

MANUFACTURE OF FERROUS
AND NONFERROUS METALS

Nonmetallic Inclusions in a Chromium Steel Intended for the Power Engineering Industry

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Abstract—The behavior of oxygen in the course of manufacturing large steel ingots containing 1.5–20% Cr, the formation of oxides depending on the contents of deoxidizing agents and oxygen, and the composition of the oxide phase in ingots and forgings made of the steel are considered. The steel is manufactured using an arc steel-melting furnace and unit for complex treatment of steel (ASF–ACSPU technology) and the ASF–ACSPU technology and electroslag remelting (ESR). It is shown that the oxide phase composition depends on the contents of strong deoxidizing agents and oxygen and the development of secondary oxidation. Chromium- and manganese-containing spinels are characteristic species of the secondary and tertiary oxides in the chromium steel in the case of deficient aluminum and silicon.

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INTRODUCTION

According to the market data, steels with various chromium contents (from 3.5 to more than 9%), which are most widely used in the power engineering industry, will account up to 40% of the highly alloyed products.

Chromium, which is the basic alloying element in these steels, has some characteristic features. First, it decreases the activity coefficient of oxygen [1], i.e., increases its solubility in steel ($e_O^{Cr} = -0.037$ [2], -0.039 [3], -0.040 [4, 5], -0.052 [6], and $-(0.041-0.064)$ [7]). Second, the affinity of chromium to oxygen is higher than that of iron; therefore, chromium can serve as a deoxidizer to form an oxide phase in the metal volume. Moreover, chromium is inclined to microsegregation. According to [8], the ratio of chromium contents in interdendritic regions and dendrites in a steel with up to 4% Cr (ingots from 1 kg to 2.9 t in weight solidified at rates of $10^{-2}-10^{-3}$ cm/s) is 1.5–4. Therefore, in developing a deoxidizing technology for high-chromium steels, the aforementioned peculiarities should be taken into account. The possibility of the formation of chromium oxide in steels with 1.5–2% Cr, which are widely used for rotors and rocket production, also cannot be ruled out.

The manufacturing technology of chromium steel for blanks of turbine runners, turbine disks, turbogenerator retaining rings, and other critical parts (>9% Cr) presupposes a multistage production string, which includes arc steel-melting furnace (ASF), unit for out-of-furnace treatment, casting of ingot or cast electrode in a vacuum or under protective atmosphere, and ESR

of cast electrode. At every stage, conditions for the interaction of oxygen with elements dissolved in steel, among which Fe, Cr, Mn, Si, Al, Ti, V, and Ca are present in high concentrations, are realized. The chemical affinity of these elements to oxygen can be expressed in the form of the following row: Ca, Al, Ti, V, Si, Mn, Cr, Fe. Depending of the real content, activity, and temperature, oxides differing in the composition and morphology form. They are removed partially from steel by floating and during argon blowing and ESR. Some oxides remain in the cast metal and are subjected to hot plastic deformation.

The morphology and localization of residual oxides depend substantially on deoxidation conditions and determine the manufacturing, mechanical, and service properties of metalware to a large extent.

The types and morphology of inclusions in chromium steels and conditions for the formation of one or another type of inclusions are discussed in a number of studies [9, 10]. According to the experimental data, chromium-containing inclusions differently affect the service, manufacturing, and mechanical properties of steel depending on their compositions. Therefore, taking into account the fact that, thermodynamically, the precipitation of oxides cannot be prevented, the formation of less harmful oxide compositions should be ensured.

In the present paper, we attempted to formulate recommendations for a deoxidation technology that provides the optimum parameters of the oxide phase in chromium steels intended for the power engineering industry.

Table 1. Contents of oxygen and nonmetallic inclusions and their compositions in steel melted under various manufacturing conditions

Steel	Melt	Deoxidation method	Sampling place	[O], ppm	TCNI, ppm	Oxide phase composition, %					
						Al ₂ O ₃	SiO ₂	FeO	MnO	Cr ₂ O ₃	TiO ₂
35KhN3MFA	A	VCD + Al	No data	8–18	16–23	35–56	33–47	0.3–0.8	9–12	5–10	1–3
35KhN3MFA	B	Si + Al	No data	5–18	18–27	36–75	22–55	<1	0	<0.24	<0.9
30Cr2Ni4MoV	C	VCD + Al	Top	13–36	50	43	30	6	6	1	3
30Cr2Ni4MoV			Bottom	17–26	38	34	38	6	6	2	2.5
30Cr2Ni4MoV	D	VCD + Al	Top	18–23	22	44	34	6	4	2	3
30Cr2Ni4MoV			Bottom	16–33	27	44	35	3	5	1	2

Note: VCD is vacuum carbon deoxidation and TCNI is the total content of nonmetallic inclusions.

Table 2. Contents of oxygen and nonmetallic inclusions and their compositions in steel 15Kh2NMFA [11]

Steel	Melt	Deoxidation method	Sampling place	[O], ppm	TCNI, ppm	Oxide phase composition, %					
						Al ₂ O ₃	SiO ₂	FeO	MnO	Cr ₂ O ₃	TiO ₂
15Kh2NMFA	E	Si + Al	Top	14–18	30–37	49–64	23–42	0	<2.4	<0.3	<1
15Kh2NMFA	E	Si + Al	Bottom	42–73	79–180	69–81	5–18	0	<0.8	<0.23	<1

EXPERIMENTAL

Specialists from the OAO NPO TsNIITMASH and OOO Joint Engineering Plants Special Steel experimentally studied the effect of a refinement technology on the contamination of rotor steel 35KhN3MFA with nonmetallic inclusions. The steel was cast in a vacuum. Two ingots 205 t in weight were cast. The steel for one of the ingots (heat A) was deoxidized with carbon in a vacuum and contained 0.01% Al and 0.02% Si. The steel for the other ingot (heat B) contained 0.01% Al and 0.22% Si. Table 1 shows the oxygen content, total content of nonmetallic inclusions, and their compositions in the flywheel forging metal prepared from the ingots; for comparison, analogous data for modern rotor forgings prepared from large ingots of steel 30Cr2Ni4MoV (heats C and D) are also given in Table 1. A forging made of the steel from heat C is highly defective (according to ultrasonic test data); a forging made of the steel from heat D is defect-free.

RESULTS AND DISCUSSION

The content of oxides in the forging metal from heat C is substantially higher (40–50 ppm) than that in the other forgings (20–25 ppm). The oxide phase in the forging 30Cr2Ni4MoV steel is characterized by a very high content of ferrous oxide (3–6%) as compared to that (1%) in steel 35KhN3MFA; the total contents of iron and manganese oxides in both 30Cr2Ni4MoV and 35KhN3MFA steels are almost the same (~10–12%). The (FeO + MnO) content in the forgings made of steel 35KhN3MFA, which was deoxidized with carbon in a vacuum (heat A) is 10–

13%; the (FeO + MnO) content in the forgings made of the same steel but deoxidized with aluminum and silicon (heat B) does not exceed 1%. This is likely to be related to the use of silicon, whose deoxidizing effect increases upon cooling and secondary deoxidation in the course of vacuum casting of a large ingot.

This assumption is confirmed by comparison of our data with the data obtained in studying the oxide phase in the forgings made of steel 15Kh2NMFA deoxidized with silicon and aluminum (more than 0.25% Si and 0.01% Al). Table 2 shows the data for the forgings prepared from 123-t ingots [11].

Data on the oxide compositions in the ingots prepared by heats B and E are shown to coincide completely. Thus, a silicon addition to 0.3% Si leads to a decrease in the (MnO + FeO) content in the oxide phase composition to less than 1–2%.

It should be noted that the content of oxides (30–180 ppm) in a modern ingot (heat E) is several times higher than that (18–27 ppm) in the heat B ingot. To explain this fact, it is reasonable to study the evolution of the oxide composition and the oxygen content in the course of melting and casting. Steels of these grades were subjected to out-of-furnace treatment, which includes two degassing processes to remove hydrogen (first) and to perform deep desulfurization (second). During intermediate period between the two degassing processes, slag deoxidation with aluminum chop was performed, the chemical composition of the metal was corrected, slag-making components and silicocalcium were added, and the metal was heated. In this case, the oxygen content in the metal was 0.010% after slag deoxidation, and oxides were present in the