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ELECTRIC ARC SPRAYING OF INTERMETALIC Fe–Al COATINGS USING DIFFERENT SOLID AND POWDER WIRES

Yu.S. Borisov, A.L. Borisova, N.V. Vihilyanska, I.A. Demyanov and **O.M. Burlachenko**
E.O. Paton Electric Welding Institute of the NAS of Ukraine
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine. E-mail: office@paton.kiev.ua

The mechanism of formation and structure of coatings based on the system iron-aluminium, sprayed by electric arc method using wires of solid cross-section and a flux-cored wire were investigated. The grain-size composition, structure and microhardness of particles (spraying products of electrode wires of iron and aluminium) captured from the spraying jet, as well as structure, phase composition and microhardness of electric arc coatings of the system iron-aluminium were studied. It was found that during spraying of Fe + Al and Fe + AlMg wires, the interaction of particles in the jet does not occur and the products of spraying represent particles of iron and aluminium with the appropriate hardness. In this case, the formation of intermetallics in the coatings also does not occur and they have a heterogeneous structure consisting of the components based on iron and aluminium. It was found that intermetallic FeAl structure is formed only after heat treatment of sprayed coatings at 650 °C. During spraying of flux-cored wire FCW(Fe–Al) in the process of melting the sheath and the filler, the interphase interaction occurs, which results in the formation of coatings with a microhardness of 2460 ± 290 MPa, the main phase of which is intermetallic Fe_3Al. 21 Ref., 1 Table, 6 Figures.

Keywords: *electric arc spraying, intermetallic, iron-aluminium, coating, solid cross-section wire, flux-cored wire, microstructure*

Alloys based on iron aluminides belong to the promising structural materials designed to operate at temperatures of 600–1000 °C. They are characterized by a low cost, high resistance to wear, corrosion and oxidation also in aggressive sulfur-containing environments [1, 2].

The use of alloys based on iron aluminide as protective coatings is largely predetermined by the possibility of increasing the service life of different elements of mechanisms operating under the conditions of increased wear and corrosion, reducing the cost of coated products as compared to high-alloy steels, as well as the possibility of using simple and inexpensive technology of their spraying [3, 4]. These materials own their properties to an ordered crystalline structure with strong chemical bonds in combination with a close package of atoms, which leads to an increased resistance to creep, recrystallization and high-temperature corrosion as compared to traditional metal alloys [5].

Coatings based on Fe-Al intermetallics are produced by thermal spraying methods: plasma [6], high-velocity oxygen fuel [7] and detonation [8]. In these methods, as spraying materials intermetallic powders produced by spraying [9], mechanical alloying and mechanochemical synthesis are used [10, 11].

An alternative method of producing iron-aluminium coatings is electric arc spraying (EAS), in which coatings are formed as a result of combined spraying of Fe- and Al-containing wires. In the case when as spraying materials composite wires FeAl [12] or flux-cored wires (FCW) [4] are used, consisting of an iron sheath with an aluminium powder filler, as a result of spraying, in the coatings interaction of melts of iron and aluminium with the formation of intermetallic phases Fe_3Al and FeAl occurs. In spraying using combined spraying wires of a solid cross-section, coatings with a pseudo-alloy structure are formed [13]. In particular, in spraying using wires of iron and aluminium, coatings consist of initial components of iron and aluminium, their oxides and solid solutions based on Fe and Al [14]. In this case, the synthesis of intermetallic phases Fe_xAl_y does not occur or their presence does not exceed 5 wt.% [15], and the formation of intermetallics Fe_2Al_5, Fe_3Al and FeAl occurs in the case of further heat treatment of coatings at 650 °C [14].

At the PWI, the studies of peculiarities of forming electric arc coatings based on the Fe–Al system have been carried out since the 1990s. The electric arc coatings of the steel-aluminium system containing 10 % of aluminium, which were developed by the authors [16], were used by the Lviv branch of the Central De-

Yu.S. Borisov — https://orcid.org/0000-0002-6019-8464, A.L. Borisova — https://orcid.org/0000-0002-7376-3370,
N.V. Vihilyanska — https://orcid.org/0000-0001-8576-2095, I.A. Demyanov — https://orcid.org/0000-0003-4536-9971,
O.M. Burlachenko — https://orcid.org/0000-0003-2277-4202,

sign Bureau «Soyuzenergoremont» to protect screen pipes of boilers from a high-temperature ($T \leq 550$ °C) sulfur corrosion at a weak gas abrazive wear and were successfully operated at Burshtyn, Transnistria and Kryvyi Rih GRES-2 power plants during the period of 1–4 years.

The use of ferrochromaluminium-based flux-cored wires in EAS method allows producing coatings with a high level of physical and mechanical properties (σ_{adh} = 20.4 MPa, Young's modulus (E) is $7.83 \cdot 10^{-4}$ MPa, porosity is 4 ± 0.7 %, fatigue limit of steel 45 with coating (σ_{-1}) is 220 MPa) [17]. The developed coatings were successfully applied for restoration of parts of agricultural machinery of a number of enterprises in Moldova [18].

In [19] it is noted that the comparison of coatings deposited by thermal spraying methods from compact wires with the same ones from flux-cored wires or flexible rods shows that the latter provide a set of higher service properties. At the same time, until nowadays detailed studies and comparison of features of formation of intermetallic coatings from compact and powder materials were not carried out.

The aim of the work is to study the peculiarities of intermetallic Fe–Al coatings formation in the conditions of electric arc spraying with the use of dissimilar and flux-cored wires.

Materials and methods of investigations. Spraying of coatings of the Fe–Al system was performed applying electric arc method using EM-14M metallizer. The coating was produced by a combined spraying of solid cross-section wires (steel wire Sv08A and aluminium wire A99; steel wire Sv08A and aluminium AMg6 alloy wire). To spray coatings based on Fe–Al intermetallics, a flux-cored wire was manufactured, consisting of a sheath of steel St08kp (rimmed) and a filler — Al powder of grade PA-4.

The calculation to form the flux-cored wire with the composition 86 Fe + 14 Al (wt.%), consisting of a tubular metal sheath St08kp and Al powder, consists in calculation of the required bulk density of Al powder, in which the powder uniformly fills the entire cavity of the metal pipe with a diameter of 303 cm. The bulk density of Al powder, which provides a uniform filling of the volume of the inner cavity of the pipe, is calculated by the formula

$$\gamma_{\text{b.d.Al}} = \frac{P}{V_{\text{t}}},$$

where P is the mass of Al powder (14 g); V_{p} is the volume of the cavity of the metal pipe formed from the strip St08kp, which is calculated by the formula

$$V_{\text{t}} = S_{\text{t}} L_{\text{t}},$$

where S_{p} is the cross-sectional area of the metal pipe, which is calculated by the formula

$$S_{\text{t}} = \frac{\pi D^2}{4} = 0.785 \cdot 0.303^2 = 0.072 \text{ cm}^2,$$

and L_{p} is calculated by the formula

$$L_{\text{t}} = \frac{P_{\text{t}}}{B\delta\gamma_{\text{st}}},$$

where P_{p} is the mass of the pipe (86 g); B is the width of the strip (1.2 cm); δ is the thickness of the strip (0.04 cm); γ_{st} is the density of St08kp (7.8 g/cm^3).

Hence:

$$L_{\text{t}} = \frac{86}{1.2 \cdot 0.04 \cdot 7.8} = 229.7 \text{ cm},$$

$$V_{\text{t}} = 229.7 \cdot 0.072 = 16.54 \text{ cm}^3,$$

$$\gamma_{\text{b.d.Al}} = \frac{14}{16.54} = 0.85 \frac{\text{g}}{\text{cm}^3}.$$

As a result of the calculations, it was found that to form the flux-cored wire from a mixture of 86Fe + 14Al (wt.%), which corresponds to the formula of Fe_3Al intermetallic, it is necessary to use Al powder with a bulk density of 85 g/cm^3. To produce such a powder, the initial Al powder (bulk density is 1.3 g/cm^3) was treated in an attrition mill for 75 min at a speed of 400 rpm and the ratio of the mass of the balls to the mass of the charge 7:1 with addition of zinc stearate in the amount of 2 wt.% to achieve a bulk density of powder of 0.85 g/cm^3.

The filling factor of the manufactured flux-cored wire FCW(Fe–Al) amounts to 16 %. The structure of the wire is presented in Figure 1.

The diameter of the used wires of both solid cross-section and flux-cored wire was 2 mm.

Based on the studies of peculiarities of the formation of coatings from dissimilar wires [13] and considering the literature data [14], for electric arc spraying

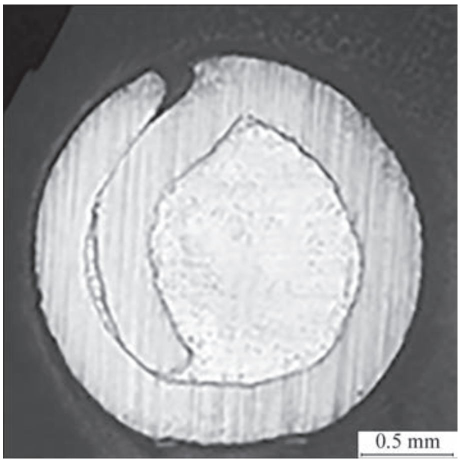

Figure 1. Structure of flux-cored wire FCW (Fe–Al)

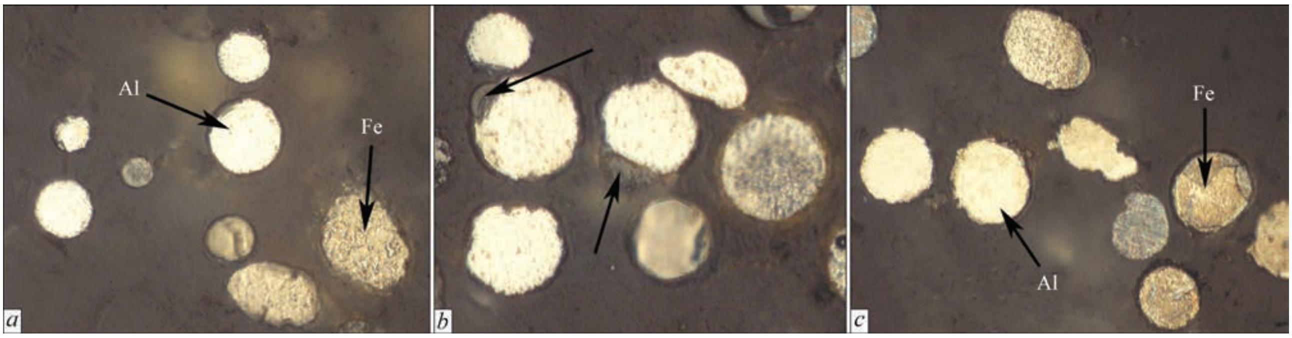

Figure 2. Microstructure of products of wires spraying: *a*, *b* — Fe + Al; *c* — Fe + AlMg; *a*, *c* — ×400; *b* — ×800

of coatings based on Fe-Al intermetallics, the following technological parameters of the process were selected: current is 200 A, voltage on the electrodes is 38 V, compressed air pressure is 0.65 MPa, spraying distance is 200 mm. This spraying mode provides a stable melting process of the used electrode wires.

In order to study the nature of the development of the processes of interaction of melt particles in the wires, formed by spraying dissimilar wires of a solid cross-section Fe + Al and Fe + AlMg, during movement at spraying distance between each other and with the environment, determination of their sizes and investigation of the structure of spraying products was collected in a water bath with the sizes of 500×500×200 mm. The bath is installed under a jet of a sprayed material at a distance of 200 mm. In the produced weldment, the structure and dispersion of particles were investigated applying the metallographic method by measuring their size on metallographic sections by means of an optical microscope. To detect the microstructure, etching of metallographic sections of powder particles was performed with 10 % alcohol solution of nitric acid for 4–5 min.

During metallographic examinations, the Neophot-32 optical microscope with a device for digital photography was used, and microhardness measurements were performed in the PMT-3 device. X-ray structure analysis (XSPA) of the coatings was performed by means of the DRON-3 diffractometer in CuK_α-radiation with a graphite monochromator at a step movement of 0.1° and an exposure time at each point of 4 s, with the following computer processing of the obtained digital data.

Characteristics of products of a combined spraying of Fe + Al and Fe + AlMg wires

Parameters of particles, μm	Sv08A + Al		Sv08A + AMg6	
	Fe	Al	Fe	AlMg
Grain-size composition of spraying products, %				
<40	18	35	23	30
40–50	19	25	22	28
50–60	18	18	18	20
60–70	12	8	12	12
70–80	12	8	9	8
80–90	8	1	6	1
90–100	7	2	5	1
>100	6	3	5	1
Average size of particles, μm				
d_{av}	63	52	59	51
Microhardness, MPa				
$HV_{0.05}$	2570±810	320±90	2790±590	470±110

Results of investigations. The study of the microstructure of particles of products of a combined spraying of Fe + Al and Fe + AlMg wires showed that they consist of iron and aluminium particles (Figure 2), i.e. interaction between iron and aluminium particles during spraying process was not detected. The particles are mostly spherical in shape, but particles of irregular elongated shape are also found. The microhardness of sprayed particles corresponds to either the microhardness of pure iron (2500–2700 MPa), or pure aluminium (300–500 MPa).

On some aluminium particles a presence of dome-shaped formations of solid and hollow structure is observed, which are located on their surface (indicated by arrows in Figure 2, *b*). Probably, these formations represent aluminium oxide, as far as when particles are passing through the spraying jet, on the surface of aluminium particles an oxidation process with the formation of an oxide film develops. A similar phenomenon is observed during plasma spraying of aluminium-containing materials [20].

The characteristics of the products of combined spraying of Fe + Al and Fe + AlMg wires are presented in Table.

The study of the size of the sprayed particles (Table) showed that the main fraction of aluminium particles (~ 60 %) has a size of <50 μm, iron (~ 50 %) is 40–70 μm, the average size of aluminium particles is 51–52 μm, iron is 59–63 μm. It is known that the size of particles of the products of spraying metal melts mainly depends on the value of their surface tension [21]. Therefore, this difference in the dispersion of the products of spraying dissimilar wires (Fe and Al) is associated with the fact that aluminium has a lower coefficient of surface tension (σ_{Al} = 914 MJ/m^2) than iron (σ_{Fe} = 1850 MJ/m^2), and in the process of a com-

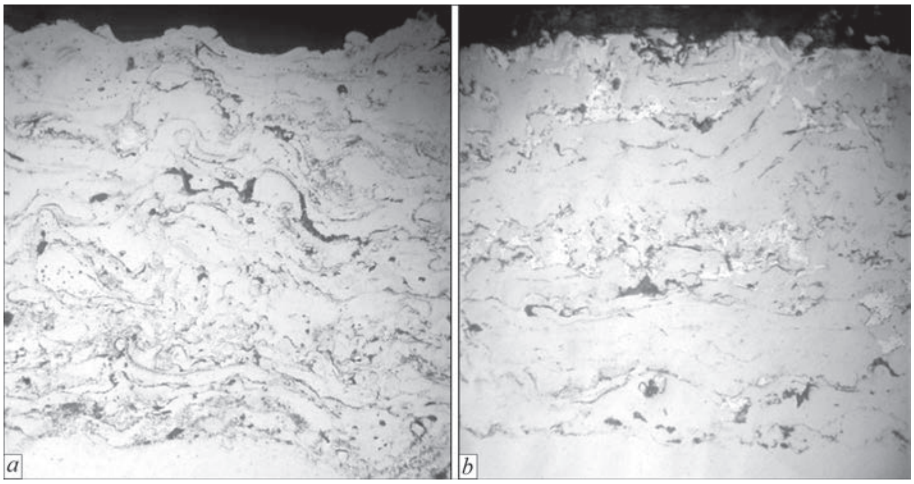

Figure 3. Microstructure of electric arc coatings (×200): *a* — Fe + Al; *b* — Fe + AlMg

bined spraying a more intensive spraying of the aluminium melt occurs. No significant difference in the dispersion of the products of spraying wires of pure aluminium and aluminium AMg6 alloy was detected because of a slight difference in their coefficients of surface tension.

As a result of metallographic (Figure 3) and XSPA (Figure 4) analyzes of sprayed coatings, it was found that the coatings, produced by combined spraying of Sv08A wires with aluminium (Fe + Al) and Sv08A with aluminium AMg6 alloy (Fe + Al) consist of a mixture of iron and aluminium. The microhardness of the areas of coatings Fe + Al and Fe + AlMg based on iron is 2400–2600 MPa and aluminium is 700–800 MPa.

It is known that the formation of Fe-Al intermetallics can be achieved by heat treatment of the coatings produced by combined spraying of iron and aluminium wires [14]. In this work, the heat treatment of the Fe + AlMg coating was carried out at a temperature of 650 °C for two hours with the following cooling in water. The time of treatment was chosen from the calculations of the diffusion coefficient of aluminium into iron in a solid phase. In this mode of heat treatment in the coating, the formation of intermetallic phases Fe_2Al_5, Fe_3Al and FeAl (Figure 4, *c*) occurs,

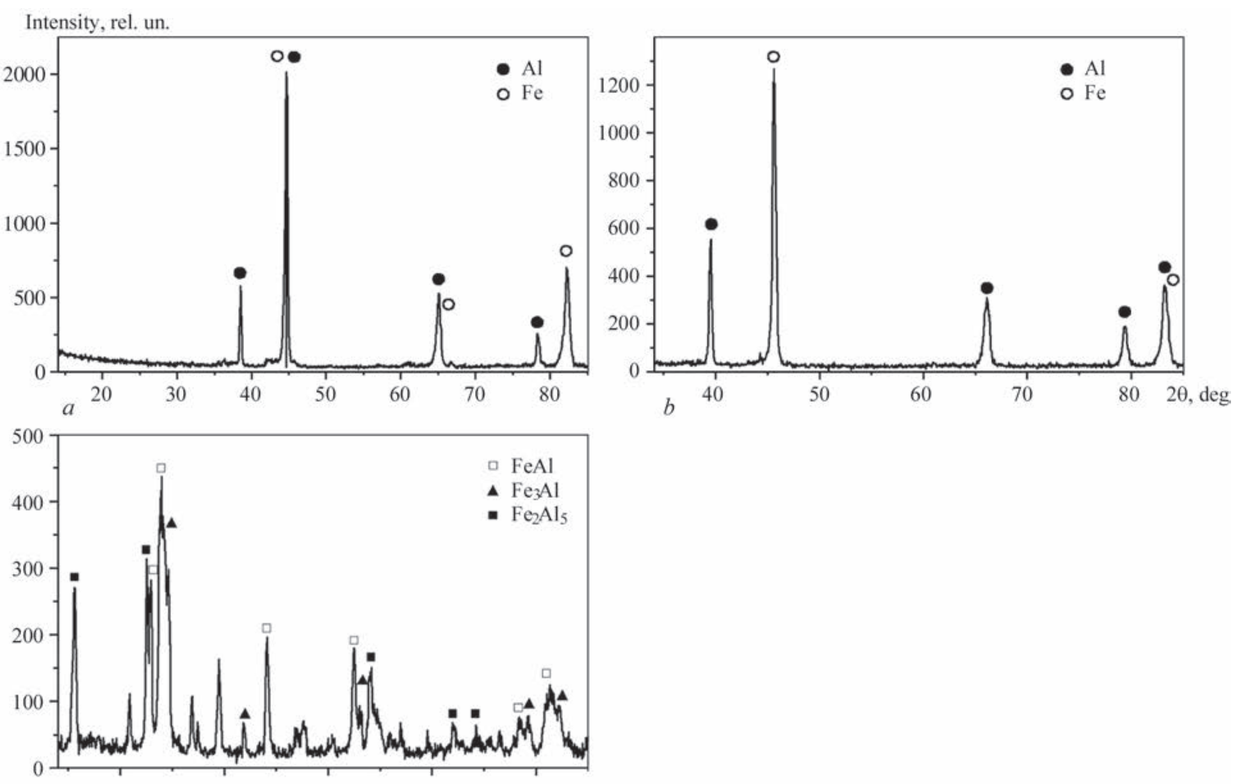

Figure 4. X-ray patterns of electric arc coatings: *a* — Fe + Al; *b* — Fe + AlMg; *c* — Fe + AlMg after treatment

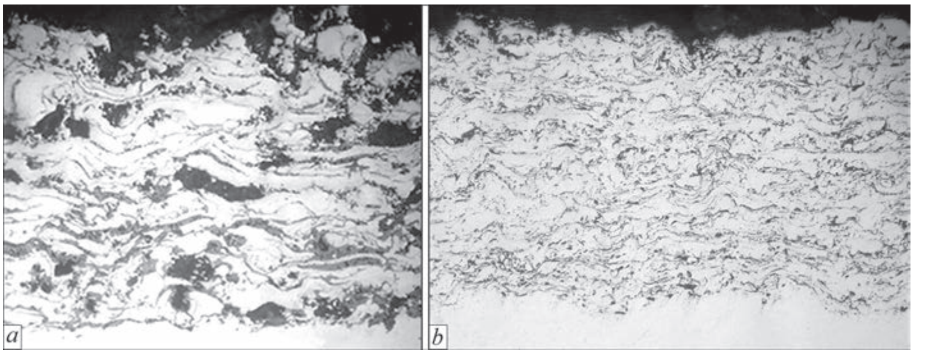

Figure 5. Microstructure (×400) of Fe + AlMg electric arc coating after heat treatment (*a*) and from flux-cored wire FCW (Fe–Al) (*b*), ×200

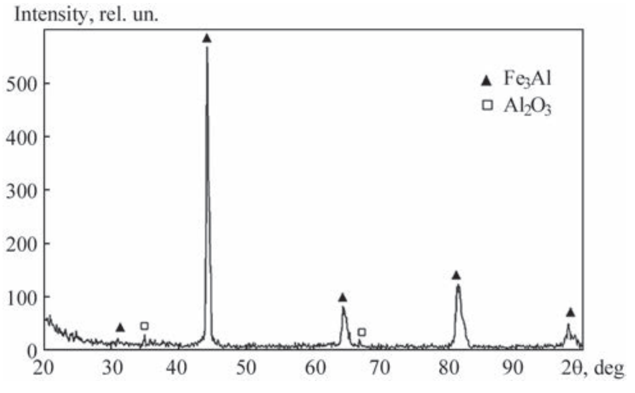

Figure 6. X-ray pattern of electric arc coating produced by spraying flux-cored wire FCW (Fe–Al)

whereas pure aluminium and iron were not detected applying the method of XSPA.

Comparing the microstructure of the coating after heat treatment (Figure 5, *a*) with the coating before heat treatment (Figure 3, *b*), an increase in strongly pronounced oxide interlayers with the presence of porosity along the boundaries of the lamellae is observed. At the same time pure aluminium and iron are not observed in the coating, and it consists of diffusion layers of lamellar structure. This indicates a complete proceeding of diffusion processes during heat treatment at the selected mode. The microhardness of the Fe + AlMg coating after heat treatment amounts to 2750 ± 760 MPa.

In the case of spraying flux-cored wire containing Al (FCW (Fe–Al)) powder as a filler, in the microstructure interlayers of pure aluminium of the coating are not observed (Figure 5, *b*). This suggests that all the aluminium powder in the spraying process reacted with the melt of steel sheath or oxidized. The microhardness of the coating amounts to 2460 ± 290 MPa.

XSPA of the FCW (Fe–Al) coating (Figure 6) showed that it consists of Fe_3Al phase, for which the flux-cored wire composition with the impurities of aluminium Al_2O_3 oxide was intended. This indicates that in the process of spraying FCW, a complete interaction of the steel sheath melts with the aluminium filler with the formation of intermetallic and a slight oxidation of aluminium particles occurs.

Conclusions

1. The study of the process of dispersion of melts of dissimilar Fe and Al wires in the conditions of electric arc spraying showed that as a result of combined spraying of wires, the interaction of particles during movement in the flow does not occur, and the spraying products consist of separate particles of iron and aluminium. The dispersion of the products of spraying wires of iron and aluminium is determined by the values of the surface tension of the melts of these materials and their average size is 59–63 μm during the use of Sv08A wire and 51–52 μm in the case of using A99 and AMg6 wires.

2. During deposition of coatings applying electric arc method in the case of combined spraying of iron and aluminium wires, the structure of the coating consists of Fe and Al lamellae. The intermetallic FeAl-structure of the coating in this case is formed by heat treatment of the coating at 650 °C for two hours.

3. When using a flux-cored wire consisting of a steel sheath and a filler (aluminium powder), intermetallic coatings are formed in the process of electric arc spraying, the main phase of which is Fe_3Al, which is a product of interfacial interaction between the sheath melts (Fe) and the powder filler (A1).

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