Comparative evaluation of austenite grain in high-strength rail steel during welding, thermal processing and plasma surface hardening

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Abstract. In the process of plasma surface hardening, a surface layer that consists of zones of different sizes with different phase and structural composition is formed. The minimum grain size for plasma surface heating is determined by the initial austenitic grain. Its size depends on the dispersion of the initial structure. The rate of plasma heating at 200-1000 °C/s affects the size of the initial grain. The further growth of austenite crystallites with an increase of temperature essentially depends on the heating rate: small rates and high temperatures of plasma surface heating can lead to a significant enlargement of the grain. Increase of the heating temperature in the zone of thermal influence during welding from 900 to 1040 °C of rail steel 76F leads to the growth of the austenitic grain from No. 9 to No. 7 and individual grains – from No. 8 to No. 3. The largest austenite grains while heated at 1000 and 1040 °C form separate zones where conglomerates of large grains predominate. Stiffness of 76F steel, heat-strengthened on the troosto-sorbitol structure, deteriorates substantially when the temperature of rapid heating increases from 900 to 1040 °C. This also increases the instability of stiffness.

1. Introduction
In production of rails, modern technologies of converter production with continuous casting of steel and continuous rolling are used. The differential hardening is used in production of rails of steels 76F and 76HF, and the volume hardening – in production of steel 76F (Russia) and steel 76F. The hardness of the hardened rail head made of the steel 76F layer is HV 374-401 [1-3]; the depth of the hardened layer varies from 7 to 15 mm. The hardness of the base material is within the limits of HV 250-300. The microstructure of rail steels is sorbitol, precipitate of free ferrite is practically absent. The distinctive feature of the hypereutectoid rail steel, it is ordinary steel (they are NE and HX hypereutectic steels) “Nippon Steel” (Japan), is the presence of primary austenite grains, deposits of iron carbide [2-4] along the boundaries. It should be noted that the rails, produced by R350HT (Austria), are distinguished by a
large primary austenitic grain – an estimated grain score of 3-4. The size of the austenitic grains of the 76F rails is somewhat smaller. The steel structure for the vs-350YA rails and 76F one is finer-grained – their austenitic grain score was 5-6 [4,5]. It is known that grinding the pearlite structure, namely, grinding the grain in an austenitic structure, which has yet to be converted into perlite, or grinding perlite blocks, is effective from the point of view of improving the stiffness of pearlite steel. In order to ensure grain grinding in the austenite structure during hot rolling [5,6], rolling temperature is reduced and the reduction ratio is increased, and heat treatment is also used in the form of low-temperature re-heating after hot rolling of the rails. However, in the manufacture of rails, from the point of view of providing formability during hot rolling, there are limitations imposed on the reduction of the rolling temperature and the increase in the reduction ratio, because of which it is not possible to achieve sufficient grinding of the austenite grains [6]. In addition, as regards the transformation into perlite within the austenite grains by the use of embryos, there are problems connected with the difficulty in controlling the amount of embryos, and the perlite conversion inside the grains is unstable. That's why it is not possible to achieve sufficient grinding of the pearlite structure [1,5]. Because of these problems, a method of fundamental improvement of stiffness of rails with a perlite structure is considered. In this structure low-temperature re-heating is performed after hot rolling of the rail, and then the perlite conversion is performed by accelerated cooling to grind the pearlite structure [5]. However, recently, high-carbon rails have been manufactured to improve wear resistance, that's why there is a problem that consists in the fact that large carbides remain inside the austenite grains during the above-described treatment by low-temperature re-heating, that reduces the plasticity and stiffness of the pearlite structure after accelerated cooling. For practical problems of the extractive metallurgy of high-strength rail steels, it is important to determine the size and shape of the former austenite grain in the course of various types of the heat treatment and welding, since it is the size and shape of the austenite grain that significantly affects the final structure and properties of structures. For methods of surface hardening of steels, regulation of grain size is an important condition to obtain products with specified properties [5,6]. Considering these circumstances, there emerged a necessity of a rail with a pearlite structure with excellent wear resistance [5,6] and stiffness, in which both wear resistance and resistance to damage to the pearlite structure have been improved.

The aim of the work is to evaluate the influence of the heating rate on the kinetics of the growth of austenite grains in high-strength rail steels.

2. Equipment and materials for research

Welding regimes during continuous burning-off are determined by the programs for changing the main parameters, given for the R65 rails in [1]. As a main parameter, that determined the energy input, burning-off time is accepted, which for the R65 rails is 180 s. Welding of control lots of rails in the amount of 10 pcs was performed on a stationary machine K1000.

Welded samples of rails 1.22 m long after the removal of the burr were tested for static and mechanical bending according to the standard method adopted in the world practice. Experimental studies on the heat treatment and plasma surface hardening were carried out on technological equipment: the source of heating of the surface of products during processing by low-temperature plasma is the direct-acting plasmatron PDU-2 [5-6]. Metallographic studies were carried out on a Metcom2 microscope equipped with an image analyzer SIAMS 600. Electron microscopic studies were performed on the basis of the INRTU with the help of electron microscope JIB-4501 JEOL – multibeam spot system equipped with an electron and ion gun JIB-4501 completed with a nitrogen-free energy-dispersive microanalysis system, transmission electron microscope Tecnai G2 20F S-TWIN FEI. Microhardness was measured on a PMT-3 instrument. Samples were heated for quenching (in the zone of phase transformations) at a rate of 10, 200 and 1000 °C/s. For comparison, the initial austenite grain size for the same steel was determined for fast (2 °C/s) and slow (0.03 °C/s) furnace heating. Fast furnace heating was carried out in a furnace heated to 950 °C. Samples of 1.2 mm thick were quenched from temperatures close to the point Ac3. For different heating rates, grain size was determined on samples, quenched from the lowest temperature, at which ferrite was absent in the structure, i.e., the initial size
of the austenite grain was determined. The austenitic grain was detected by etching of quenched samples in a saturated water solution of picric acid with the addition of 1% of synthetic fatty alcohol salts [5,6]. To determine the actual austenite grain, method of high-temperature etching in a mixture of borax with nitrate (melt) was chosen, which is especially effective, since it makes it possible to detect grains at short exposures at an Ac3 temperature. [5,6]. The research results and discussion. The estimation of austenite grain after welding showed that a coarse-grained structure of primary austenite grains, a grain score of 2-3, are observed along the joint line and adjacent metal layers. On the grain boundaries of primary austenite, a solid grid of ferrite precipitates is clearly observed, that indicates the low plastic properties of this section. From the practice of contact welding, it is known [1] that a reduction in the energy input during welding makes it possible to improve the structure of metal along the joint line and adjacent areas, in particular, reduce the grain size and ferrite precipitate along their boundaries. Figure 1 shows the austenitic grain of 76F steel after heating to different temperatures. It can be seen that the size of the austenite grain in the heat affected zone depends significantly on the heating temperature. With an increase in the heating temperature in the heat affected zone, size of the austenite grains increases, especially after 1000 °C. When heating to 900 °C, the smallest and most uniform grains of austenite are observed, their average area is 304 μm².

The largest grain of austenite is formed when heating to a temperature of 1040 °C (Figure 1). It is important to note that with an increase in the heating temperature, an uneven growth of austenite grains occurs. The individual grains of austenite during heating to 1000 °C enlarged to 4th number, and when the samples were heated to 1040 °C, austenite grain was additionally significantly enlarged, and individual grains were enlarged to 3d number.

**Figure 1.** Schematic representation of the rail joint during welding at the stage of heating and burning-off (1,2), cooling (3), metallography of the joint (4, macrostructure) and the size of the austenite grain in the heat affected zone at different temperatures.

Since the heating temperature of the rail steel significantly affects the size of the austenite grain, it can be assumed that this factor can significantly affect the stiffness. For a more correct analysis of the evaluation of the heating rate on the growth of austenite grain, it is necessary to distinguish the hereditary
The hereditary grain is obtained under standard conditions of the technological test and characterizes the propensity of steel to grain growth [5-6]. The actual grain is a grain that results from one or another heat treatment operation. It may be more or less if we compare it with the hereditary grain, depending on whether the heating temperature of steel for quenching is higher or lower. If the size of the initial grain during heating does not depend on the heating rate, then the further growth of the already formed grain essentially depends on the heating rate [5,6]. This can be explained by the combined effect of time and temperature. At the same heating temperature, a lower heating rate leads to a large grain size. That is associated with a significant grain growth rate in the initial holding period at a temperature above Ac3.

It has been determined [5,6] that the grain growth from the initial size to a stable one is a feature of the curve of the grain growth of mild steels with a temperature as the plasma heating rate increases. In order to determine the influence of the main parameters of the plasma surface hardening (thermal power of the plasma jet (arc), rate of hardening, processing distance) on the maximum heating temperature on the metal surface, experiments were carried out using the technique [5], results are shown in Figure 2. In case of plasma heating, average size of the initial austenite grain, formed with heating rates of 10, 200, 1000 °C/s and temperatures of 830, 870 and 900 °C, respectively, was not the same. At the same time, with rapid furnace heating (2 °C/s) in the zone of phase transformations, initial grain size is close to the value of the initial grain during plasma heating at a rate of 10 °C/s. Figure 3 shows the growth curves of the grain of steel with an increase in temperature of plasma heating at different heating rates. It can be seen that in the temperature range of 800-850 °C, growth of the austenite grain depending on the heating rate differs insignificantly. Influence of the heating rate becomes significant during heating to higher temperatures (Figure 3, 4).

Conducted studies showed that with an increase of heating temperature of the rail steel, and, consequently, total residence time of metal at the maximum temperature, collective growth of the austenite grain is clearly manifested. This means that the parameters of carbide phase particles in medium-carbon steels do not provide a sufficient barrier effect, and the rate of the grain growth can be determined by the content of alloying elements in the high-temperature zone [5]. For furnace (slow heating), this critical temperature for steels is 850 °C, after that an intensive growth of the austenite grain begins. At the same time, high heating rates during the plasma hardening suppress the growth of austenite grain, and, consequently, at cooling, a more finely dispersed martensite structure is formed in comparison with the martensite structure formed during the conventional hardening of medium carbon steels. It should be noted that the causes of grain stabilization in rail steels have not been sufficiently studied. It was pointed out in [6] that obstacles to the grain growth arise directly in the α → γ transformation region.
transformation process as a result of the existence of a mixed mechanism for the formation of austenite (diffusion and diffusionless).

3. Conclusion
1. In the process of plasma surface hardening, a surface layer consisting of zones of different sizes with the different phase and structural composition is formed. The minimum grain size for plasma surface heating is determined by the initial austenitic grain. Its size depends on the dispersion of the initial structure. The rate of plasma heating at 200-1000 °C/s affects the size of the initial grain. The further growth of austenite crystallites with an increase of temperature essentially depends on the heating rate: small rates and high temperatures of plasma surface heating can lead to a significant enlargement of grain.

2. The increase of the heating temperature in the zone of the thermal influence during welding from 900 to 1040 °C of rail steel 76F leads to the growth of austenitic grain from No. 9 to No. 7, and individual grains – from No. 8 to No. 3. The largest austenite grains during heating at 1000 and 1040 °C form separate zones where conglomerates of large grains predominate.

3. The stiffness of 76F steel, heat-strengthened on the troosto-sorbitol structure, deteriorates substantially when the temperature of rapid heating increases from 900 to 1040 °C. This also increases the instability of stiffness.

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