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EFFECT OF SUPERSONIC ARC SPRAYING WITH CORED WIRES ON WEAR RESISTANCE OF COATINGS

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Abstract: This study investigates the abrasive wear resistance of supersonic electric arc coatings made from cored wires (CW) of the Fe-Cr-Si-Mn-B-C alloying system. Results indicate that increasing the chromium content in the CW charge from 6 to 17 wt.% enhances the wear resistance of the coatings in both subsonic and supersonic spraying modes. Additionally, incorporating up to 2% boron significantly boosts wear resistance. Supersonic spraying increased coating wear resistance by 20-70%. Coatings produced via supersonic spraying showed wear resistance twice that of high-carbon hardened U12 steel (hardness: 840 $HV_{0.3}$), which is used as a standard for comparison.

Keywords: electric arc coatings, supersonic spraying, wear resistance.

1. INTRODUCTION

Plasma-electrolyte oxidation is effective for increasing the service life of parts operating under conditions of wear and corrosion [1, 2]. However, this method is quite expensive. At the same time, various parts with shaft geometries, such as crankshafts, camshafts, piston fingers, spools, variators, rotors, covers of electric motors, straw shakers, and a wide variety of cylindrical parts, typically operate under challenging conditions where contact with abrasive particles is unavoidable. Consequently, these parts wear out quickly, making it impossible to further operate the units in which they are used. These parts are usually complex and expensive, and replacing them with new ones significantly increases the cost of production. In modern conditions, the cost of restoring parts depends on their structural complexity, technological processing features, and the geometry of the defects present. Typically, the cost of repair reaches 5–30% of the cost of new parts [3, 4].

Among the known gas-thermal methods, the arc spray method (ASM) of spraying coatings is considered the simplest and most cost-effective. It does not require expensive equipment or highly qualified personnel and is therefore easily implemented in production. A significant disadvantage of ASM is the limited range of modern electrode materials. However, the use of cored wires (CW) as electrode materials for ASM has significantly expanded its scope [5–8]. Coatings applied by ASM are 3 to 10 times cheaper than those applied by other gas-thermal methods (gas-flame, HVOF, HVAF, detonation, and plasma). Nevertheless, their low adhesion, cohesion, and high residual tensile stresses prevent their application in harsh conditions involving high working loads.

In current scientific research, efforts to increase the kinetic energy of sprayed droplets of molten metal forming the coating have led to the development of the supersonic method of electric arc spraying using inert or combustible gases [9–15]. This approach significantly complicates the design of electric arc

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spraying devices and increases the cost of the coating process. Furthermore, it does not substantially reduce the amount of oxides in the sprayed layer and only selectively enhances the physical and mechanical characteristics of the coatings.

Recently, a cost-effective method of producing supersonic electric arc coatings from CW using a Laval nozzle has been employed [16]. This method increases the pressure of the spraying air jet, thereby enhancing the kinetic energy of the molten droplets impacting the surface of the sprayed part without the use of inert or combustible gases. This improvement is essential for achieving a significant increase in hardness, adhesive, and cohesive strength of coatings while simultaneously reducing their porosity and residual tensile stresses. Such a comprehensive enhancement of the physical and mechanical characteristics of coatings will reduce the likelihood of micro-cracks forming both during mechanical processing and further operation.

The aim of this work is to demonstrate the potential for increasing the wear resistance of arc spray coatings (ASC) by using a supersonic air jet for electric arc spraying of flux-cored wires, and to rank the results based on the composition of the CWs.

2. METHODS AND MATERIALS

The method used is ultrasonic spraying of electric arc coatings. Laval nozzles with two symmetrical air channels (Fig. 1) [14] were utilized for supersonic electric arc spraying of CW coatings in the electro metallizer. A supersonic air jet with a Mach number of 2 was achieved. The air jet pressure increased from 0.6 to 1.2 MPa, doubling the air jet speed from 300 to 600 m/s. During the spraying of CW, the speed of dispersed droplets of melt increased from 60–90 to 160–220 m/s. After metal deposition, the coating was grinding.

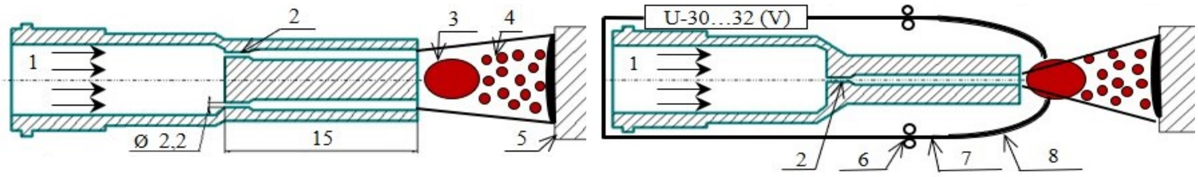


Figure 1. Schemes of the metallizer nozzle for the formation of supersonic air flow (front (*a*) and top (*b*) views, respectively): 1 – air flow, 2 – critical section of the nozzle, 3 – melting of electrode materials, 4 – metal-air flow, 5 – steel substrate with a coating sprayed on the surface, 6 – wires, 7 – guides for feeding electrodes to the arc burning zone, 8 – rollers for moving the wire.

Cored wires with a diameter of 1.8 mm consisted of a shell of ductile steel (with a carbon content of 0.08 wt.%), filled with different powder particles. A strip 0.4 mm thick and 10 mm wide was used to produce the CW shell (Fig. 2). Various ferroalloys (ferrochrome, ferromanganese, ferrosilicon), boron carbide, and pure chromium and iron powders were used as CW charge materials. The charge filling coefficient of the CW was 25%.

We analyzed the properties of coatings sprayed with CW of the following compositions: 90Cr6MnSi, 90Cr17MnSi, 90Cr6BMnSi, 90X10BMnSi, 90Cr17BMnSi, 90Cr6B2MnSi, 90Cr10B2MnSi, 90Cr17B2MnSi, Cr10B2MoTi, 90Cr10B2MoTiVNi, 60CrB3Al6, 60Cr20B3Ti, 200Cr10Nb3MoB, and 200Cr10Nb5MoB. The CW batch was formulated to contain 0.9 to 2.0 wt.% carbon, believed to ensure optimal physical and mechanical characteristics of the sprayed coating. To ensure the coating's microhardness ranged between 500 to 1100 $HV_{0.3}$, important for restoring both lightly and heavily loaded parts, the boron content in the CW charge was varied from 0 to 3 wt.%. For ASC on parts operating in neutral and corrosive environments, the chromium content in CW was adjusted between 6 to 20 wt.%.

An abrasive wear resistance test with a fixed abrasive was carried out using an abrasive disk (Fig. 3) with a diameter of 150 mm and a width of 8 mm made of electro corundum with a grain size of 250–315 µm. The disk rotation frequency was 160 rpm, and the load around the linear contact was 15 N. During the tests, the specimens were in contact with the disk for 1800 m. The degree of wear was assessed by the weight loss of each specimen at the end of the wear test using a KERN ABJ 220 4M electronic scale with a weighing accuracy of 2×10^{-4} g. Abrasive wear resistance ($1/\Delta W$) of coatings was determined by the average mass loss (ΔW) of at least three samples tested for wear in contact with an electro corundum disk (fixed abrasive test mode). ΔW was calculated from the difference in the samples' mass before and after testing.

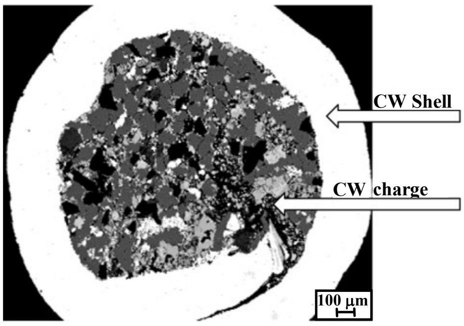


Figure 2. Cross section of powder wire.

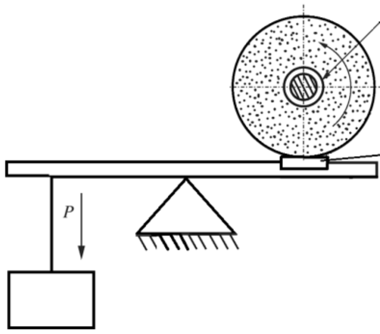


Figure 3. Scheme of the setup for studying the abrasive wear resistance of ASCs in contact with a rigidly fixed abrasive: *1* – specimen; *2* – abrasive corundum wheel; *P* – load.

3. RESULTS AND DISCUSSION

3.1. Structure of CW Coatings

Carbon from the molten powder wire droplets burns out during arc spraying of coatings. The carbon content in the coating depend on the spraying mode, namely: arc voltage, spraying distance, and air jet pressure. A semi-quantitative assessment of the content of C, Ti, and Al in the coating was determined by formula (1) proposed by Prof. M.M. Student:

$$C_{ASC} = C_{carbides} \cdot 0.8 \cdot \left(1 - \frac{L-50}{500}\right) \cdot \left(1 - \frac{U-28}{100}\right) \cdot \left(1 - \frac{P-4}{15}\right) \quad (1)$$

where C_{ASC} – is the real carbon content in the coating (wt.%), $C_{carbides}$ – is the carbon content in carbides added to the PW charge (wt.%), L – is the spraying distance (mm), U – is the arc voltage (V), and P – is the sputtering air pressure (1–10 MPa).

Using the example of a CW 90Cr6MnSi coating, the effect of air jet pressure (Fig. 4.a), arc voltage (Fig. 4.b), and spraying distance (Fig. 4.c) on the carbon content of the C_{ASC} coating was established. Depending on the sputtering mode used, only 0.52 to 0.73 wt.% of carbon remained in the coating structure from the available 1.05 wt.% in CW.

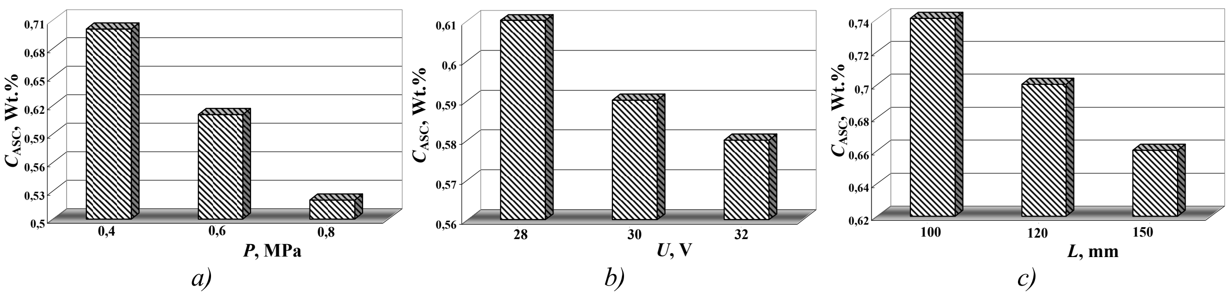


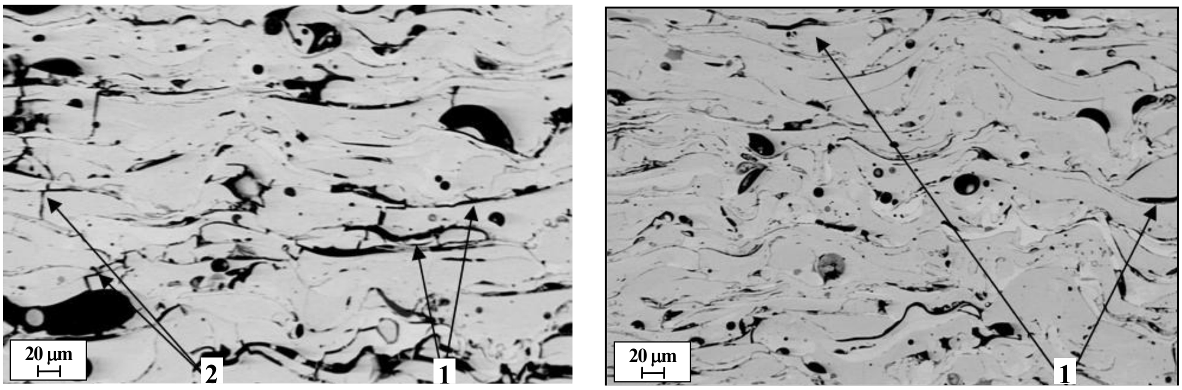
Figure 4. Influence of parameters of the spraying mode (air pressure *P* (*a*), arc voltage *U* (*b*) and spraying distance *L* (*c*)) on the carbon content of C_{ASC} in the coating sprayed with CW 90Cr6MnSi.

Changing the spraying distance had minimal impact on the boron content in ASC. However, using a higher pressure for the spraying air flow slightly reduced the oxygen content in the coatings (Table 1). This was explained by the alloying of CW melt droplets with chromium and a reduction in oxidation duration due to an increased flight speed to the substrate. The presence of boron in the molten droplets further reduced the oxygen content in the ASC structure. For instance, the oxygen content in the CW 90Cr17MnSi coating sprayed at an air pressure of 1.2 MPa was 6.5 wt.%, while in CW 90Cr17B2MnSi, it was 2.3 wt.%, a decrease compared to coatings sprayed at 0.6 MPa. Conversely, for the coating sprayed with electrodes from unalloyed high-carbon steel U12, increased air pressure led to a significant (over 70%) rise in oxygen content in the ASC structure (Table 1).

Table 1. Oxygen content into coatings depending on the air flow pressure during spraying process

No	Cored wires type	Air flow pressure, MPa	
		0.6	1.2
		The oxygen content in the coatings, Wt. %	
1	CW 90Cr17MnSi	7.0	6.5
2	CW 90Cr17B2MnSi	2.5	2.3
3	Wire U12 (1.2% C)	7.0	12.0

Oxide phases were primarily located between the lamellae of the coating (Fig. 5), though some oxides formed inside the lamellae and as fully oxidized droplets. At a spraying pressure of 1.2 MPa, the thickness of inter-lamellar oxides in the coating was 1 to 3 µm (Fig. 5 *b*), while at 0.6 MPa, it could reach 5 to 7 µm (Fig. 5 *a*). It was also noted that air stream pressure significantly affects the porosity of the coatings. For instance, with a CW 90Cr17B2MnSi coating, increasing air flow pressure from 0.6 to 1.2 MPa reduced total porosity from 8% to 3%, and pore sizes from 30 to 10 µm.



a) *b)*

Figure 5. Microstructure of coatings obtained by spraying from CW Cr18B3Si2 at an air flow pressure of 0.6 (*a*) and 1.2 (*b*) MPa. 1 – oxides located between lamellae; 2 – micro cracks formed in the coating.

The X-ray diffraction analysis revealed that the matrix phase of coatings from CW No. 1, No. 4, and No. 7 (as numbered in Table 2) was martensite with a small amount of austenite. As the chromium content in the CW charge increased to 10% (CW No. 2, No. 5, and No. 8), the residual austenite content in the sprayed coatings also increased.

Table 2. Types of powder wires used for arc spray coatings, phase composition and content of phases in the coatings obtained by their spraying, and their microhardness.

No.	CW types	Phase composition of coatings / phase content, vol. %	Microhardness of coatings, $HV_{0,3}$
1	CW 90Cr6MnSi	α_m-FeCr / 95; γ-FeCr / 5	500–640
2	CW 90Cr10MnSi	α_m-FeCr / 75; γ-FeCr / 25	520–660
3	CW 90Cr17MnSi	α_{m+f}-FeCr / 85; γ-FeCr / 15	510–630
4	CW 90Cr6BMnSi	α_m-FeCr / 70; γ-FeCr / 15; $FeCr_2B$ / 15	700–900
5	CW 90Cr10BMnSi	α_m-FeCr / 45; γ-FeCr / 40; $FeCr_2B$ / 15	730–950
6	CW 90Cr17BMnSi	α_{m+f} -FeCr / 65; γ-FeCr / 20; $FeCr_2B$ / 15	670–930
7	CW 90Cr6B2MnSi	α_m-FeCr / 50; γ-FeCr / 25; $FeCr_2B$ / 25	700–1000

Table 2. Types of powder wires used for arc spray coatings, phase composition and content of phases in the coatings obtained by their spraying, and their microhardness. (Continuation)

8	CW 90Cr10B2MnSi	α_m-FeCr / 25; γ-FeCr / 50; $FeCr_2B$ / 25	720–1100
9	CW 90Cr17B2MnSi	α_{m+f}-FeCr / 62; γ-FeCr / 13; $FeCr_2B$ / 25	670–970
10	CW 90Cr10B2MoTi	α_m-FeCr / 25; γ-FeCr / 50; $FeCr_2B$ / 25	600–1100
11	CW 90Cr10B2MoTiVNi	α_m-FeCr / 25; γ-FeCr / 50; $FeCr_2B$ / 25	600–1100
12	CW 60CrB3Al6	α_{m+f}-FeCr / 60; γ-FeCr / 15; $FeCr_2B$ / 25	600–950
13	CW 60Cr20B3Ti	α_{m+f}-FeCr / 62; γ-FeCr / 13; $FeCr_2B$ / 25	600–950
14	CW 200Cr10Nb3MoB	γ-FeCr / 70; $FeCr_2B$ / 15; FeCrNbC / 15	600–900
15	CW 200Cr10Nb5MoB	γ-FeCr / 70; $FeCr_2B$ / 15; FeCrNbC / 15	600–900

* α_m – α phase in the form of martensite; α_{m+f} – α phase in the form of a mixture of martensite and ferrite.

Further increasing the chromium in the CW charge (CW No. 3, No. 6, No. 9, and No. 13) resulted in the presence of martensite, austenite, and ferrite in the ASC structure. In the presence of 1 wt.% boron in the CW charge, $FeCr_2B$ borides amounting to up to 15 vol.% were identified in coatings from CW No. 4 – No. 6 and No. 15. When the CW charge contained more than 2 wt.% boron, ASC spraying by CW No. 7 – No. 13 the borides content increased to 25 vol.%. Increasing the carbon content to 2% in CW No. 14 and No. 15 led to the formation of an austenite matrix phase with inclusions of complex alloyed FeCrNbC carbides in the coatings. With an increase in the chromium content to 10 wt.% and boron to 2 wt.% in the CW charge, the microhardness of coatings sprayed with CW No. 8, No. 10, and No. 11 increased, reaching a maximum value of 1100 $HV_{0.3}$.

3.2. Abrasive Wear Resistance of CW Coatings

As the chromium content in the CW charge (Samples No. 1, No. 2, No. 3) increased from 6 to 17 wt.%, the wear resistance of the coatings improved in both subsonic and supersonic spraying modes (Fig. 6 *a*).

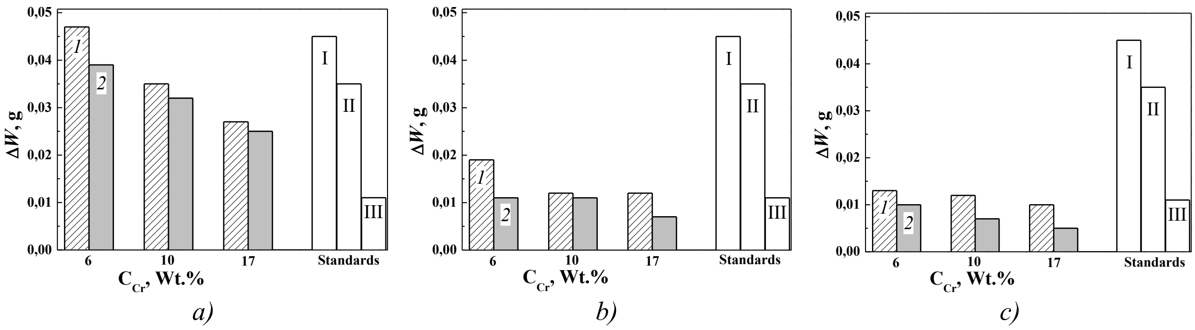
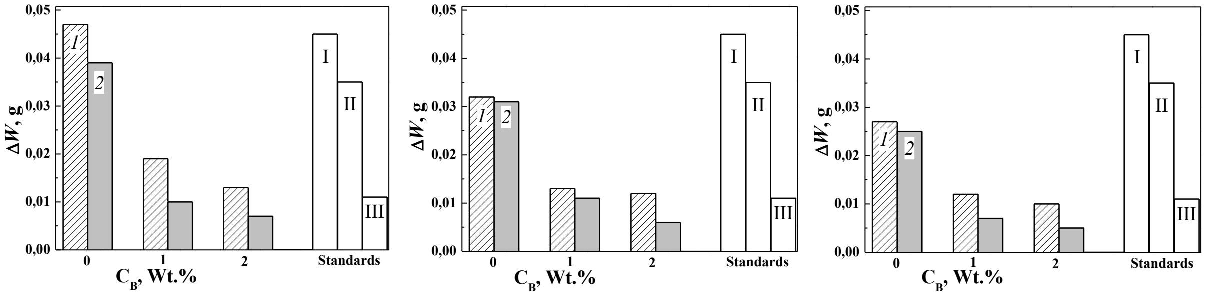


Figure 6. Effect of Cr content C_{Cr} on weight loss ΔW of: CW 90Cr(6–17)MnSi (*a*); CW 90Cr(6–17)BMnSi (*b*); CW 90Cr(6–17)B2MnSi (*c*); *1* and *2* – Correspond to the subsonic and supersonic modes of spraying coatings, respectively. I, II, III – Represent the weight loss ΔW of U12 steel with hardness of 460 $HV_{0.3}$, 640 $HV_{0.3}$, and 830 $HV_{0.3}$, respectively, used as standards for comparison.

The wear resistance of these coatings was comparable to U12 steel with a hardness of 450 and 580 $HV_{0.3}$ (marked I and II in Fig. 6 *a*). Adding up to 2 wt.% boron to the CW charge significantly enhanced the wear resistance of the coatings (Fig. 6 *b*, 6 *c*). The supersonic ASC spraying mode further increased the wear resistance by 20-70%, depending on the chromium and boron content. The best wear resistance was observed with CW (No. 9) containing the highest chromium and 2 wt.% boron, achieving twice the wear resistance of the reference U12 steel with a hardness of 840 $HV_{0.3}$ (column III in Fig. 6 *c*).
Given the significant impact of Cr and B on the abrasive wear resistance, the influence of varying boron content (0 to 3 wt.%) was analyzed for coatings with different chromium contents: CW 90Cr6B(0–2)MnSi with 6 wt.% chromium (Fig. 7 *a*); CW 90Cr10B(0–2)MnSi with 10 wt.% chromium (Fig. 7 *b*); CW 90Cr17B(0–2)MnSi with 17 wt.% chromium (Fig. 7 *c*). It was observed that higher boron content and higher spray air pressure increased the abrasive wear resistance of the coatings. Even with 6 wt.% chromium, the addition of 1 wt.% boron and supersonic spraying resulted in higher wear resistance than

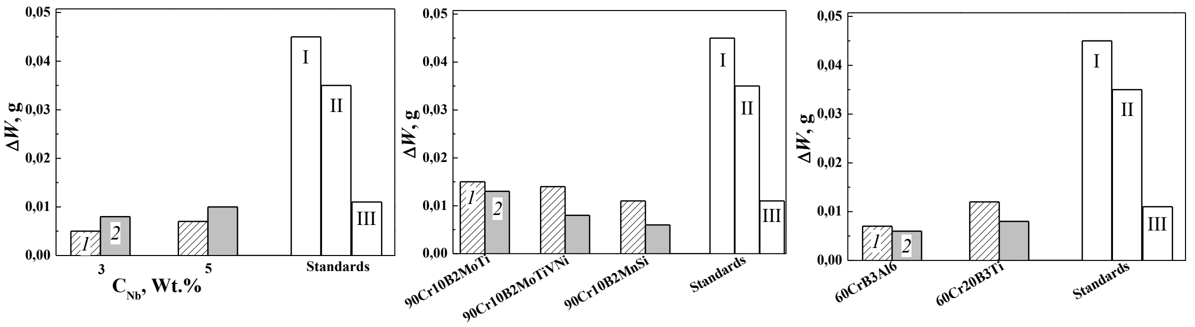
U12 steel with a hardness of 830 $HV_{0.3}$ (III in Fig. 7 *a*). Increased chromium content further enhanced boron's positive effect on wear resistance (Fig. 7 *b*, *c*).



a) *b)* *c)*

Figure 7. Effect of B content on weight loss ΔW of: CW 90Cr6B(0–2)MnSi (*a*); CW 90Cr10B(0–2)MnSi (*b*); CW 90Cr17B(0–2)MnSi (*c*). Designations: *1, 2,* I, II, III as described in Fig. 6.

Adding 3 to 5 wt.% niobium carbide to the CW charge resulted in slightly lower wear resistance compared to chromium boride in the same amount (Fig. 8 *a*). The wear resistance of niobium coatings decreased under the supersonic mode due to intensive carbon burning from molten droplets at high air jet pressure, reducing carbide content in the coating.



a) *b)* *c)*

Figure 8. Influence of niobium content C_{Nb} on weight loss ΔW of CW 200Cr10Nb(3–5)MoB (*a*) and comparison of mass loss for coatings from flux-cored wires with unchanged C, Cr, and B content but additions of Mo and Ti (CW 90Cr10B2MoTi), Mo, Ti, V, and Ni (CW 90Cr10B2MoTiVNi), or Mn and Si (CW 90Cr10B2SiMn) (*b*), and comparison with unchanged C and B content but different Cr content with additions of Al (CW 60CrB3Al6) or Ti (CW 60Cr20B3Ti) (*c*). Designations: *1, 2,* I, II, III as described in Fig. 6.

Replacing ferromanganese and ferrosilicon with ferromolybdenum, ferrovanadium, and nickel did not significantly increase wear resistance in either subsonic or supersonic modes (Fig. 8b). Ferrosilicon and ferromanganese form deep eutectics with the steel shell and PW charge, aiding complete fusion of charge components, resulting in more homogeneous ASCs compared to additions of ferromolybdenum, ferrovanadium, and nickel. Increasing boron content in CW up to 3% did not further increase wear resistance (Fig. 8 *c*) due to significant residual tensile stresses in coatings, leading to micro cracks.

4. CONCLUSIONS

- High-pressure (1.2 MPa) air jet in electric arc spraying increases air jet speed from 300 to 600 m/s and droplet speed from 150 to 300 m/s.
- Carbon content in coatings, dependent on arc voltage, spraying distance, and air jet pressure, is reduced during electric arc spraying. Empirical formulas have been proposed to determine carbon content based on spraying modes.
- Increasing chromium content from 6 to 17 wt.% in the Fe-Cr-Si-Mn-B-C alloy system improves wear resistance in both subsonic and supersonic modes. Adding up to 2 wt.% boron further enhances wear resistance, with supersonic spraying increasing it by 20–70%, depending on

chromium content. The maximum benefit of supersonic spraying results in wear resistance twice that of U12 steel with a hardness of 840 $HV_{0.3}$. These results of this investigation underscore the importance of optimizing CW composition and using advanced spraying techniques to achieve high wear resistance in coatings.

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