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Experience in producing rails from bainitic steels 30KhG2S2AFM and 30KhG2SAFN

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Abstract. The operational resistance of railway rails is mainly determined by the resistance to contact fatigue defects and wear resistance, and, in addition to the impact characteristics of rolling stock wheels, depends on the chemical composition, structure and mechanical properties of rail steel. Currently, the ways to improve the operational properties of traditional pearlitic rails by increasing the microstructure dispersion are almost exhausted. One of the solutions to increase the service life of rails may be the transition to their production from bainitic steels, characterized by higher mechanical properties, resistance to the formation of surface contact and fatigue defects and increased cold resistance. Operational tests conducted abroad in the early 2000s showed that rails made of bainitic steel do indeed have increased resistance to formation of contact fatigue defects compared to rails made of pearlitic steel, but they are subject to more intensive wear. It was concluded that the resistance of bainitic rails to head damage by surface contact and fatigue defects is a consequence of the removal of the damaged rolling surface layer as a result of wear. In 2004 – 2006, JSC EVRAZ United West Siberian Metallurgical Plant conducted research and produced an experimental batch of bainitic rails, which showed the promise of using such steel and the possibility of simultaneously providing increased wear resistance and low-temperature reliability. However, at that time, the plant did not have the full capabilities to ensure the high metallurgical quality of steel: the identified shortcomings are related to the insufficient purity of the metal for non-metallic inclusions. As part of the resumption of work on the development of bainitic rails, two experimental medium-carbon steels B1 and B2, differing in alloying schemes, were smelted, rolled onto rails of type P65 and cooled in calm air. The presented results of mechanical tests showed the positive effect of increased chromium and nickel alloying on mechanical properties and structure.

Keywords: rail rolling, bainitic steel, tempering, microstructure, impact strength, resistance to formation of contact fatigue defects, scanning electron microscopy

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Опыт производства рельсов из бейнитной стали марок 30ХГ2С2АФМ и 30ХГ2САФН

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Аннотация. Эксплуатационная стойкость железнодорожных рельсов определяется в основном сопротивлением возникновению дефектов контактной усталости и износостойкостью, и зависит, помимо характеристик воздействия колес подвижного состава, от химического состава, структуры и механических свойств рельсовой стали. В настоящее время пути повышения эксплуатационных свойств традиционных перлитных рельсов за счет увеличения дисперсности микроструктуры практически исчерпаны. Одним из решений для повышения срока службы рельсов может стать переход на производство их из сталей бейнитного класса, отличающихся более высокими механическими свойствами, стойкостью к образованию поверхностных контактно-усталостных дефектов и повышенной хладостойкостью. Проведенные в начале 2000-х годов за рубежом эксплуатационные испытания показали, что рельсы из бейнитной стали действительно обладают повышенной по сравнению с рельсами из стали перлитного класса сопротивляемостью к зарождению контактно-усталостных дефектов, однако подвержены более интенсивному износу. Был сделан вывод, что стойкость бейнитных рельсов к повреждениям головки поверхностными контактно-усталостными дефектами является следствием удаления поврежденного слоя поверхности катания в результате износа. В 2004 – 2006 гг. на АО «ЕВРАЗ Объединенный Западно-Сибирский металлургический комбинат» проведены исследования и выпуск опытной партии бейнитных рельсов, которые показали перспективность применения такой стали и возможность обеспечения одновременно повышенной износостойкости и низкотемпературной надежности. Однако в тот период комбинат не располагал в полной мере возможностями обеспечения высокого металлургического качества стали: выявленные недостатки связаны с недостаточной чистотой металла по неметаллическим включениям. В рамках возобновления работ по освоению рельсов бейнитного класса проведена выплавка, прокатка рельсов типа Р65 и охлаждение на спокойном воздухе двух опытных среднеуглеродистых сталей Б1 и Б2, отличающихся схемами легирования. Представленные результаты механических испытаний показали положительное влияние повышенного легирования хромом и никелем на механические свойства и структуру.

Ключевые слова: прокатка рельсов, бейнитная сталь, отпуск, микроструктура, ударная вязкость, стойкость к образованию контактно-усталостных дефектов, сканирующая электронная микроскопия

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Introduction

As is well known [1 – 3], the service life of railway rails is influenced by numerous technological and operational factors. Among the latter, the most critical – judging by the number of rails removed due to defects or severe damage – are the resistance of rail steel to contact fatigue defects and its wear resistance. These properties, in turn, depend largely on technological parameters such as chemical composition, microstructure, mechanical properties, the level of non-metallic inclusions, and the magnitude and distribution of residual stresses.

Traditionally [4], rail steels have a high carbon content (0.6 – 0.8 wt. %) and a pearlitic microstructure. Improvements in the wear resistance of pearlitic steels have been achieved by optimizing both chemical composition and heat treatment parameters, which allow for a reduction in the interlamellar spacing of cementite plates within pearlite colonies. This refinement enhances the strength, ductility, and hardness of the steel.

In modern pearlitic rail steels, the interlamellar spacing has reached its theoretical lower limit [5], estimated at 0.06 – 0.07 μm. Therefore, further improvements in the performance of pearlitic rails appear to be nearly exhausted. A promising alternative is the production of rails from bainitic steels, which feature a finer microstructure and, as a result, offer superior mechanical properties and increased resistance to contact fatigue defect (CFD) formation.

In the late 1990s and early 2000s, with support from railways in Western Europe and the United States, several experimental bainitic steel grades suitable for manufacturing heat-treated rails were developed by metallurgical institutes and industrial enterprises [6 – 10].

Initial field trials of hot-rolled rails made from B360 bainitic steel, conducted near Frick Station in Switzerland in 1999, confirmed that this material offers significantly improved resistance to the initiation and growth of contact fatigue defects [8].

However, some bainitic rail grades have shown more intensive wear compared to the widely used heat-treated pearlitic rails. According to studies conducted by the Materials and Processing Research Center (NKK Corporation, Japan), the wear resistance of pearlitic steels is primarily determined by their hardness and microstructural characteristics. It has been concluded in [10; 11] that the high resistance of bainitic rails to contact fatigue damage is due to the gradual removal of the surface layer affected by rolling contact – a phenomenon referred to as the so-called "magic grinding effect".

These findings suggest that bainitic rails require further investigation before they can be considered a reliable alternative to heat-treated pearlitic rails [7].

Materials and research results

Studies conducted at EVRAZ United West Siberian Metallurgical Plant (EVRAZ ZSMK) between 2004 and 2006 demonstrated that a lower bainite microstructure – typically used in critical structural applications requiring high strength – can be obtained in rails made from medium-carbon steel alloyed with chromium, molybdenum, nickel, and vanadium [12; 13]. Test results for experimental rails after rolling, normalizing, and tempering confirmed the potential of using such steel to simultaneously achieve enhanced wear resistance and improved low-temperature reliability. Field testing of an experimental batch of bainitic rails produced in 2005 by the EVRAZ Novokuznetsk Metallurgical Plant using E30KhG2SAFM steel showed promising results, provided that further improvements in steel purity – specifically with respect to non-metallic inclusions – could be achieved. At the time, however, the plant did not yet have the full technical capabilities to ensure consistently high metallurgical quality and precision rolling using modern equipment. In light of increasingly stringent performance requirements for rails operating under the extremely harsh conditions of the Eastern Railway Network – characterized by prolonged exposure to very low temperatures – it has become necessary to develop a new bainitic steel composition and define a suitable production route, taking into account the current capabilities of the modernized rail manufacturing facilities.

In 2022, EVRAZ ZSMK resumed the development of bainitic rail steel production technology aimed at meeting modern operational demands. Two pilot heats with improved chemical compositions were produced. Rolling was carried out in the rail and beam shop using the plant's standard process flow, with the use of a tandem universal mill and a separate finishing stand. Complete cooling of the experimental rolled products was carried out in bundles on a cooling bed, in still air, without forced convection.

Two medium-carbon steels, provisionally designated B1 and B2, were tested. Steel B1 featured a higher content of molybdenum and silicon, while steel B2 was characterized by increased levels of chromium and nickel (Table 1). For comparison, the chemical composition of the E30KhG2SAFM bainitic steel grade produced in 2004 is also provided [13].

The chemical compositions of the experimental grades differ considerably in their silicon, chromium, nickel, and molybdenum content. Compared to E30KhG2SAFM, steel B1 has a higher silicon content and slightly elevated levels of chromium and molybdenum.

To determine the mechanical properties of the rails, tensile tests were carried out using cylindrical specimens with a diameter of 6 mm and a gauge length of 30 mm (Type III, GOST 1497–84). Impact bending tests were performed at +20 °C and –60 °C using *U*-notch specimens (Type I, GOST 9454–78), in accordance with GOST standards for impact strength. Hardness was measured both on the running surface and across the cross-section of the rail head.

The results of the mechanical tests (Table 2) show that, compared to rails made from B1 steel, rails made from B2 steel exhibit higher strength properties: yield strength is 20 % higher, and ultimate tensile strength is 9.2 % higher. However, B2 steel has a 27 % lower elongation at fracture, while the values of area reduction are similar for both steels.

At +20 °C, the impact strength values of the two steels are fairly close. However, at –60 °C, the B2 steel demonstrates a significantly higher impact strength – 48 % higher than that of B1 steel. These results indicate a positive effect of nickel on impact strength at sub-zero temperatures.

Compared to rails made from E30KhG2SAFM steel, the B1 steel rails show higher strength properties (yield strength is 9.6 % higher, and tensile strength is 10.1 % higher), although their elongation is somewhat lower (by 9.4 %) at comparable values of area reduction. It is worth noting that the impact strength of B1 steel rails is significantly higher than that of E30KhG2SAFM rails. This improvement is attributed to the higher purity of the steel in terms of trace elements and non-metallic inclusions, as well as better structural refinement achieved through processing in the universal rail rolling mill.

The hardness distribution across the cross-sections of the experimental rails is presented in Table 3.

Rails made from B2 steel generally exhibit higher hardness compared to those made from B1 steel, which is attributed to differences in the overall level of alloying. Notably high hardness was also recorded in the foot fillet regions of both steel grades. This is primarily due

Table 1. **Chemical composition of the studied steels**

Таблица 1. **Химический состав исследуемых сталей**

Steel	Chemical composition, wt. %					
	C	Mn	Si	Cr	Mo	Ni
B1	0.30 – 0.35	1.40 – 1.60	1.30 – 1.50	1.00 – 1.10	0.20 – 0.30	–
B2	0.30 – 0.35	1.40 – 1.60	0.80 – 1.10	1.30 – 1.50	–	1.00 – 1.10
E30KhG2SAFM	0.32	1.48	1.21	1.00	0.20	0.07

Table 2. **Mechanical properties of bainitic steel rails**

Таблица 2. **Механические свойства рельсов из бейнитной стали**

Steel	Tensile properties				Impact strength, *KCU*, J/cm^2	
	σ_y, N/mm^2	σ_t, N/mm^2	δ, %	ψ, %	at +20 °C	at –60 °C
B1	960 – 980	1390 – 1430	14.0 – 15.0	27 – 32	50 – 65	24 – 34
B2	1150 –1180	1510 – 1570	10.0 – 11.5	27 – 30	58 – 64	36 – 47
E30KhG2SAFM	880 – 890	1270 – 1290	15.0 – 17.0	25 – 33	32 – 37	11 – 17

N o t e . σ_y – yield strength; σ_t – tensile strength; δ – elongation at fracture; ψ – reduction of area; *KCU* – impact strength.

Table 3. **Hardness on the head rolling surface and on the cross section of the experimental rails**

Таблица 3. **Твердость на поверхности катания головки и по сечению опытных рельсов**

Steel	Hardness, HB							
	rail head					web	rail foot	
	running surface	10 mm from running surface	left fillet	right fillet	22 mm from running surface		fillet 1	fillet 2
B1	394 – 399	392 – 398	380 – 395	392 – 396	380 – 384	376 – 387	414 – 426	418 – 422
B2	444 – 462	440 – 448	454 – 458	446 – 450	418 – 421	410 – 420	508 – 520	510 – 516
E30KhG2SAFM	375	375	–	–	363	363	388	388

to the increased cooling rate in these areas, resulting from the thinner cross-sections of the rail profile. A similar hardness pattern was observed previously in rails made from E30KhG2SAFM steel.

Microstructural analysis conducted using an Olympus GX71 optical microscope revealed zones of structural heterogeneity in the rail head of B2 steel. These inhomogeneities were caused by uneven plastic deformation during rolling and appeared as alternating carbon-enriched and carbon-depleted regions. Upon cooling from rolling heat, martensitic transformation occurred in the carbon-rich zones, while bainitic structures formed in the carbon-depleted ones (Fig. 1). The combination of high strength, ductility, and toughness observed in the material is a result of this mixed microstructure. As the distance from the fillet surface increases, the proportion of bainite in the structure also grows, which is consistent with variations in the cooling rate across the rail head section.

The microstructure at the base of the B2 rail foot and in its fillets consists predominantly of martensite (Fig. 2). The formation of martensite in this region is associated with the relatively high cooling rate under still air conditions, which is intensified by the smaller cross-sectional area compared to the head.

The microstructure of the B1 rail head is shown in Fig. 3. Near the fillet surface, a partially decarburized layer is visible, along with fine polygonal ferrite grains. The microstructure is predominantly composed of lower bainite exhibiting a needle-like morphology. As the depth increases, upper bainite begins to appear. This phase has a feathery morphology, comprising alternating fragmented ferrite and cementite plates. Beyond a depth of 20 mm, the structure transitions almost entirely to upper bainite.

The microstructures of the rail foot and fillet regions are shown in Fig. 4. In the foot, both lower and upper bainite are present (Fig. 4, *a*), while the fillet areas consist mainly of lower bainite with isolated regions of martensite (Fig. 4, *b*).

According to published studies [14 – 17], the most favorable microstructure for bainitic rail steels is a combination of lower bainite and lath martensite. This is because, during the transformation of austenite into

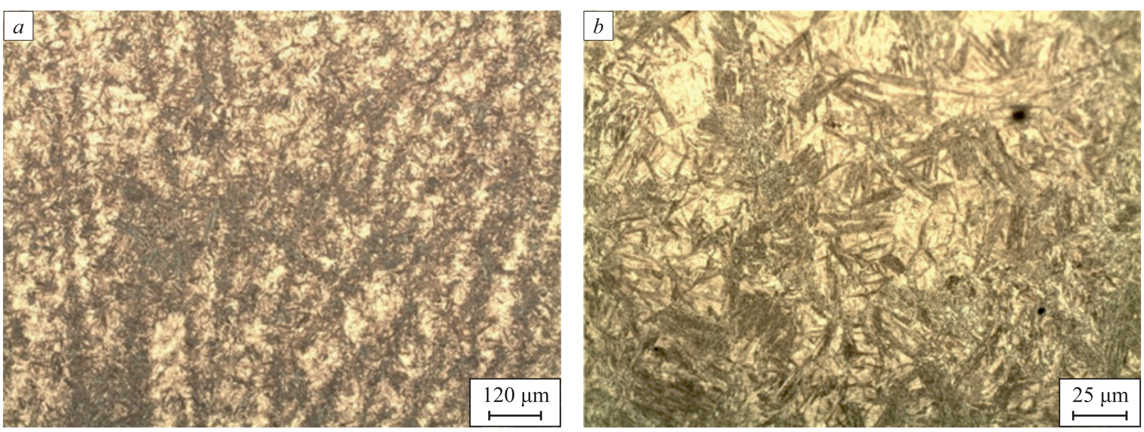

Fig. 1. Microstructure of B2 steel rail head:
a – structural heterogeneity at a depth of about 2 mm (sections of lower bainite (dark), sections of martensite (light));
b – microstructure at a depth of up to 10 mm from the head rolling surface

Рис. 1. Микроструктура головки рельса из стали Б2:
a – структурная неоднородность на глубине около 2 мм (участки бейнита нижнего (темные), участки мартенсита (светлые));
b – микроструктура на глубине до 10 мм от поверхности катания головки

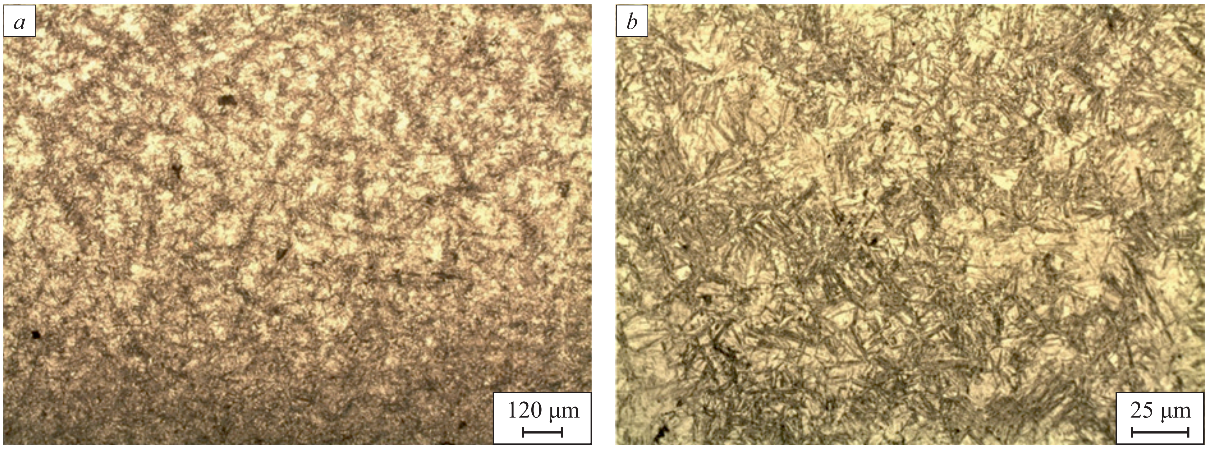

Fig. 2. Microstructure of B2 steel rail foot:
a – martensite at foot base; *b* – martensite in foot fillets

Рис. 2. Микроструктура подошвы рельса из стали Б2:
a – мартенсит в основании подошвы; *b* – мартенсит в перьях

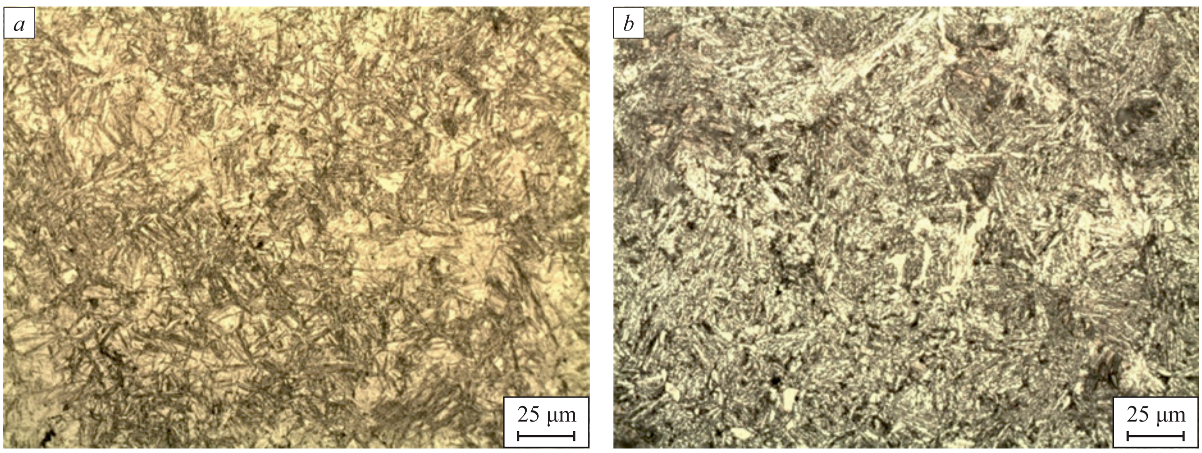

Fig. 3. Microstructure of B1 steel rail head:
a – lower bainite and small grains of polygonal ferrite near the fillet surface;
b – microstructure at a depth of about 20 mm (mainly upper bainite)

Рис. 3. Микроструктура головки рельса из стали марки Б1:
a – нижний бейнит и мелкие зерна полигонального феррита вблизи поверхности выкружки;
b – микроструктура на глубине около 20 мм (преимущественно верхний бейнит)

lower bainite, retained austenite becomes segmented into thin regions by the bainitic laths. Subsequent martensitic transformation within these confined regions leads to the formation of an extremely fine lath martensite structure. The finer the microstructure, the greater the strength and toughness of the steel. Steels with this type of mixed structure exhibit both high ductility and fracture toughness. Moreover, as contact stress increases, the wear rate of such steels rises more slowly than that of pearlitic rail steels [10; 17 – 19].

The results of the study suggest that B2 steel is suitable for the production of rails cooled in still air after rolling. To improve processability – specifically, to facilitate straightening and reduce internal microstresses – it is recommended to test a reduced carbon content of 0.28 – 0.30 %, while maintaining the levels of the other alloying elements.

Conclusions

A comparative evaluation of the hot-rolled rail steel produced from experimental compositions B1 and B2 demonstrated that increased alloying with chromium (1.2 – 1.5 %) and nickel (1.0 – 1.1 %) leads to a 20 % increase in yield strength, a 9.2 % increase in ultimate tensile strength, and a 48 % increase in impact strength at –60 °C compared to the alloying scheme based on molybdenum at 0.20 – 0.30 %.

Microstructural analysis of the rails made from both experimental steel grades revealed the formation of nee-

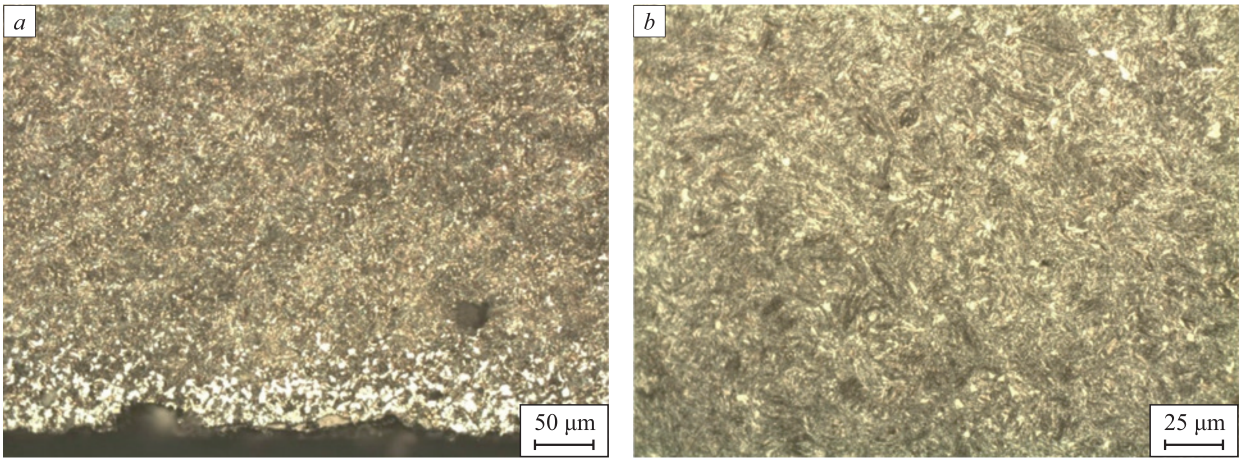

Fig. 4. Microstructure of the foot and foot fillets of rail:
a – decarbonized layer, bainite near the foot base;
b – lower bainite, areas of martensite (dark areas of needle-like structure) in the foot fillets

Рис. 4. Микроструктура подошвы и перьев рельса:
a – обезуглероженный слой, бейнит вблизи основания подошвы;
b – нижний бейнит, участки мартенсита (темные участки игольчатой структуры) в перьях

dle-like upper and lower bainite during continuous cooling in still air. In the B2 steel rails, a higher fraction of martensite was observed in the head, which contributed to increased strength and hardness.

To further develop the technology and achieve a more stable structure consisting predominantly of lower bainite, it is recommended to use B2 steel as a base composition, while reducing the carbon content to 0.25 – 0.30 %.

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G. N. Yunin – preparation of recommendations for production, organization of work on smelting and rolling of experimental rails.

T. N. Oskolkova – consulting work on preparation for production of experimental rails, assistance in the article formation.

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А. М. Юнусов – организация и контроль проведения опытной прокатки, сбор и анализ данных по этапам производства, проведение лабораторного исследования опытного металла, подготовка отчета.

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