Wear resistance of steel obtained by surfacing a flux-cored wire 30N8Kh6M3STYu

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Abstract. The wear resistance of steel 30N8Kh6M3STYu as a result of surfacing by flux-cored wire was investigated. It was found that the average value of the relative mass wear of such a metal is 0.0002818 g/m, and the average value of the linear wear is 0.0006194 mm/m. The average value of the coefficient of friction after running in increased from 0.192 to 0.211, and the average value for the test was 0.207. The microhardness of the matrix of such a metal as a result of aging is in the range of 639–683 HV, the microhardness of the eutectic is 650–786 HV and the hardening phase is in the range of 783–882 HV. It has been shown that the steel hardening mechanism of such a system is determined by the compounds of carbides, for the most part, TiMo0.707C0.5, Cr3C2, and a small amount of TiC, SiC, intermetallic compounds, mostly Cr0.92Mo3.08, Fe0.875Mo0.125, Fe2Ti, and a small amount of Mo0.984Ni0.016, Ti3Al, Ni3Ti, and Fe24N10 nitride formed as a result of aging. The established complex of dispersed phases precipitated after aging determines the wear resistance of such steel. The flux-cored wire created on the basis of 30N8Kh6M3STYu steel can be used for surfacing parts working under friction of metal on metal.

1. Introduction
The competitiveness of industrial enterprises is largely determined by the duration of the production equipment. The effectiveness of using such equipment depends on technological interruptions, and scheduled and emergency repairs. Parts subject to wear usually have a short period of operation, which determines the total life of the equipment. These parts include shafts for various purposes, working in conditions of friction of metal on metal.

A promising way to increase the service life of such parts is to apply wear-resistant coatings of maraging steel on their working surfaces, including those deposited by flux-cored wire [1-4]. They have high strength, ductility and good adaptability, which makes them a promising structural material for the technology of the present and the future [5-8].

Basically, information on maraging steels refers to high alloy steel containing nickel, cobalt and molybdenum of the system Fe– (8-18%) Ni – (5-10%) Co – (3-8%) Mo– (0.5-4 %) Ti– (0.2-2.5%) Al [5, 6]. The high percentage of expensive and scarce alloying elements in such steels limits the possibility of their widespread use.

Currently, the most widely used are economically alloyed steels with the effect of secondary hardening related to precipitation hardening alloys. The main alloying system for such steels is Fe – Ni – Cr [9, 10]. With a content of 5–14% Ni and 5–9% Cr in such steels, a pure martensitic structure is obtained. To reduce the critical temperatures of the onset of martensitic transformation in steels with a Ni and Cr content at a lower level, as well as to increase the strength of martensite after quenching, it is advisable to use C [11, 12]. At a concentration of C in the range of 0.25-0.3%, it is possible to apply
the effect of intermetallic and carbide hardening, for which molybdenum is used in most cases [5, 6, 9, 11, 12]. At the same time, such steels have a low degree of hardening and, as a result, low indicators of wear resistance [9]. Therefore, they can find application mainly for the manufacture of parts and assemblies operating in conditions of moderate wear.

A higher hardening effect of steels can be achieved by creating various dispersed intermediate phases. The effectiveness of hardening by such phases is determined by the composition and structure of the released particles, size, nature of distribution in the matrix, interaction with it, and the effect of precipitates on the structure [11, 12]. These factors determine the higher service properties of steel. The effective phases causing significant hardening include carbides, titanium and aluminum nitrides, and complex compounds based on them [5-7, 9, 11].

At the same time, it is known that to increase the wear resistance of such steel by increasing the hardening effect, it is possible with the additional introduction of Si in its composition. Silicon can significantly reduce the solubility in martensite of Ti, Mo and Al, forming ultrafine reinforcing particles. Strengthening the effect of secondary hardening of steel can be achieved with the introduction of Si in its composition up to 2.0% [13].

In this regard, the aim of the work is to study the structure, durometric properties, phase composition and wear resistance of steel of the Fe-(0.27-0.33%)C-(7.5-8.5%)Ni-(5.5-6.5%)Cr-(2.8-3.2%)Mo-(0.8-1.4%)Si-(0.8-1.2%)Ti-(0.7-1.0%)Al system in the state after aging.

2. Results of the experiments and discussion

The results of chemical analysis of the studied metal 30N8Kh6M3STYu obtained by surfacing an experimental flux-cored wire are shown in Table 1.

|   | C   | N  | Ni  | Mn  | Cr  | Mo  | Si  | Ti  | Al  | S  | P  | Fe   |
|---|-----|----|-----|-----|-----|-----|-----|-----|-----|----|----|------|
|   | 0.3238 | 0.0093 | 8.12 | 0.17 | 6.34 | 3.08 | 1.34 | 1.08 | 0.80 | 0.0156 | 0.0127 | remain |

It was established that the hardness of such a metal after surfacing is in the range of 45-47 HRC. The test results for the wear of the metal obtained by surfacing PP30N8Kh6M3STYu after aging are shown in Table 2.

| Friction path S, m | Average value | Relative wear, g/m | Average value | Relative wear, mm/m |
|-------------------|---------------|-------------------|---------------|-------------------|
| 0-113             | 0.0020        | 0.0000179         | 0             | 0                 |
| 113-226           | 0.0063        | 0.0000557         | 0.003         | 0.0000295        |
| 226-339           | 0.0463        | 0.0004103         | 0.070         | 0.0006195        |
| 339-452           | 0.0379        | 0.0003354         | 0.096         | 0.0008554        |
| 452-565           | 0.0401        | 0.0003551         | 0.083         | 0.0007374        |
| 565-678           | 0.0375        | 0.0003324         | 0.090         | 0.0007964        |
| 678-791           | 0.0432        | 0.0003823         | 0.106         | 0.0009439        |
| 791-904           | 0.0336        | 0.0002976         | 0.080         | 0.0007079        |
| 904-1017          | 0.0361        | 0.0003197         | 0.080         | 0.0007079        |
| 1017-1130         | 0.0352        | 0.0003115         | 0.090         | 0.0007964        |
| 0-1130            | 0.3182        | 0.0002818         | 0.698         | 0.0006194        |
The average mass wear of the samples for the friction path of 113 m (after 300 revolutions) is 0.0020 g. For the friction path of 1130 m (after 3000 revolutions) the mass wear is already 0.3182 g, while the wear along the length reaches 0.698 mm. The average value mass wear per test was 0.0002818 g/m. The average value linear wear per test was 0.0006194 mm/m (Table 2).

Figure 1 shows the dependence of the friction moment on the friction path.

![Figure 1](image1.png)

**Figure 1.** The values of the friction moment of the specimen deposited by PP30N8Kh6M3STYu from the friction path

The dependence shows a gradual change in the moment of friction. At the running-in stage, to the friction path of 169 m, a sharp rise in the oscillating curve to 38.71 N·m is observed. Subsequently, the average values of the friction moment are stabilized in the range of 29-39 N·m. The maximum value at which a critical level of elastic strain energy of 51.73 N·m is reached, at the end of the friction path at 942 m is observed. Decreases in the values of the friction moment to 9-10 N·m, which corresponds to the minimum wear rate at a friction path of 979 m is observed. The average value of the friction moment slightly increases from 27.91 N·m for the friction path of 207 m to 29.72 N·m with the friction path of 1130 m. The average value of the friction moment for the entire friction path of 1130 m was 26.59 N·m.

The change in the values of the clamping force of the sample is shown in Figure 2.

![Figure 2](image2.png)

**Figure 2.** The values of the clamping force of the specimen deposited by PP30N8Kh6M3STYu from the friction path
As seen, the average value of the clamping force during the test falls slightly from 0.790 kN to 0.766 kN, although there are two stages in the middle of the friction path, when the clamping force increases to 0.842-0.851 kN.

The values of the friction coefficient of the metal deposited by PP30N8Kh6M3STYu, depending on the friction path, are shown in Figure 3. Fluctuations in the curve of the friction coefficient are caused by the action of particles of the destroyed layer and the repetition of adhesion-detachment cycles by contacting samples. The average value of the coefficient of friction after running-in increased from 0.192 (for the friction path 565 m) to 0.211 (for the friction path 1130 m), and the average value for the test was 0.207.

![Figure 3. The coefficient of friction of the metal deposited by PP30N8Kh6M3STYu from the friction path](image)

Durometric studies of such a metal found that the microhardness of the matrix is in the range of 639-683 HV, the microhardness of the eutectic is 650-786 HV and of the hardening phases in the range of 783-882 HV.

The results of the X-ray phase analysis of this metal after aging are shown in Figure 4. The results of the interpretation of the metal diffractogram are summarized in Table 3.

![Figure 4. The diffractogram of the deposited metal by PP30N8Kh6M3STYu after aging](image)
The basis of the matrix of the coating metal after heat treatment is martensite. This structure consists of 14 main kinds of compounds of phase components. In it, carbide particles are present, for the most part, TiMo$_{0.70}$C$_{0.5}$, as well as a small amount of Cr$_3$C$_2$, and a very small amount of SiC, TiC. Another group of compounds are intermetallic compounds. This is mostly Cr$_{0.92}$Mo$_{3.08}$, Fe$_{24}$N$_{10}$, Fe$_{2}$Ti, as well as a small amount of Mo$_{0.98}$Ni$_{0.016}$, Ti$_3$Al, Ni$_3$Ti, and a very small amount of FeCr, FeAl, NiTi$_2$. A small amount of Fe$_{24}$N$_{10}$ nitride is observed in the structure.

The results obtained show that a feature of the transformation of the structure of the metal of the 30N8Kh6M3STYu coating as a result of heat treatment is the appearance in the structure of four carbides with the participation of Fe, Cr, Mo, Si, Ti, Ni, nine intermetallic phases with the participation of Fe, Cr, Ni, Ti, Mo, Al, and iron nitride Fe$_{2}$N$_{10}$, instead of iron carbide Fe$_2$C$_2$ and five intermetallic phases with the participation of Fe, Ni, Ti, Si, Mo in the metal structure after surfacing.

A typical micro-region of the fine metal structure obtained by transmission electron microscopy is shown in Figure 5. As can be seen, the predominant precipitates in the martensitic matrix are FeCr compounds (Fig. 6, a) of considerable length, surrounded on all sides by Ti$_3$Al intermetallic particles (Fig. 6, b). In addition, large particles of complex carbide TiMo$_{0.70}$C$_{0.5}$ (Fig. 6, c) and intermetallic

| №   | Phase designation and card number | Peak intensity | Type of grid | Grid parameters |
|-----|----------------------------------|---------------|--------------|-----------------|
| 1   | Fe (96-901-3474)                 | S.            | cubic        | a = 2.8730 Å    |
| 2   | Fe$_{0.63}$Si$_{0.27}$Cr$_{0.1}$  | Av.           | cubic        | a = 2.8720 Å    |
| 3   | Cr$_0.8$Ni$_{0.2}$ (96-152-5377) | Av.           | cubic        | a = 2.8730 Å    |
| 4   | TiMo$_{0.70}$C$_{0.5}$ (96-153-2051) | S.              | trigonal (hexagonal axes) | a = 3.0821 Å, c = 5.0405 Å |
| 5   | Cr$_3$C$_2$ (96-591-0109)        | Av.           | orthorhombic | a = 2.8200 Å, b = 5.5200 Å, c = 11.4600 Å |
| 6   | Cr$_{0.92}$Mo$_{3.08}$ (96-153-8537) | Av.              | trigonal (hexagonal axes) | a = 2.9820 Å, c = 28.8100 Å |
| 7   | Fe$_{24}$N$_{10}$ (96-231-0872)  | Av.           | trigonal (hexagonal axes) | a = 9.2150 Å, c = 4.3440 Å |
| 8   | Fe$_{0.875}$Mo$_{0.125}$ (96-231-0291) | Av.              | cubic        | a = 2.9098 Å, c = 2.9099 Å |
| 9   | Fe$_2$Ti (96-231-0985)           | Av.           | hexagonal    | a = 3.1930 Å, c = 4.2670 Å |
| 10  | Mo$_{0.984}$Ni$_{0.016}$ (96-152-3377) | L.                | cubic        | a = 3.1441 Å, c = 3.14528 Å |
| 11  | Ti$_3$Al (96-153-2768)           | L.            | hexagonal    | a = 5.77640 Å, c = 4.6640 Å |
| 12  | TiC (96-153-9506)                | L.            | cubic        | a = 4.3500 Å, c = 4.34847 Å |
| 13  | Ni$_3$Ti (96-101-0453)          | L.            | hexagonal    | a = 5.0960 Å, c = 8.3040 Å |
| 14  | NiTi$_2$ (96-152-7849)          | V.L.          | cubic        | a = 11.3193 Å, c = 11.3164 Å |
| 15  | FeCr (96-152-4008)              | V.L.          | cubic        | a = 2.9000 Å, c = 2.90020 Å |
| 16  | FeAl (96-154-1194)              | V.L.          | cubic        | a = 2.9100 Å, c = 2.90971 Å |
| 17  | SiC (96-101-1032)               | V.L.          | cubic        | a = 4.3580 Å, c = 4.35754 Å |
Cr$_{0.92}$Mo$_{3.08}$ (Fig. 6, d) are observed. The established complex of these phases that precipitated as a result of aging determines to a greater extent the wear resistance of such steel.

![Figure 5](image-url)  
**Figure 5.** General view of the characteristic micro-region of the fine structure of the deposited metal

![Figure 6](image-url)  
**Figure 6.** The main reflections from microdiffraction of the regions of the fine structure of the deposited metal (see Fig. 5): a) region 1 – FeCr phase; b) region 2 – phase Ti$_3$Al; c) region 3 – phase TiMo$_{0.707}$C$_{0.5}$; d) region 4 – phase Cr$_{0.92}$Mo$_{3.08}$
3. Conclusion

1. The wear mechanism of the metal obtained by surfacing a 30N8Kh6M3STYu flux-cored wire is largely due to the presence of a martensitic matrix hardened by carbide and intermetallic compounds, which determine the level of wear resistance of the deposited such metal.

2. The flux-cored wire created on the basis of 30N8Kh6M3STYu steel can be used for surfacing parts working by friction of metal on metal.

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Acknowledgments

This research was made possible through the Russian Science Foundation grant (project №17-19-01224).