Heat Resistance of Nickel-Manganese-Molybdenum Steel with Boron-Nitride Hardening

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Abstract. The metal of a coating made of steel N8G6M3FTB, deposited by a flux-cored wire containing boron nitride, titanium diboride and zirconium diboride, was studied. The metal was subjected to surface oxidation at a temperature of 900 ℃. It was found that the average weight gain of the metal scale of such a coating at 900 ℃ is 0.0087 kg/(m²∙h), which is 2.24 times less than that of steel 30Kh2V8F. It was revealed that the basis of metal scale, along with hematite and magnetite, are compounds with good protective properties. The results obtained show that the coating of steel N8G6M3FTB alloyed by boride compounds can be used for applying on the surface of parts operating at high temperatures.

1. Introduction

In the conditions of fierce competition in the market for rolled products, much attention is paid to its quality and production efficiency, which largely depend on the state of the metallurgical tool. Knives are one of the most worn parts of metallurgical equipment, which involves the processes of hot deformation of alloys subject to abrasive wear at elevated temperatures. The change of such a tool, mainly due to wear of the cutting edges, is a frequent and very time-consuming operation that restrains the operation of the entire mill.

Improving the tool life can be achieved by surfacing the work surfaces with wear-resistant materials [1–4]. At the same time, the resistance of such a tool at high temperatures depends not only on the metal resistance to abrasive wear, but also on the composition and structure of oxide films formed on the surface [5]. Due to its high hardness, which remains at hot working temperatures, the scale has significant abrasive properties, which enhances tool wear. The main element that increases the scale resistance of steels is chromium [6–8]. With an increase in the chromium content in iron, the onset of intense oxidation of steel shifts toward higher temperatures. High heat resistance (scaling resistance) of chromium-containing steels is due to the formation of very strong refractory chromium oxides or spinel oxides of the FeCr2O4 type on their surface [9]. Therefore, at metallurgical enterprises, knives are widely used, the cutting edge of which is deposited by steel of type 3Kh2B8. At the same time, continuous improvement of rolling production, an increase in the rolling speed and productivity of mills, and an increase in the share of rolled products from alloyed and special steels require an improvement in the properties of the tool. This is directly related to the introduction of new materials and surfacing technologies, providing an increase in the resource of a metallurgical tool subject to thermal power.
It is known that to harden a tool operating at high temperatures, it is advantageous to use composite surfacing alloys in the structure of which refractory particles of carbides, borides, and nitrides serve as hardening phases [10, 11]. From this point of view, the processes of applying wear-resistant coatings from economically alloyed martensitic-steel steels deposited by flux-cored wire containing boride compounds are finding wider application [12, 13].

Previous studies of metal deposited by flux-cored wire N8G6M3FTB found that such metal as a result of aging has a significant hardening effect and can be used for wear-resistant surfacing [14]. However, the features of oxidation of such a metal at high temperatures, containing a complex of compounds of boron nitride, titanium diborides, and zirconium, have not been studied.

In this regard, the aim of the work is to study the scale formation and changes in the structure and phase composition of steel N8G6M3FTB with boride-nitride hardening as a result of exposure to high temperatures in the air.

2. Objects and methods of research
The object of the research was cast steel of the coating deposited by flux-cored wire based on steel N8G6M3FTB alloyed with a complex of boron compounds (1.0% BN+2.5% TiB2+1.0% ZrB2). The calculated composition of the experimental cored wire is shown in table 1.

| Ni  | Mn  | Mo | FeV | FeTi | FeNb | BN  | TiB2 | ZrB2 | Na2SiF6 | Fe  |
|-----|-----|----|-----|------|------|-----|------|------|--------|-----|
| 8.5 | 6   | 3.5| 3.0 | 5.2  | 3.3  | 1.0 | 2.5  | 1.0  | 0.3     | 9.0 |

For comparison, the metal obtained by surfacing of 30Kh2V8F chrome-tungsten steel was widely used for the manufacture of a hot metal deformation technological tool.

Tests of the experimental composition of the coating metal for scale resistance (heat resistance) were carried out in a calm air atmosphere according to GOST 6130-71 [15]. An increase in the mass of samples at a temperature of 900 ℃ during a test period of 25 hours was chosen as a characteristic of scale resistance.

Metallographic studies of oxidized samples were carried out on a JEOL JCM – 5700 scanning electron microscope with a JED-2300 energy dispersive spectrometer.

X-ray phase analysis of oxidation products was carried out on a Shimadzu XRD-7000 multifunctional X-ray diffractometer. To process and analyze diffraction spectra, the Match! Software package version 3.8.1.151 was used.

3. Results of the experiments and discussion
The change in the mass gain of the metal deposited by N8G6M3FTB flux-cored wire alloyed with boride compounds and the metal deposited by 30Kh2V8F wire depending on the exposure time in an oxidizing atmosphere is shown in figure 1.

The graph shows a jump in the increase in the mass of scale on the surface of the metal N8G6M3FTB allowed with boride compounds occurs during the first hour. Over the next four hours, the increase in the mass of scale is negligible. After five hours of testing, the growth rate of scale increases, but to a much lesser extent than in the first hour of testing, and in the future this dependence is almost straightforward. So, if in 1 hour of testing the increase in the mass of scale was about 0.0389 kg/m², then in 5 hours it was only 0.0636 kg/m², and after 25 hours only 0.2166 kg/m². The thickness of the scale after 1 hour of testing at 900 ℃ is only 32.36...36.71 microns, and after 5 hours –55.69...65.50 microns. When a sample of metal N8G6M3FTB alloyed with boride compounds is cooled after the last 25 hours of testing, partial detachment of the scale from the surface occurs due to internal stresses. The thickness of the remaining part of the scale is 55.32...73.34 microns.
Figure 1. Change in the mass gain $\Delta m$ of the metal N8G6M3FTB with borides and 30Kh2V8F from the exposure time at 900 °C.

The scale formation indices of steel 30Kh2V8F are significantly worse than the metal N8G6M3FTB alloyed with boride compounds. So if in 1 hour of testing the increase in the mass of scale was only about 0.0397 kg/m$^2$, in 5 hours it already amounted to 0.0986 kg/m$^2$, and after 25 hours it was 0.4858 kg/m$^2$. The thickness of the scale after 1 hour of testing at 900 °C is 44.17...52.29 microns, and after 5 hours - 70.07...81.17 microns. On the surface of a sample of 30Kh2V8F steel of the past 25 hours, the thickness of the oxide layer has increased significantly and is already 491.67...519.37 microns.

To identify the causes of increased scale resistance of the metal deposited by flux-cored wire N8G6M3FTB alloyed with boride compounds, the structure and phase composition of the deposited metal and scale were studied.

The microstructure of the thin section of the lateral surface of the N8G6M3FTB metal alloyed by boride compounds with a scale obtained after holding for 25 hours with the location of the scan points is shown in figure 2.

Figure 2. The lateral surface of a thin section of a metal of composition N8G6M3FTB alloyed by boride compounds with an oxide layer after a scale test at 900 °C - 25 hours with the location of the scan areas at points.

The figure shows that the structure of the scale consists of separate layers: the outer light and the inner darker. Almost uniform oxidation of the metal surface occurs, since a line of contact between the metal and the scale is traced. The interface is not perfectly flat. Roughnesses and gradations are observed due to different rates of phase formation reactions. Since the rates of chemical reactions at the phase boundary are quite high, their growth is completely determined by
the supply of atoms to the phase boundary due to diffusion. Therefore, the dimensions of each phase depend on the diffusion coefficients, the relationship between them, and also on the concentrations of elements at its boundaries [16–19].

The chemical composition of the scanned areas is presented in table 2.

Table 2. The chemical composition of the scanned metal regions of the composition N8G6M3FTB alloyed by boride compounds after a scale test at 900 °C - 25 hours.

| Point №* | N  | O  | V  | Ti | Mn | Fe  | Ni  | Zr  | Nb  | Mo  |
|----------|----|----|----|----|----|-----|-----|-----|-----|-----|
| 1        | 0  | 0  | 4.17 | 4.33 | 5.97 | 68.99 | 10.99 | 0.25 | 1.19 | 4.11 |
| 2        | 0  | 0  | 7.75 | 2.79 | 3.96 | 57.78 | 7.37 | 2.75 | 9.55 | 8.05 |
| 3        | 0.37 | 1.57 | 5.96 | 4.29 | 3.45 | 64.00 | 10.95 | 0.36 | 5.19 | 3.86 |
| 4        | 9.75 | 11.76 | 5.07 | 3.92 | 2.58 | 34.12 | 12.17 | 1.15 | 2.8  | 16.68 |
| 5        | 4.52 | 6.36 | 3.85 | 2.19 | 1.24 | 16.02 | 8.54 | 2.93 | 3.54 | 50.81 |
| 6        | 14.23 | 17.18 | 2.12 | 1.9  | 3.44 | 51.22 | 2.98 | 1.53 | 4.18 | 1.22 |

*Scan points 1, 2 correspond to the base metal; point 3 of the transition zone and points 4, 5, 6 of the scale.

The results of chemical analysis show that the concentration of the main alloying elements Nb, Mo, V, Zr in the metal increases as it approaches the transition layer (points 1, 2), and the concentration of Ni, Ti, and Mn decreases slightly. In the transition layer (point 3) there is a high concentration of Ni, Nb, Mo, V, Ti, and oxygen and nitrogen appear. Approaching the scale surface (points 4, 5), the concentration of Mo and Zr increases, and the concentrations of Mn, Ti, V, Nb, Ni decrease. Directly at the surface (point 6), all the main alloying elements are observed, and the concentrations of oxygen and nitrogen are maximum.

The results obtained indicate the formation of a weak chemical microinhomogeneity in the deposited coating. The high concentration of the main alloying elements is due to their low activity in diffusion processes when exposed to high temperatures [20].

The typical structure of the outer surface portion of the scale with the location of the scan points is shown in figure 3. The chemical composition of the scanned objects is shown in table 3.

Figure 3. The surface of the oxide layer of a metal of composition N8G6M3FTB alloyed by boride compounds after a scale test at 900 °C - 25 hours with the location of the scan areas at points

It is seen that the surface layer of the scale is a chaotic mixture of rather densely packed particles of rounded shape with sizes up to 5 microns. All particles contain oxygen and nitrogen. Most particles contain all major alloying elements. However, there are particles that do not contain either Zr, or Mo, or Nb, or all of these elements (points 1, 4, 7, 10, 11, 14, 15, 16).

An X-ray analysis of a metal of the composition N8G6M3FTB alloyed with boride compounds after holding it for 25 hours at a temperature of 900 °C showed that the scale consists not only of the oxide phase, but also of the remnants of non-oxidized grains of solid solution and nitrides, borides and intermetallides. The scale base along with hematite Fe2O3, magnetite Fe3O4 and MnO are various
compounds of the main alloying elements such as NbB2, Fe3C0.279N1.116, Ni0.6V0.4, Ni0.906Ti0.094, BN, V4O7, ZrN, TiC, ZrO2, NbBO4, Fe3C.

Table 3. The chemical composition of the scanned areas of the surface of the oxide layer of the metal with the composition N8G6M3FTB alloyed by boride compounds after a scale test at 900 ℃ - 25 hours.

| Point № | N  | O  | V  | Ti | Mn | Fe  | Ni  | Zr  | Nb  | Mo |
|---------|----|----|----|----|----|-----|-----|-----|-----|----|
| 1       | 17.23 | 21.95 | 3.31 | 1.21 | 9.51 | 43.66 | 0.02 | 0.98 | 2.13 | 0  |
| 2       | 11.65 | 11.88 | 4.05 | 0.91 | 9.06 | 58.71 | 0.84 | 0.85 | 1.54 | 0.51 |
| 3       | 0.7   | 1.12 | 2.26 | 0.96 | 11.42 | 80.71 | 2.74 | 0   | 0   | 0.09 |
| 4       | 7.5   | 9.19 | 3.25 | 1.38 | 10.45 | 63.33 | 0.41 | 1.57 | 2.92 | 0  |
| 5       | 12.55 | 16.4 | 3.28 | 1.33 | 9.36  | 51.03 | 0.84 | 1.97 | 1.96 | 1.28 |
| 6       | 10.75 | 14.05 | 3.44 | 1.54 | 9.13  | 55.81 | 0.09 | 0.18 | 2.62 | 2.39 |
| 7       | 7.74  | 9.59 | 5.17 | 2.17 | 9.25  | 64.54 | 0.46 | 0.53 | 0.55 | 0  |
| 8       | 13.51 | 17.81 | 3.11 | 1.04 | 8.09  | 47.23 | 2.39 | 1.43 | 3.52 | 1.87 |
| 9       | 16.67 | 21.63 | 2.68 | 0.84 | 8.72  | 44.36 | 0.21 | 1.96 | 2.49 | 0.44 |
| 10      | 15.52 | 19.03 | 2.22 | 0.91 | 13.77 | 47.25 | 0.79 | 0   | 0.51 | 0  |
| 11      | 8.71  | 11.41 | 2.99 | 1.31 | 12.97 | 61.4 | 1.21 | 0   | 0   | 0  |
| 12      | 11.72 | 14.44 | 2.74 | 1.14 | 14.43 | 48.85 | 0.6  | 2.02 | 2.89 | 1.17 |
| 13      | 6.38  | 8.1  | 3.79 | 1.63 | 10.11 | 66.49 | 0.48 | 0.56 | 1.47 | 0.99 |
| 14      | 1.59  | 1.57 | 3.95 | 1.43 | 10.98 | 79.82 | 0.66 | 0   | 0   | 0  |
| 15      | 3.15  | 3.4  | 4.54 | 2.04 | 11.03 | 73.87 | 0.77 | 0   | 1.2  | 0  |
| 16      | 0.51  | 0.66 | 5.97 | 2.09 | 11.39 | 78.52 | 0.86 | 0   | 0   | 0  |

Thus, the presence of compounds with high protective properties in the scale composition determines the increased heat resistance of the deposited metal. The increase in the mass of the scale of such a metal is 2.24 times less than that of the metal deposited by 30Kh2B8F wire. The results show that metal deposited by a flux-cored wire PPN8G6M3FTB alloyed with a complex of boron compounds (1.0% BN+2.5% TiB2+1.0% ZrB2) can be used to apply wear-resistant coatings to tools operating at high temperatures.

4. Conclusion

The coating of steel N8G6M3FTB with boride-nitride hardening is subject to slight surface oxidation. The average weight gain of the metal scale of such a coating at 900 ℃ is 0.0087 kg/(m²∙h). Such a coating can be used for applying on the surface of parts operating under conditions of abrasive wear at high temperatures up to 900 ℃.

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