

# Developing of complex for hot plastic deformation modeling of steel type 20-30CrNiMoV for heavy forging

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**Abstract.** Production of heavy forging of bars weighing more than 235 tons for such products as rotors made of steel type 20-30CrNiMoV is a critical independent work, failure to perform which entails high costs related to repeated production (in case of defective product) and untimely launch of production plants. One of the frequent causes of a defective product is the impossibility of ultrasonic testing in the barrel-gate zones on the rotor workpiece, which is due to the microstructure of the metal, namely the grain size. Determining the stages of deformation process which causes such defects in structure is the main goal of this work.

## 1 Formatting the title, authors and affiliations

Decrease of defective products at all processing stages of metallurgical production is a priority task for researchers and production engineers. As is known, the grain size under deformation depends on the following parameters: degree of deformation  $\varepsilon$ , rate of deformation  $\dot{\varepsilon}$  s<sup>-1</sup>, temperature  $T$ . These physical parameters in turn are associated with the process parameters, such as tool operation time on the workpiece,  $T$  of metal on the surface. Prediction of the structure change at different degrees of deformation and at a certain temperature is described on the basis of the theory of plastic deformation and can be modeled for specific technological processes [1,2].

In turn, during deformation, recrystallization always occurs, which can be of three types: static, metadynamic and dynamic. One of the ways to optimize production processes at the stage of hot plastic deformation (HPD) of ingots is to model the structure using mathematical models and the finite elements method.

There are several phenomenological models that establish the connection between the stressed and deformed state of the medium [3-20]:

- Johnson-Cook model;
- Steinberg-Cochran-Guinan- Lund model;
- Zerilli-Armstrong model;
- Mechanical threshold stress model (MTS);
- Preston-Tonks-Wallace model.

At the present time in order to model the evolution of structure during the HPD process, the microstructure characteristics relationship models (volume fraction of recrystallized grains and grain size) with HPD parameters based on equations of Avrami-Kolmogorov type [3-8] are most widely used. They show a high predictive capability,

but require a lot of experimental data in order to determine unknown constants.

Kinetics of dynamic recrystallization can be described by the following set of equations (1-4):

$$X_{DRX} = 1 - \exp \left[ -\beta_d \cdot \left( \frac{\varepsilon - a_{10} \cdot \varepsilon_p}{\varepsilon_{0.5}} \right)^{k_d} \right] \quad (1)$$

$$\varepsilon_{0.5} = a_5 \cdot d_0^{h_5} \cdot \varepsilon^{n_5} \cdot \dot{\varepsilon}^{m_5} \cdot \exp \left( \frac{Q_5}{R \cdot T} \right) + c_5 \quad (2)$$

$$\varepsilon_p = a_1 \cdot d_0^{n_1} \cdot \dot{\varepsilon}^{m_1} \exp \left( \frac{Q_1}{R \cdot T} \right) + c_1 \quad (3)$$

$$\varepsilon_c = a_2 \cdot \varepsilon_p \quad (4)$$

where  $d_0$  – initial grain size,  $\mu\text{m}$ ;  $\varepsilon_{0.5}$  – degree of deformation at 50% of the volume of recrystallized grains;  $a_1, n_1, m_1, Q_1, c_1, a_2, a_5, h_5, n_5, m_5, Q_5, c_5, \beta_d, a_{10}, k_d$  – rheological parameters of the material, determined on the basis of the results of experimental studies.

To determine the size of dynamically recrystallized grains, the polynomial empirical equation with temperature dependence according to the Arrhenius law was used (5):

$$d_{DRX} = a_8 \cdot d_0^{h_8} \cdot \varepsilon^{n_8} \cdot \dot{\varepsilon}^{m_8} \cdot \exp \left( \frac{Q_8}{R \cdot T} \right) + c_8 \quad (5)$$

where  $a_8, h_8, n_8, m_8, Q_8, c_8$  are the material rheological parameters determined on the basis of the results of experimental studies (if  $d_{DRX} > d_0$ , then  $d_{DRX} = d_0$ ).

Grain growth during the annealing of a non-deformed metal, or in the intervals between deformations, can be described by the following equation (6):

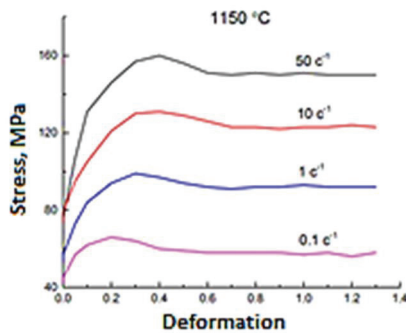
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$$d_{gg} = \left[ d_0^m + a_9 t \exp\left(-\frac{Q_9}{RT}\right) \right]^{\frac{1}{m}} \quad (6)$$

where  $a_9, Q_9, m$  – are the material parameters determined on the basis of the results of experimental studies.

To determine the constant rheological parameters for steel type 20-30CrNiMoV included in the model, steel grade 26HN3M2FA was chosen and experiments with the use of the Gleeble 3800 complex were carried out: melting of 12 kg of ingots followed by forging into bars and annealing in order to obtain a structure with grains of different sizes (50, 200, 1000  $\mu\text{m}$ ), simulating different zones of the ingot. An experiments matrix was developed to study the effect of the rate, degree and temperature of deformation on the size of austenite grain to determine the rheological parameters included in the phenological model.

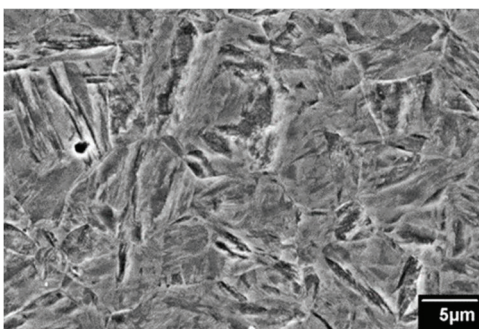
Curves of deformation according to which the coefficients describing the kinetics of dynamic recrystallization for steel 26HN3M2FA were determined, are shown in Fig. 1. Kinetic parameters were determined using the method of minimizing the error between calculated and experimental values of the flow stress in the section of the deformation curve from the maximum value to the value corresponding to the steady-state stage of deformation.



**Fig. 1.** Curves of deformation of dynamic recrystallization

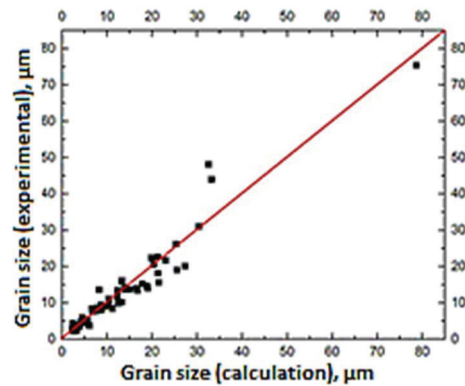
Deformation curves for determination of dynamic recrystallization kinetics for 26HN3M2FA steel.

Unknown coefficients were determined on the basis of the results of microstructural studies of grain size after different deformation modes. Figure 2 shows typical microstructure of 26HN3M2FA steel with dynamically recrystallized structure.



**Fig. 2.** Microstructure of the 26HN3M2FA steel (after deformation in the mode T=1150°C,  $\dot{\epsilon}=50 \text{ c}^{-1}$ ,  $\epsilon=1,3$ ,  $\tau=0 \text{ c}$ .)

Comparison of experimental and calculated grain sizes for 26HN3M2FA steel is shown in Fig. 3. Average calculation error for the 26HN3M2FA steel was 5,2%



**Fig. 3.** Comparison of experimental and calculated grain sizes for 26HN3M2FA steel

## 2 Comparison of calculated and experimental values of dynamically recrystallized grains for 26HN3M2FA steels

More than 540 studies were carried out in order to determine the rheological parameters of 26HN3M2FA steel. As a result, a model that describes the deformation of 26XH3M2FA steel was developed (7-8):

$$d_{DRX} = 67352.5 \times d_0^{-0.051} \times \varepsilon^{-0.672} \times \dot{\varepsilon}^{-0.075} \times \exp\left(\frac{94000}{R \times T}\right) \quad (7)$$

$$d = d_{DRX} X_{DRX} + (1 - X_{DRX}) d_0 \quad (8)$$

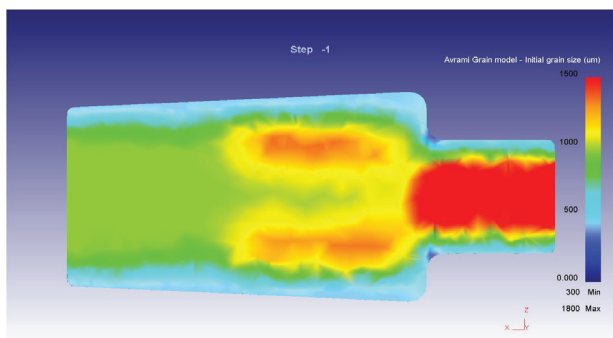
For modeling of the actual structure formation in the process of industrial HPD, obtained mathematical dependences (values of the coefficients) and rheological properties of materials are downloaded to the program that allows to calculate deformation processes using the finite element method. The model (7-8) is applied to determine grain in each element. In the environment of finite element modeling, the initial geometry of the workpiece and deforming tool, the initial and boundary conditions, including the initial distribution of grain sizes are set. After that, the process conditions in the form of time dependencies of the workpiece position relative to the tool, its speed and the surface temperature of the workpiece are set.

Result of the calculation is the dependence of characteristics of the grain structure microstructure at the final moment of forming at each point of the workpiece on the HPD parameters (set by the corresponding time dependencies) (9):

$$d = f(F_{GPD}(\tau), x_i, y_i, z_i) \quad (9)$$

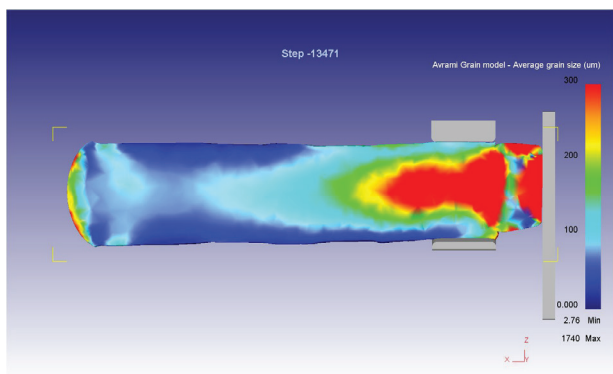
This model was used to study the distribution of grain for a rotor workpiece of bar with mass 235 tons in order to identify the least deformable zones.

Distribution in the initial ingot was modeled using the DeForm software package (40,000 items were studied).



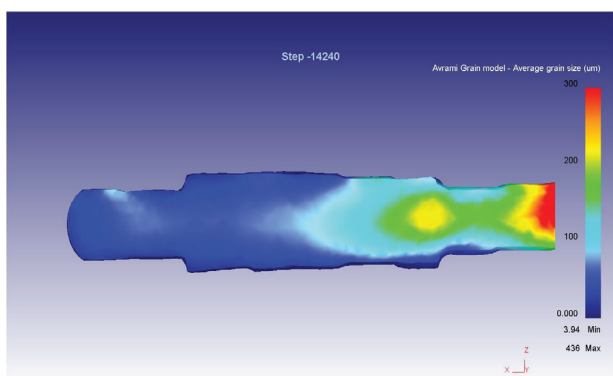
**Fig. 4.** Stage of hot deformation model of rotor forging

Further, the entire forging process was modeled taking into account the actual deformation conditions with measurement of geometric pattern, time and temperature. As a result, the most critical stage of forging the rotor workpiece was determined: deformation into circle.



**Fig. 5.** Stage of hot deformation model of rotor forging

And the final distribution of grain after heating:



**Fig. 6.** Final stage of hot deformation model

It can be seen that the most problematic zone is «barrel-gate» with a grain size of more than 170  $\mu\text{m}$ . These results are fundamental for predicting the technology of rotor deformation and adjusting the factory technology.

### 3 Conclusion

1. A phenomenological model describing the process of deformation for unique heavy forging (more than 230 tons) for power machine made of 20-30CrNiMoV type steel was developed.

2. On the basis of large array of experimental data, the unique constant parameters of a steel of the selected type, which determine the rheological properties of the material for the following thermal-deformation modes, were determined for the first time:  $T=1230-900^{\circ}\text{C}$ ; degree of deformation 0,17-1,3; rate of deformation from 0.1 to 50  $\text{s}^{-1}$

3. Numerical modeling of the rotor workpiece forging process from an ingot of 235 tons was performed, and occurrence of critical zones with large grains (more than 170  $\mu\text{m}$ ) and the stage of formation of these zones was predicted for the first time.

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