Influence of diameter of the cored wires on abrasive wear resistance of arc sprayed coatings

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Abstract. To obtain wear-resistant coatings, the cored wires (CW) with a diameter of 1.6...1.8 mm as electrode materials are mainly used. Using the large-diameter CW enable significantly increase the filling of their shells with powder charges and, as a consequence, to essentially raise the content of alloying elements in the coating structure. The model cored wires of two basic alloying systems Fe – Cr – C and Fe – Cr – B with a diameter of 1.6 and 2.4 mm used for spraying. Three types of the cored wires (namely 50CrNi2B5MnSi, 250Cr21WVMnSi, 50Cr6Mn2MoSi) used in this study. It is found that more oxide phase (40...100 %) was in coatings formed with CW with a diameter of 2.4 mm compared with coatings formed with CW with a diameter of 1.6 mm with lower filling. It is established that the abrasive and gas-abrasive wear resistance of coatings with 250Cr21WVMnSi CW decreased, and with 50CrNi2B5MnSi CW increased due to the increase in the thickness of the lamellae in their structure with the use of CW of larger diameter. It was found that the higher the coefficient of microheterogeneity and chromium content in the lamellae, the higher the corrosion resistance of coatings.

1. Introduction  
Electric arc spraying of coatings is widely used in industry for protection against corrosion, restoration of the size of machine parts, as well as against abrasive and gas-abrasive wear, both at room and at elevated temperatures [1-9]. For spraying wear-resistant coatings, cored wires (CW) with a diameter of 1.6...1.8 mm are mainly used as electrode materials. Such CW cannot always provide a high filling factor with the charge, and therefore cannot provide the required content of alloying elements in the coatings. At the same time, CW coatings operated under abrasive wear conditions, especially in corrosive environments, require at least 12 wt.% chromium in their composition [10-14]. The use of CW of large diameters makes it possible to significantly increase their filling factor with the charge, and, therefore, to significantly increase the content of alloying elements in the coating structure. However, there are no studies in the world literature that would show the effect of the diameter of the CW and the productivity of spraying coatings on the structure and abrasive wear resistance. This hinders the development of the method of electric arc spraying of coatings and does not allow the creation of new CW with a high content of alloying elements.
2. Experimental and materials

Electric arc coatings (EAC) were obtained using original equipment, developed and manufactured at the Karpenko Physico-Mechanical Institute of the NAS of Ukraine. For spraying, model CW of basic alloying systems Fe – Cr – C and Fe – Cr – B with a diameter of 1.6 and 2.4 mm were used (table 1, figure 1).

![Figure 1. A typical scheme of formation of electric arc coatings.](image)

**Table 1. Chemical composition of the used model cored wires.**

| CW type (CW designation) | Ø CW (mm) | Content of elements (wt. %) |
|--------------------------|-----------|-----------------------------|
|                          |           | Fe  | C   | Si  | Mn  | Cr  | Ni  | B   | V   | Mo  | W   |
| 50CrNi2B5MnSi (A)        | 1.6       | 90.6| 0.55| 0.19| 1.09| 0.20| 1.38| 5.95| -   | -   | -   |
|                          | 2.4       | 91.1| 0.45| 0.30| 1.20| 0.22| 1.75| 4.96| -   | -   | -   |
| 250Cr21WVMnSi (B)        | 1.6       | 74.4| 2.80| 0.30| 0.39| 21.10| -  | 0.60| 0.40|
|                          | 2.4       | 74.0| 2.51| 0.62| 0.38| 21.40| -  | 0.52| 0.55|
| 50Cr6Mn2MoSi (C)         | 1.6       | 91.7| 0.41| 0.40| 1.56| 5.40| -   | -   | 0.50|
|                          | 2.4       | 90.6| 0.47| 0.40| 1.40| 6.60| -   | -   | 0.51|

To obtain the same chemical composition of cored wires, iron powder was additionally added to the CW charge of a larger diameter. The cross-section of both investigated flux-cored wires is shown in figure 2. Metallographic studies were performed on PO-21 and Carl Zeiss Stemi 2000 optical microscopes and on LEO-840 scanning electron microscopes (with an attachment for microelement analysis) and ZEISS EVO-40XVP (with an INCA Energy X-ray microanalysis system). The phase composition of the coatings was studied on a DRON-3.0 diffractometer in Cu Kα radiation with tube focusing according to the Bragg-Brentano scheme.

![Figure 2. Cross section of flux-cored wires with a diameter of: (a) 1.6 and (b) 2.4 mm.](image)
The elastic-plastic properties of the developed coatings were investigated by the method of dynamic indentation on the device "Micron-gamma" with automatic registration of load diagrams \( P - h \), where \( P \) is the load on the indenter (Berkovich's diamond pyramid), \( h \) is the depth of its penetration into the coating.

The abrasive wear of the coatings was investigated under the conditions of a rigidly fixed abrasive using an abrasive corundum disk with a grain size of 20 μm in diameter and 150 and 8 mm wide, the rotation frequency of which was 2.7 s\(^{-1}\), and the load in the contact zone - \( P = (14.7 \pm 0.25) \) N. Gas-abrasive wear of the coatings was investigated at a temperature of 200 °C for 50 hours. Abrasive wear resistance was assessed by the weight loss of the samples after testing at an abrasive speed of 36 m/s. Quartz sand with a grain size of up to 200 μm was used as an abrasive.

EAC is characterized by a heterogeneous structure, the degree of heterogeneity of which was proposed to be estimated by the value of the microheterogeneity coefficient \( K_{MH} \) according to the formula (1):

\[
K_{MH} = \frac{\sum |c_i - \overline{c}|}{n \times \overline{c}}
\]

where \( n \) is the number of rectangular sections with an area of 35 \( \cdot \) 10\(^{-4} \) mm\(^2\), highlighted in the photo of the EAC microstructure (figure 3), on which the content of each \( c_i \) element within a separate lamella and the average content of the coating element are determined by spectral analysis.

![Figure 3. Scheme of carrying out Micro X-ray spectral analysis to determine the local content of alloying elements in the coating.](image)

The corrosion characteristics of the coated samples were determined in potentiodynamic mode on an AutoTafel potentiostat (ACM Instruments) in 3% aqueous NaCl solution. The reference electrode was a silver chloride electrode of the EVL-1M1 type, the auxiliary one was platinum, with a potential change of 1 mV/s. The corrosion rate was determined by extrapolating the linear sections of the polarization curves to the corrosion potential. For electrochemical studies, the working part of the samples with an area of 0.5 cm\(^2\) was isolated, applying an insulating waterproof lacquer coating around it.

3. Results and discussion

3.1. Influence of CW diameter on the structure of coatings from model CW of different diameters

During electric arc spraying of coatings between the ends of the wires there is an arc in which the wires melted, and their melt was dispersed by air jet into droplets, which, hitting the sprayed surface, deformed in the form of "saucers" (lamellae) and layer by layer formed the coating. To analyze the fractional and chemical composition of the drops, they were caught in a snow target. Metallographic
and spectral analysis revealed that among the droplets there are completely oxide droplets, droplets with an outer layer of oxides and droplets without oxides in general. It was found that with increasing CW diameter and arc current, the volume of molten metal at the ends of the CW increased and therefore the air jet dispersed it into droplets of larger diameter (figure 4). As a result, the thickness of the lamellae (as a structural feature of the coatings) increased in the coatings of all alloying systems (figure 5).

![Figure 4. Morphology of droplets obtained by spraying of the A flux-cored wire into a snow target at an arc current that determines the spraying performance: (a) 125, (b) 150 and (c) 180. This droplet morphology is typical for all studied CW.](image)

![Figure 5. Influence of the arc current values I on the lamella thickness t in the structure of coatings obtained from three cored wires (indicated in the table 1 as A, B, C) with a diameter of 1.6 (light columns) and 2.4 (dark columns) mm: (a) CW 50CrNi2B5MnSi, (b) CW 250Cr21WVMnSi and (c) CW 50Cr6Mn2MoSi.](image)

Since the coating process was carried out using an air jet, it turned out that in many cases the lamellae of the coatings are separated from each other by thin layers of oxide phases (figure 6). It was shown that with increasing the spraying distance from 80 to 120 mm (which is equivalent to an increase in the residence time of the droplets in the air stream), the content of the oxide phase in the coatings doubled. In the coatings formed with CW with a diameter of 2.4 mm, 40…100 % more oxide phase was found than in the coatings formed with CW with a diameter of 1.6 mm. This is due to the larger volume of the charge in the CW of larger diameter, the cavities between the powders of which are filled with air, which intensively oxidizes the melt droplets inside the CW and at their ends during spraying.

Phase analysis showed that the matrix phase of the coating structure with cored wire designated as C (50Cr6Mn2MoSi) was martensite with a small amount of iron oxide Fe₃O₄ (table 2). Whereas the matrix phase of the coating with cored wire designated as B (250Cr21WVMnSi) was residual austenite with a small amount of martensite and oxides of chromium and iron (Cr₂O₃ + Fe₃O₄). The rapid crystallization of droplets on the steel-bases contributed to the formation of a large amount of residual austenite in the coating structure. The matrix phase of the coating with cored wire designated as A 50CrNi2B5MnSi CW was martensite, which revealed nanoscale inclusions of complex-doped boride
FeCrB and a small amount of iron oxide Fe$_3$O$_4$. In this case, the rapid crystallization of the droplets led to the formation of a large number of crystallization centers of borides, which due to lack of time managed to grow only to nanoscale.

![Figure 6](image)

**Figure 6.** Oxide layers between the lamellae in the structure of the coatings sprayed of the A flux-cored wire from a distance of 80 (a), 100 (b), 120 (c) mm.

| CW type (CW designation) | α-Fe (wt. %) | γ-Fe (wt. %) | oxide (wt. %) | FeCrB (wt. %) |
|--------------------------|-------------|-------------|--------------|-------------|
| 50CrNi2B5MnSi (A)        | 47 martensite | -           | Fe$_3$O$_4$ | 40          |
| 250Cr21WVMnSi (B)        | 28 martensite 60 residual austenite Cr$_2$O$_3$+Fe$_3$O$_4$ | - | - |
| 50Cr6Mn2MoSi (C)         | 90 martensite | -           | Fe$_3$O$_4$ | -           |

3.2. Influence of lamella thickness in the structure of coatings on their physical and mechanical properties

The porosity of the coatings of all alloying systems increased with increasing thickness of the lamellae in the structure of the sprayed coatings and, accordingly, the diameter of the CW (figure 7). This pattern is due to the increase in the diameter of the droplets that formed the coating. With an increase in the diameter of the droplets they bounce off the substrate surface more intensively (figure 8), which led to the appearance of microcavities between the lamellae in the coating structure.

![Figure 7](image)

**Figure 7.** Effect of lamella thickness $t$ on the porosity $\phi$ in the structure of coatings sprayed with cored wire 1.6 (1) and 2.4 (2) mm in diameter, designated as A (CW 50CrNi2B5MnSi, a), B (CW 250Cr21WVMnSi, b) and C (CW 50Cr6Mn2MoSi, c).

It was found that the microhardness of coatings sprayed with CW designated by A (CW 50CrNi2B5MnSi) and C (CW 50Cr6Mn2MoSi) reused with increasing thickness of lamellae in the structure of coatings, which was especially evident when used for spraying CW of larger diameter (figure 9a, c). This was explained by the evaporation and burnout of alloying elements from droplets, especially carbon during their spraying. As the diameter of the droplets increased, the amount of carbon burned out of the droplets decreased. And the higher carbon content in the martensitic matrix phase of the coatings was responsible for increasing their microhardness.
Figure 8. A typical picture of the bouncing of melt droplets of different diameters from the sprayed surface.

Figure 9. Influence of lamella thickness $t$ on the microhardness $HV_{0.3}$ of coatings sprayed with cored wire 1.6 (1) and 2.4 (2) mm in diameter, designated as A (CW 50CrNi2B5MnSi, a), B (CW 250Cr21WVMnSi, b) and C (CW 50Cr6Mn2MoSi, c).

However, in coatings with 250Cr21WVMnSi CW found the opposite trend of the influence of the thickness of the lamellae on the microhardness using a wire of larger diameter (figure 9b). This is due to the phase composition of these coatings, namely the significant amount of residual austenite in them, which has a lower microhardness than high-carbon martensite. Of the small droplets formed during the spraying of CW of smaller diameter, much more carbon burned out (figure 10), which means that the content of austenite in the lamellae of the coating was lower, and martensite higher.

Figure 10. Influence of the diameter of molten metal droplets obtained by spraying cored wires B (CW 250Cr21WVMnSi, a) and C (CW 50Cr6Mn2MoSi, b) on the content of carbon and chromium in them.

The adhesion of coatings with 50CrNi2B5MnSi CW and 250Cr21WVMnSi CW (CWs designated A and B) slightly decreased with increasing lamella thickness in the structure of coatings, caused especially by the use of CW of larger diameter (figure 11a, b). This is due to the occurrence of tensile
stresses in the sprayed coatings. As a result of their influence, microcracks appeared in the coatings or even their network was formed, which significantly reduced their adhesion to the steel base.

For the coating with 50Cr6Mn2MoSi CW (CW designated C), the inverse regularity was found (figure 11c). As the thickness of the lamellae in the structure of the coating and the diameter of the CW increased, its adhesion to the steel base increased. This was explained by the higher thermal energy of the droplets, the lower combustion of carbon from them and the formation of coatings with the matrix phase of high-carbon martensite. The more carbon in martensite, the lower the coefficient of thermal expansion of the coating, which causes a lower level of residual tensile stresses in it.

![Figure 11](image)

**Figure 11.** Relationship of the lamella thickness $t$ in the structure of coatings sprayed with cored wires $A$ (CW 50CrNi2B5MnSi, $a$), $B$ (CW 250Cr21WVMnSi, $b$) and $C$ (CW 50Cr6Mn2MoSi, $c$) with a diameter of 1.6 ($1$) and 2.4 ($2$) mm and of the adhesion values $\sigma_{ad}$ of the coatings to the steel substrate.

### 3.3. Influence of lamella thickness in the structure of coatings on their wear resistance

With increasing thickness of the lamellae in the structure of coatings sprayed 250Cr21WVMnSi CW (especially larger diameter), their abrasive wear resistance decreases (figure 12). This result was explained by the greater amount of residual austenite in the coating (table 2), which has a lower microhardness than martensite. Smaller droplets burn out more carbon than larger ones. Therefore, in the coating sprayed with CW of a diameter of 1.6 mm less carbon than in the coating with CW of a diameter of 2.4 mm, and hence less residual austenite.

![Figure 12](image)

**Figure 12.** Influence of lamella thickness $t$ in the structure of coatings sprayed with cored wires $B$ (CW 250Cr21WVMnSi, $a$) and $C$ (CW 50Cr6Mn2MoSi, $b$) with a diameter of 1.6 ($1$) and 2.4 ($2$) mm on their abrasive wear resistance by weight loss of samples $\Delta w$.

With increasing thickness of the lamellae in the coatings sprayed with CW 50CrNi2B5MnSi (CW designated $A$) especially larger diameter), their abrasive wear resistance increased. This is due to the increase in the hardness of such coatings and the lower level of residual tensile stresses (figure 13). In such coatings, tensile stresses are relaxed due to the formation of microcracks, which, however, do not reduce abrasive resistance.
The nature of the change in gas-abrasive wear resistance of coatings from these CW is similar to that obtained for abrasive wear resistance. Gas-abrasive wear resistance of coatings with 250Cr21WVMnSi CW (CW designated B) decreased with increasing thickness of lamellae and diameter of CW (figure 14a), while for coatings with CW 50CrNi2B5MnSi (CW designated A) – it increased and for coatings with CW of larger diameter was higher (figure 14b).

**Figure 14.** Influence of lamella thickness $t$ in the structure of coatings with cored wires CW 50CrNi2B5MnSi (a) and CW 250Cr21WVMnSi (b) marked as A and B respectively with a diameter of 1.6 (1) and 2.4 (2) mm on their gas-abrasive wear resistance by loss of sample mass $\Delta w$.

### 3.4. Corrosion resistance of coatings sprayed with flux-cored wire 250Cr21WVMnSi

To ensure high corrosion resistance of the coatings, it is important that their microheterogeneity in terms of chromium content is low, and that its content in each lamella of the coating exceeds 12 wt. % (first threshold of corrosion resistance). To fulfill this condition, it is necessary to ensure a sufficient number of chromium-containing components in the composition of the CW charge, which have achieved by an increase in the diameter of the CW, and complete fusion of the chromium-containing charge and steel shell. To meet the requirement for complete fusion of CW components, a eutectic mixture of powders (FeSi + FeMn) was added to the composition of its charge.
Figure 15. Influence of lamella thickness t in the structure of coatings with CW 250Cr21WVMnSi (CW designated A) with diameter 1.6 (1) and 2.4 (2) mm on the coefficient of microheterogeneity of coatings $K_{MH}$ (a) and their corrosion resistance in 3% aqueous NaCl solution by corrosion current density $j_{c}$ or (b).

On the example of coatings with 250Cr21WVMnSi CW of both diameters it was found that the microheterogeneity of coatings decreased and corrosion resistance increased with increasing thickness of the lamellae in their structure, due to a more complete fusion of the charge and shell (figure 15a). CW of larger diameter contains a larger amount of charge, which causes insufficient fusion of its chromium-containing charge and shell, so coatings with CW of larger diameter are more heterogeneous and less corrosion resistant (figure 15b).

4. Conclusions

It was found that the thickness of the lamellae in the coatings of all analyzed alloying systems increased with increasing volume of molten metal at the ends of the CW with the corresponding formation of droplets of larger diameter during air dispersion, which was realized through the use of CW of larger diameter with a correspondingly high filling factor of its shell with a charge and increased arc current.

It is shown that the amount of oxide phase in the structure of coatings doubles with increasing spray distance CW from 80 to 120 mm. More oxide phase (40… 100%) was found in coatings formed with CW with a diameter of 2.4 mm with a higher filling factor of its shell charge compared with coatings formed with CW with a diameter of 1.6 mm with lower filling. This is due to the larger volume of the charge in the CW of larger diameter, the cavities between the powders in which are filled with air, which intensively oxidizes the melt droplets inside the CW and at their ends during spraying.

It is established that the porosity and microhardness of coatings from the developed CW increases with increasing thickness of the lamellae in their structure and, accordingly, the diameter of the CW. The increase in microhardness is due to less evaporation and burnout of alloying elements from the droplets forming the coating. Increase in porosity is caused by of the bouncing of melt droplets of different diameters from the sprayed surface, which contributes to microcavities between the lamellae of the coating.

It was found that with increasing the thickness of the lamellae in the structure of coatings with 250Cr21WVMnSi CW and 50CrNi2B5MnSi CW their adhesion to the steel base decreased slightly due to the occurrence of tensile stresses in coatings, which cause microcracks or cracks in their structure. At the same time, the adhesion of coatings with 50X6M2C CW to steel increased, which was associated with higher carbon content in large lamellae and favorable conditions for the formation of high-carbon martensite, which has the lowest coefficient of thermal expansion and causes the lowest residual tensile stresses in coatings.

It is established that the abrasive and gas-abrasive wear resistance of coatings with 250Cr21WVMnSi CW decreased, and with 50CrNi2B5MnSi CW increased due to the increase in the thickness of the lamellae in their structure with the use of CW of larger diameter.

It was found that the corrosion resistance of coatings from the developed CW correlates with the coefficient of microheterogeneity and chromium content in the lamellae of coatings: the higher the
coefficient of microheterogeneity and chromium content in the lamellae, the higher the corrosion resistance of coatings.

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