MODELING OF TEMPERATURE INFLUENCE ON RESISTANCE TO PLASTIC DEFORMATION OF ELECTRTECHNICAL STEELS IN HOT ROLLING

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Modeling of temperature influence on resistance to plastic deformation of electrotechnical steels in hot rolling

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Abstract. Electrotechnical steels include dynamo and transformer steels, so that to dynamo belong steels with content of silicon from 0.8% to 2.5%, and to transformer - with content of silicon to 4.8%. From the flatness of the electrotechnical sheet steel, and, respectively, the elements stamped from it, the filling factor of the magnetic circuit depends. The rolling force exerts the greatest influence on the elastic deformations of the roller system, and, consequently, on the violation of the uniform distribution of the drawing coefficient over the width of the rolled strip, and, accordingly, its flatness. To study the effect of temperature on the hot rolling force, experimental studies were carried out at the Gleeble-3800 facility. The experiments were carried out with steel with two different silicon (Si) contents: samples A - 0.43%; samples B - 1.12%. The experiments showed that the dependence of the reduction stress on the reduction deformation for samples A is maximal at T = 900 ° C, and at T = 1100 ° C and 850 ° C are minimal and practically identical. The microstructure of sample A, obtained at a deformation temperature of 850 ° C, and sample B, obtained at a deformation temperature of 900 ° C, illustrated the dynamics of the development of phase transformations.

1. Introduction
Electrotechnical steel is called an alloy of iron with silicon; is produced in the form of sheets with thickness up to 0.05 mm. Electrotechnical steel is used to fabricate magnetic circuits of electrical devices such as transformers, electric motors, generators, etc. Electrotechnical steels include dynamo and transformer steels, with silicon ranging from 0.8% to 2.5%, and transformer steels with silicon contents up to 4.8% [1].

Finished electrotechnical sheet steel must satisfy not only the requirements for magnetic properties, but also for geometric parameters, in particular, flatness.

It is known that the cores of transformers, as well as the anchors / rotors of electric machines, are collected layer by layer; each layer is a flat element formed from an electrotechnical sheet steel by stamping.

From the flatness of the electrotechnical sheet steel, and, respectively, the elements stamped from it, the filling factor of the magnetic circuit depends: the more bulk the core becomes, the smaller the filling factor, the worse the magnetic properties of the magnetic circuit.

The flatness formation of electrical steel sheet begins at the stage of hot rolling when a hot rolled strip with a thickness of 2.0 mm to 2.5 mm is rolled from a continuously cast slab in a hot rolling mill, which is a blank for a cold rolling mill.

The condition for the saving of a strip flat form is known - this is the equality to zero of the relative difference in length between the middle and the edge of the strip (Figure 1):
The flatness of the finished strip depends on the following factors:

- machine profiling of rolls;
- elastic bending of the axes of the rolls under the rolling force;
- elastic flattening of the work rolls’ surface in contact with the strip.

The rolling force exerts the greatest influence on the elastic deformations of the roll system, and, consequently, on the violation of the uniform distribution of the drawing factor over the width of the rolled strip, and, accordingly, its flatness.

2. Hot rolling force

For the correct calculation of elastic deformations of rolls, it is necessary to accurately calculate the hot rolling force, whose dependence on temperature for electrotechnical steel is nonmonotonic.

2.1. Hot rolling force temperature dependence

To study the effect of temperature on the hot rolling force, experimental studies were carried out at the Gleeble-3800 facility at the Częstochowa Polytechnic University (Częstochowa, Poland). The experiments were carried out with steel with two different silicon (Si) contents: samples A - 0.43%; samples B - 1.12%; the content of the remaining elements was preserved (except for Fe) (Table 1-2).

| Table 1. Chemical composition of samples A. |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|                 | Content of elements, % |
| Fe              | Si               | Mn              | N               | Cr              | Cu              | C               | P               | W               | Co              |
| 99.04           | 0.43             | 0.204           | 0.144           | 0.048           | 0.041           | 0.021           | 0.013           | 0.012           | 0.011           |
| S               | Ni               | As              | Al              | Pb              | Sn              | V               | B               | Nb              |
| 0.010           | 0.008            | 0.003           | 0.003           | 0.002           | 0.002           | 0.001           | 0.001           | 0.001           |

| Table 2. Chemical composition of samples B. |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|                 | Content of elements, % |
| Fe              | Si               | Mn              | N               | Cr              | Cu              | C               | P               | W               | Co              |
| 98.39           | 1.12             | 0.144           | 0.144           | 0.059           | 0.050           | 0.025           | 0.013           | 0.007           | 0.007           |
| S               | Ni               | As              | Al              | Pb              | Sn              | V               | B               | Nb              |
| 0.016           | 0.010            | 0.004           | 0.002           | 0.002           | 0.003           | 0.001           | 0.004           | 0.001           |

Samples were melted in air in a ceramic crucible placed inside an electrical resistance spiral. This explains the rather high content of nitrogen (N) in the samples. The samples were made in the form of
cylinders with a diameter of 6.85 ÷ 7.00 mm, a length of 10.00 ÷ 10.40 mm. Chromel-Alumel thermocouples of type k (NiCr-NiAl) were used to record and control the temperature.

2.2. Experimental part

Figure 2 shows the scheme of thermomechanical processing of samples, which included the following sections:

- sample heating area up to a temperature of 1150 °C;
- exposure section, 10 min;
- the sample cooling area to the deformation temperature at a rate of 5 °C/s;
- exposure of the sample before deformation, 5 s;
- sample reduction followed by cooling.

![Figure 2. Thermomechanical processing of samples.](image)

The experiments were carried out at a specialized installation of Gleeble-3800 in Czestochowa Polytechnic University (Poland, Czestochowa).

2.3. Basic information of Gleeble-3800 Process Modeling Installation of thermomechanical processing of materials.

The Gleeble-3800 is manufactured by Dynamic Systems, Inc. (USA) and is intended for modeling the processes of thermomechanical processing of various materials, including metal ones. The Gleeble-3800 is made in a modular design; various modules can be connected to the main power unit for the following tasks:

- deformation by compression or stretching;
- deformation by torsion (shear deformation);
- impact deformation;
- multiaxial deformation.

Each module has its own working chamber, which communicates with the vacuuming system, which provides vacuum to $1 \times 10^{-4}$ mm Hg.

Tests can be carried out both in a shielding gas and in air. Heating of the samples is carried out by direct transmission of electric current, with the power of the supply transformer 75 kVA, which is capable of providing a maximum heating rate up to 12000 °C / s. The temperature, heating and cooling rates are controlled by a thermocouple welded to the sample on the installation attached to the complex. Simultaneous recording of temperature at four points of the working part of the sample is possible, one of the thermocouples being the control one. The temperature regulation system
ensures that it ripples when heating at a rate of 1000 °C / s not more than 5-6 °C and maintains at a predetermined level with an error of not more than ± 1 °C.

During the experiments, samples can be cooled in various ways:
- heat sink in water-cooled copper or steel grippers;
- blowing air or inert gas;
- flow around the outside or inside the samples, or simultaneously outside and inside.

To ensure the tests, power supply, hydraulic oil, compressed air and distilled cooled water are supplied to the main unit and modules.

The maximum cooling rate achieved when testing the complex on samples 6.0 mm thick is 4500 °C / s. When the samples are cooled by air or water, the vacuum system is disconnected from the working chamber. The tests can be carried out at a temperature ranging from room temperature up to the melting point, with the use of special quartz tubes for studying the liquid-solid state. The maximum tensile strength is 10 tons, with compression - 20 tons, with impact - 20 tons. To record forces and deformations, strain gauges and displacement transducers of the movable traverse are used, respectively.

The tensile and compression test module is equipped with highly sensitive meters for longitudinal and transverse deformation, as well as with a dilatometer; all of them allow performing highly accurate measurements of displacements and determining the temperatures of phase transformations in a predetermined range of heating and cooling rates after plastic deformation or without it. Maximum deformation rates up to 200 s⁻¹ are achieved when testing on cylindrical samples by the size Ø 10 × 15 mm using a shock test module for which the speed of the movable traverse is 2.5 m / s. Thus, the deformation rates on the Gleeble-3800 cover the entire range of high-speed deformation modes of the most modern hot rolling mills.

The module for multi-axial deformation MaxStrain is designed to produce ultrafine-grained and nanocrystalline structure of metals, which is relevant for modern materials science. The number of operations of heating, cooling, deformations with a predetermined rate and degree of deformation, pauses, and chillings, which are programmed on the Gleeble-3800 complex, is practically unlimited and is determined only by the properties of the metal. The Gleeble-3800 complex is unique in the world practice.

3. Results of experiments
Figure 3 shows the dependence of the stresses while upsetting samples A for temperatures of 1100°C, 1000°C, 900°C and 850°C. Accordingly, Figure 4 shows the dependences of stresses while upsetting samples B for the same temperatures.

![Figure 3](image_url)  (a) and B (b).
The following features are seen in the diagrams: for samples A and B curves 1 (1100 °C) and 4 (850 °C) practically coincide, although for samples A the maximum stresses occur at 900 °C, and for samples B - at a temperature of 1000 °C.

**Figure 4.** The temperatures of phase transformations in samples A (a) and B (b).

4. **Discussion of results**
Obviously, these features are due to phase transformations. To confirm this experimentally, dilatometric measurements were carried out. Figure 4 presents the dilatometric curves of the samples A and B.

The temperature range of the phase transformations in sample A while heating is 922.3° C - 1116.3° C; while cooling, temperature of the beginning of the transformation is 1001.2° C, and at the test end temperature of 850° C it did not end. The temperature range of the phase transformations in sample B while heating 930.4 ° C - 1073.4 ° C; while cooling is 1002.3° C - 891.6° C With an increase of the percentage of silicon in the steel, the range of $\alpha \rightarrow \gamma$ and $\gamma \rightarrow \alpha$ transformations has narrowed and shifted to higher temperatures.

Analysis of the microstructure of sample A (figure 5b) obtained at a deformation temperature of 850 ° C confirmed the increase of ferrite in comparison with the microstructure obtained at a
deformation temperature of 900°C (figure 5a), although figure 5b shows that the quenching of the sample did not go to the end.

Figure 5. Microstructures of deformed steels at 900 °C (a) and at 850 °C (b), increase × 250.

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5. References
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