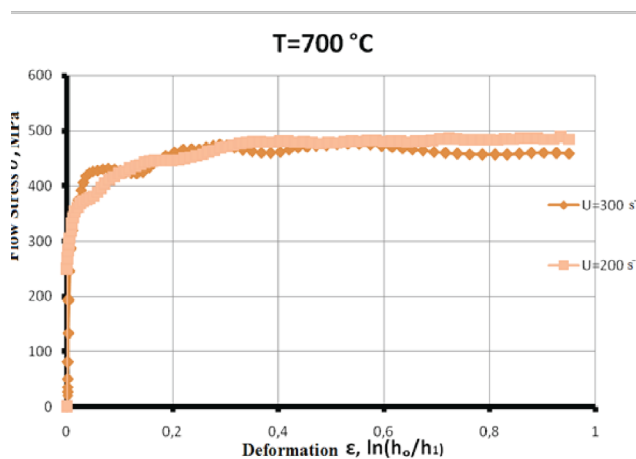


Figure 16. The dependence of the flow stress from the deformation when  $T=700^{\circ}C$ , for  $U=200s^{-1}$ ,  $U=300s^{-1}$ .

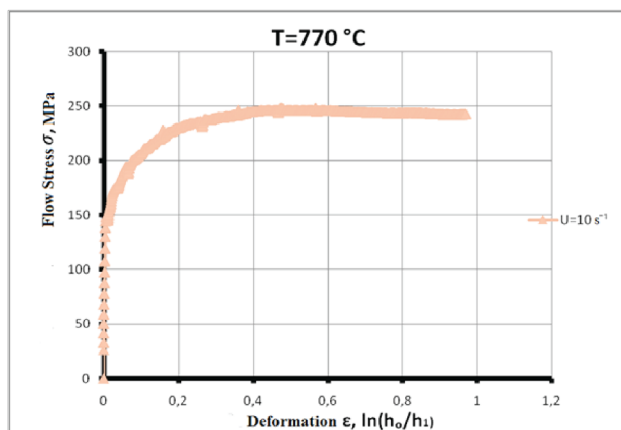


Figure 17. The dependence of the flow stress from the deformation when  $T=770^{\circ}C$ , for  $U=10s^{-1}$ .

For the full qualitative and quantitative analysis it is necessary to obtain the analytical dependence of the flow stress from the thermo-mechanical process parameters, i.e. the connection of the degree, deformation rate, temperature and resistance to the plastic

deformation.

The analysis shows that for the real analytical modeling of the plastic medium the most appropriate formula is the ratio of Hensel - Shpittel [3].

We have

$$\sigma = \alpha_1 \varepsilon^{\alpha_2} \exp\left(\frac{\alpha_3}{\varepsilon}\right) \exp(\alpha_4 \varepsilon) (1 + \varepsilon)^{\alpha_5 T} \left(\frac{\dot{\varepsilon}}{\varepsilon}\right)^{\alpha_6} \left(\frac{\dot{\varepsilon}}{\varepsilon}\right)^{\alpha_7 T} T^{\alpha_8} \exp(\alpha_9 T), \quad (6)$$

where  $\varepsilon, \dot{\varepsilon}, T$  – degree, deformation rate, temperature;  $\alpha_i$  – the experimental coefficients.

After experimental data processing in Fig. 7-17

for the steel 0HFTBch 1, in accordance with the program Reology, the coefficients  $\alpha_i$  of the equations (6) were

$$\begin{aligned} \alpha_1 &= 0,000082; \alpha_2 = 0,524152; \alpha_3 = -0,000163; \alpha_4 = 1,113630; \quad \text{determined.} \\ \alpha_5 &= -0,003363; \alpha_6 = -0,216846; \alpha_7 = 0,000336; \alpha_8 = 2,970980; \\ \alpha_9 &= -0,004952. \end{aligned}$$

Using the plasticity condition of Huber-Mises (4) and equations (3) and (5) we obtain

$$\begin{aligned} &\sqrt{3} \cdot \sqrt{\left(C_{\sigma 2} \cdot \exp \theta_2'\right)^2 + \left(C_{\sigma 3} \cdot \exp \theta_3'\right)^2 +} \\ &\left. + \left(C_{\sigma 2} \cdot \exp \theta_2' \cos A_2 F_2\right) \left(C_{\sigma 3} \cdot \exp \theta_3' \cos A_3 F_3\right) = \right. \\ &= \alpha_1 \varepsilon^{\alpha_2} \exp\left(\frac{\alpha_3}{\varepsilon}\right) \exp(\alpha_4 \varepsilon) (1 + \varepsilon)^{\alpha_5 T} \left(\frac{\dot{\varepsilon}}{\varepsilon}\right)^{\alpha_6} \left(\frac{\dot{\varepsilon}}{\varepsilon}\right)^{\alpha_7 T} T^{\alpha_8} \exp(\alpha_9 T). \quad (7) \end{aligned}$$

The equation (7) allows connecting the parameters of the point stress state (coefficient of friction, form factor) with the thermo-mechanical process parameters (degree, deformation rate and temperature). Thus, an analytic connection (7) appeared, which directly associates the factors of production and loading. The thermo-mechanical process parameters can be determined by using different methods of calculation by setting the parameters of stress state when specified coefficients  $\alpha_i$ .

The integration constants  $C_{\sigma 2}$  and  $C_{\sigma 3}$  are determined by boundary conditions

$$C_{\sigma 2} = \frac{k_0}{\exp \theta_{20}' \cdot \cos A_2 F_{20}},$$

$$C_{\sigma 3} = \frac{k_0}{\exp \theta_{30}' \cdot \cos A_3 F_{30}},$$

where  $k_0$  – resistance to the flow shear in non-cold-worked condition;

$\exp \theta_{20}', \exp \theta_{30}', \cos A_2 F_{20}, \cos A_3 F_{30}$  – values of the corresponding functions in the deformation zone for the stress intensity  $\sigma_T = 2k_0$ . Taking into account the equation (5) we can write

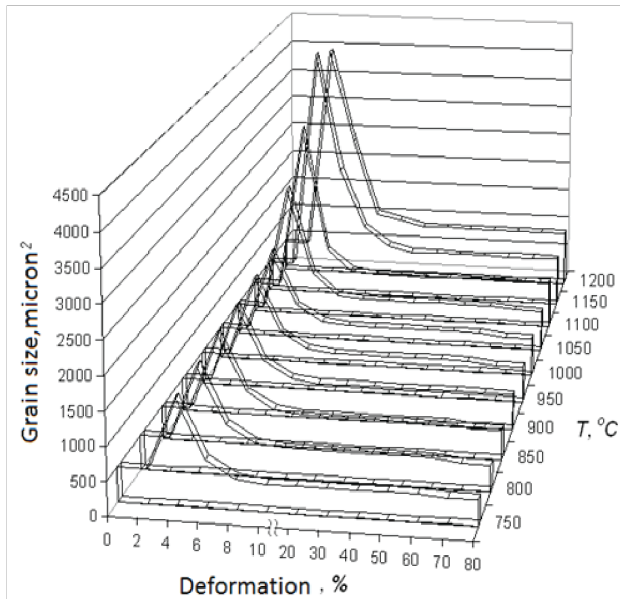
$$\begin{aligned} &\sqrt{3} \sqrt{\left(\frac{\exp(\theta_2' - \theta_{20}')}{\cos A_2 F_{20}}\right)^2 + \left(\frac{\exp(\theta_3' - \theta_{30}')}{\cos A_3 F_{30}}\right)^2 +} \\ &\left. + \frac{\exp(\theta_2' - \theta_{20}') \cos A_2 F_2}{\cos A_2 F_{20}} \cdot \frac{\exp(\theta_3' - \theta_{30}') \cos A_3 F_3}{\cos A_3 F_{30}} = \right. \\ &= \frac{\alpha_1}{2k_0} \cdot \varepsilon^{\alpha_2} \cdot \exp\left(\frac{\alpha_3}{\varepsilon}\right) \cdot \exp(\alpha_4 \varepsilon) \cdot (1 + \varepsilon)^{\alpha_5 T} \cdot (u)^{\alpha_6} \cdot (u)^{\alpha_7 T} \cdot T^{\alpha_8} \cdot \exp(\alpha_9 \cdot T) \quad (8) \end{aligned}$$

On the basis of experimental data the diagram of recrystallization for low-alloy steel 10HFTBch is built. Fig. 18 shows the grain size depends on the same thermo-mechanical parameters as resistance to the deformation of steel Fig. 7-17. This commonality allows you to connect the flow stress to the grain size, and in a condition of Huber-Mises to the stress

state of the deformed metal. Since the stresses in the deformation zone are defined by the variable value of the flow stress, which complicates the problem, we should turn to the relative characteristics in the Huber-Mises condition (5).

Thus, the connection between the theoretical and experimental data for a particular grade of steel, the

effect of the stress state integral characteristics of the medium to the grain size change is determined i. e. the structural changes for a particular grade of steel.



**Figure 18.** The diagram of the 10HTBch steel recrystallization.

The presented results allow us make a forecast of the rolling process technological modes depending on the characteristics of the medium stress state. And ultimately, obtain the size of grains determining the strength properties of the finished steel, variation by volume, optimized mass of the finished rolled products for the consumer.

### Conclusion

1. On the basis of the studies the data are provided, which sequence of use determines experimental and theoretical connection between the characteristics of the stress state of the metal and the structural changes in the deformation zone.

2. The experimental research of mechanical characteristics of steel 10HFTBch, structural changes

when hot working was carried out.

3. The experimental and theoretical approach allows us to develop technological modes of rolling of the low-alloy steel grade using a combination of plastic deformation and heat treatment in the flow of the mill taking into account obtaining the necessary metal structure customized.

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