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STRESS IN ARC SPRAY COATINGS AND THEIR INFLUENCE ON ABRASIVE WEAR RESISTANCE

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Abstract. The effect of type I residual macro-stresses (σ_{res}) on the abrasive wear resistance of arc spray coatings (ASCs) was studied. Based on studies of the phase compositions of ASCs and its influence on the level of residual stresses σ_{res}, an empirical formula for determining these stresses is proposed. The workability of ASC depends not only on the level of σ_{res} in the coating, but also on its cohesive strength σ_c. Therefore, their ratio σ_{res}/σ_c is proposed as an indicator characterizing the susceptibility of ASC to cracking. It was empirically established that when $\sigma_{res}/\sigma_c > 0.75$, the coatings are prone to microcracking, and when $\sigma_{res}/\sigma_c > 0.85$, a network of microcracks is formed in them. Heating the samples before applying ASC with cored wires, as well as tempering after their spraying, reduces the tensile residual stresses in the coatings, promotes the precipitation of dispersed carbides and borides into their structure and, as a result, significantly increases their abrasive wear resistance.

Keywords: arc spray coatings, residual stresses, wear resistance.

1. INTRODUCTION

Among the many ways to improve the tribological and corrosion characteristics of materials, plasma-electrolyte oxidation is one of the most effective, but expensive methods to use [1, 2]. The most common method of thermal spraying of coatings is arc spraying [3–7]. Namely arc-sprayed coatings (ASCs) with cored wires (CWs) are widely used to restore shaft-type parts operated under high specific loads in oil-lubricated friction conditions. The advantages of ASC compared to other thermal spray coating methods include the simplicity of the technological process, minimal costs, high productivity, and the possibility to spray on their surface a layer of the required thickness (in the range of 0.1–10 mm) with desired properties. Therefore, the ASC method allows for the restoration of worn parts' dimensions and improves wear resistance [7–9]. Recently, the ultrasonic spraying method has been actively used to improve the homogeneity and properties of ASC [10–13]. During arc-spraying, significant residual tensile stresses of I type appear in coatings, contributing to cracks in their structure. Even at the stage of mechanical processing, macrocracks may form in the coatings, contributing to destruction during operation or significantly reducing the wear resistance of coatings. For that reason, the *work aims* to establish the influence of the CW charge's component composition on the level of residual stresses of I type in the ASC and to establish their relationship with abrasive wear resistance.

2. EXPERIMENTAL PROCEDURE

A Laval nozzle with a vertical arrangement of two air channels was used for ASCs with CW in the supersonic regime in an electro-metallizer (Fig. 1) [13]. By increasing the pressure of the air jet at the exit from the nozzle from 0.6 to 1.2 MPa, a supersonic air jet with Mach 2 was obtained. As a result,

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the speed of the air jet increased by a factor of 2 (from 300 to 600 m/s), and the speed of the CW melt droplets dispersed by the air jet increased from 60–90 to 160–220 m/s. All arc coatings were sprayed with CWs with a diameter of 1.8 mm. Their shell was made from a 10 mm wide strip of 08kp steel with a thickness of 0.4 mm, and powders of ferroalloys (FeSi, FeMn), metals (Cr, Ti) and B_4C carbide were added to their charge. The filling coefficient of the experimental cored wires was 24%. The surface of all ASCs was polished before testing.

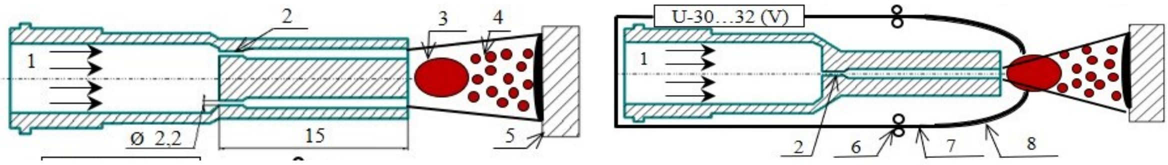


Figure 1. Schematic images of the nozzle of a metallizer for the formation of supersonic airflow (front (*a*) and top (*b*) views, respectively): 1 – airflow, 2 – critical section of the nozzle, 3 – melting of electrode materials, 4 – metal-air flow, 5 – steel substrate with a coating sprayed on the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

The ASC was tested for abrasive wear under conditions of rigidly fixed abrasive (Fig. 2). An abrasive disk made of electrocorundum of medium hardness CM-2 on a 7K15 ceramic bond, with a diameter of 150 mm and a width of 8 mm, was used. The grain size of electrocorundum was 250...315 μm (25A, 25H), the linear friction speed was 100 m/min, and the load in the zone of linear contact was 15 N. Abrasive wear resistance was estimated by the weight loss of the samples with an accuracy of 0.1 mg.

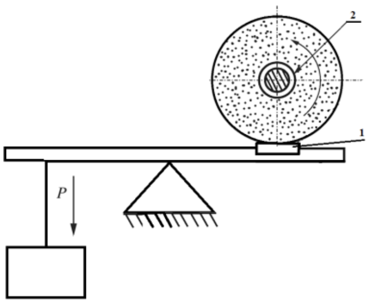


Figure 2. Scheme of equipment for studying abrasive wear resistance of ASC in contact with rigidly fixed abrasive: *1* – specimen; *2* – abrasive electrocorundum wheel; *P* – load

3. RESULTS AND DISCUSSION

Phase-structural state of ASC. In the arc during CW melting, exothermic reactions (1) occur between the boron carbide particles and chromium (or titanium) present in the CW charge with the release of a large amount of heat:

$$Cr + 2/7\ B_4C = = 4/7\ CrB_2 + 1/7\ Cr_3C_2 + 2.1\ kJ/g;\ 3Ti + B_4C = 2TiB_2 + TiC + 3,3\ kJ/g. \quad (1)$$

As a result, the formed carbides and borides of chromium are almost completely dissolved in the molten steel shell. Phase analysis of coatings made of such CW revealed supersaturated solid solutions based on α-Fe and γ-Fe and a significant amount of $FeCr_2B$ borides in their composition (Fig. 3). Spectral and X-ray structural analysis of such coatings did not fix amorphous boron in their structure. In this case, boron carbide interacted with the formation of only chromium-doped iron borides, the size of which did not exceed 200–400 nm (Fig. 4). Such coatings are characterized by high residual tensile stresses that arise during spraying. They are associated with the appearance of a network of microcracks in the coatings (Fig. 5) and a significant decrease in their wear resistance.

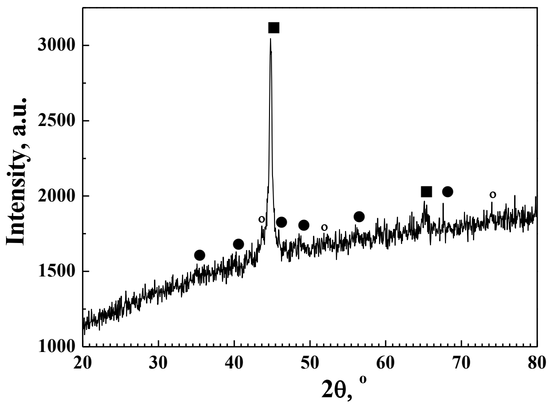


Figure 3. X-ray pattern of coating with CW 150Cr10B5MnSi:■ – γ-FeCr, ● α_m-FeCr, ○ $FeCr_2B$

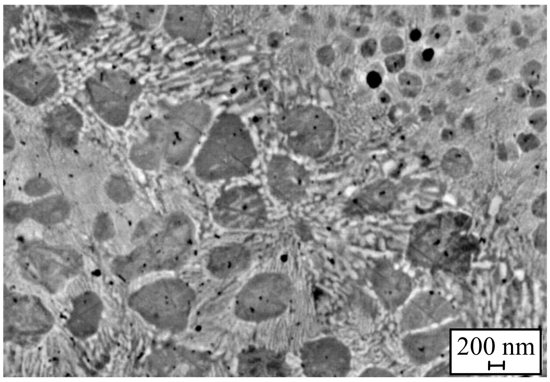
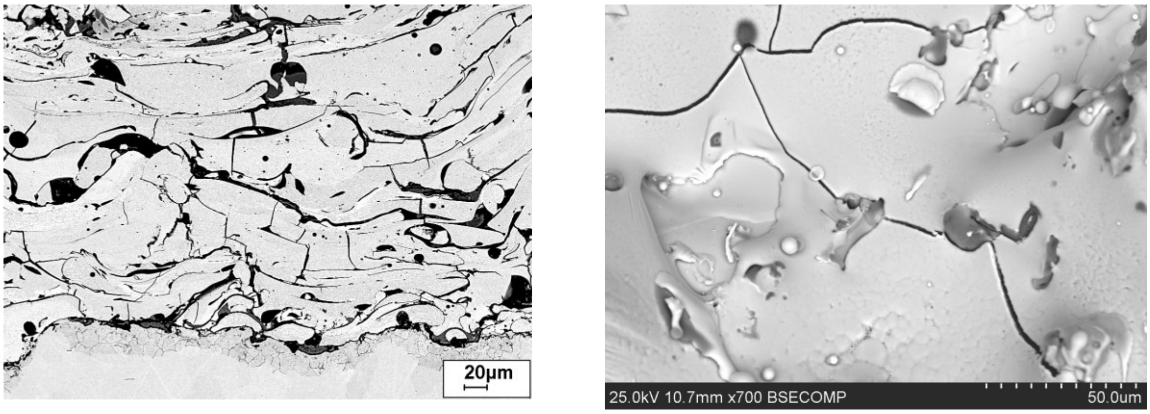


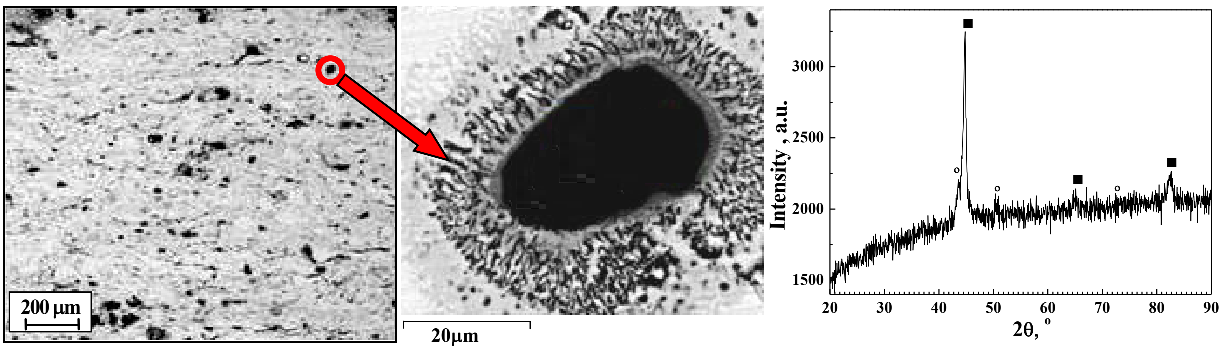
Figure 4. Dispersed $FeCr_2B$ phases in the structure of coating with CW 150Cr10B5MnSi



a) *b)*

Figure 5. Microcracks in the cross-section (a) and on the surface of coating with CW 150Cr10B5MnSi

In the structure of coatings sprayed with CW 150Ti10B5MnSi with the addition of (Ti + B_4C) to the composition, spectral analysis revealed structural components in the form of amorphous boron allocations 20...40 μm in diameter. Small allocations of $FeTi_2B$ iron borides were found along their perimeter (Fig. 6). The appearance of amorphous boron in the structure of such coatings is likely caused by the decomposition of B_4C, which begins at temperatures above 2450°C. Equation (1) shows that the amount of thermal energy released when B_4C interacts with titanium is much greater than when it interacts with chromium. Therefore, B_4C particles could heat up to a temperature above 2450°C, which created the prerequisites for their partial decomposition into carbon and amorphous boron. It is difficult to expect high hardness and abrasion resistance of ASC with such a structure.



a *b* *c*

Figure 6. Structure (*a*), amorphous boron particle (*b*), and phase composition (*c*) of ASC with CW 150Ti10B5MnSi (■ – γ-FeCr, ° – $FeCr_2B$).

The influence of tempering regime on the level of residual stresses in coatings. When determining the effect of tempering temperature on the level of residual stresses in ASC, CW was chosen, which would ensure the formation of coatings with different phase compositions. n particular, when CW Cr19Ni10 was used for sputtering, stable austenite was formed in the coating structure, CW 150Cr10Mn2 – residual austenite, CW 50Cr10Mn2 – martensite, and CW 0Cr10Mn2 – ferrite. In general, they try to increase the content of alloying elements (such as carbon and boron) to increase the hardness of ASC, but this is accompanied by an increase in residual tensile stresses of the I type in such coatings. The carbon content in the coatings has a decisive influence on the residual stresses in the coatings. When the carbon content in the coating reached 0.4 wt.%, the residual tensile stresses in ASC decreased to 20 MPa. When its content was increased by more than 0.4 wt.%, these stresses increased rapidly. Thus, with a carbon content of 1.4 wt.% in the coating, the stress level has already reached 150–160 MPa. This is due to the different phase composition of ASC with different carbon content. With carbon content in the coating of up to 0.4 wt.%, its structure was dominated by martensite, the level of tensile stress decreased with increasing carbon content. At the same time, the amount of residual austenite in the coating also increased, which led to an increase in residual tensile stresses due to further growth of its content.

After tempering at temperatures up to 400ºC, a slight tendency to decrease residual tensile stress was observed in all coatings (regardless of their phase composition) (Fig. 7). After tempering temperatures above 400°C, the residual tensile stress decreased significantly. At the same time, the residual austenite present in the structure of CW 150Cr10Mn2 coatings was transformed into tempered martensite, which was accompanied by an increase in the volume of the coating and a significant decrease in the residual tensile stresses in it. After tempering at temperatures above 400°C was applied to the coating sprayed with CW 150Cr10Mn2, residual compressive stresses were recorded in it because of corresponding structural transformations. Such stresses also occurred after tempering at temperatures above 400°C of the coating with CW 50Cr10Mn2, which was associated with the completion of martensite transformation present in its structure into the tempering martensite.

Generally, the higher the carbon content in the coating, the more residual austenite remains. Accordingly, the higher the carbon content in austenite, the greater the effect of changing its volume due to transformation into martensite. In coatings sprayed with unalloyed high-carbon CW, residual austenite transformation into martensite began at 200–300°C. As a result of CW alloying, the temperature interval of the beginning of structural transformations in coatings shifted in the direction of higher temperature. For the coating with CW 150Cr10Mn2, which contained 1.5 wt.% carbon and 10 wt.% chromium, the transformation of residual austenite into tempered martensite began during tempering from a temperature above 400°C (Fig. 7). Whereas in the coating with CW 0Cr10Mn2Al6, upon tempering from a temperature higher than 400°C, the level of tensile stresses in the coating did not decrease but increased. This is due to the release of iron intermetallic in the coating. At the same time, the volume of the coating began to decrease, which caused an increase in tensile stresses in it.

Based on the experimentally obtained dependences of the influence of the phase composition of ASC and their carbon content on the residual stresses σ_{res} in the coatings, an empirical formula was proposed for their determination:

$$\sigma_{res} = [0.25 \cdot M \cdot (0.4 - C) + 1.6 \cdot A + 0.7 \cdot F + 0.9 \cdot F_{stab}] \text{ MPa} \quad (2)$$

where M, A, F, F_{stab}, and C are the content of martensite, austenite, ferrite, aluminum-stabilized ferrite, and carbon in the ASC, wt.%.

Empirical formula (2) makes it possible to quantitatively estimate residual stresses in coatings with a known ratio of phases. At the same time, the level of residual stress in the coating is not important; rather, its relationship with cohesive strength σ_c is an indicator of resistance to crack formation. The results of the study of coatings obtained from all analyzed CW concluded that individual microcracks began to form in the coatings under the condition that the index $\sigma_{res}/\sigma_c > 0.75$. When this the index is $\sigma_{res}/\sigma_c > 0.85$, the network of cracks forms in the coating structure. From this, it is clear how important it is to identify patterns of influence of spraying parameters on this indicator.

Using the example of coatings made of CW 150Cr10B5MnSi, a relationship was established between the parameters of spraying of coatings (current and pressure of spraying air) and the index σ_{res}/σ_c

(Fig. 8). Thus, the ratio σ_{res}/σ_c practically did not change with the growth of spraying productivity (using a higher current). With an increase in the air jet's pressure from 0.3 to 0.65 MPa, the σ_{res}/σ_c indicator increased from 0.5 to 0.68, approaching the limit at which microcracks began to appear in the coating. In addition, it should be considered that it is impossible to prevent the occurrence of an additional burst of tensile stresses in the coating after the end of the filing process. The steel substrate was heated to 200–250°C before filing to avoid this. Thanks to this, it was possible to significantly reduce the σ_{res}/σ_c indicator to the value of 0.2 (Fig. 8). The change of the proposed index σ_{res}/σ_c in the range of 0–0.7 practically did not influence the abrasive wear resistance of ASC. After it exceeded this range, a network of microcracks formed in the coatings, and their wear resistance rapidly decreased. Samples or parts were pre-heated (before spraying) to avoid unwanted cracking. This prevented the decrease in the ratio σ_{res}/σ_c characteristic of ASC and increased their performance. In real conditions, it is not always possible to implement the heating of parts before spraying (this especially applies to large-sized elements). Experience has shown that in these cases, to avoid cracking of coatings during spraying on similar parts, their first layers should be applied at low currents (100–120 A) and low air pressure (0.3–0.4 MPa). Thanks to such a combination of spraying modes, it was possible to significantly increase the cohesive strength of the ASC, reduce the residual tensile stresses, and achieve such a value of σ_{res}/σ_c that no cracks appeared in the coating.

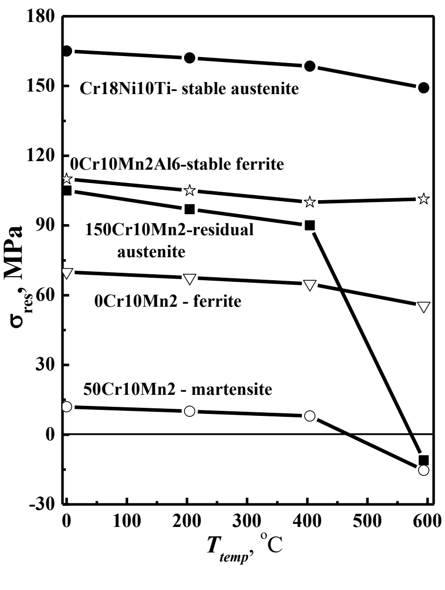


Figure 7. The influence of tempering temperature T_{temp} of ASC samples sprayed with different CWs on residual stresses σ_{res} in coatings.

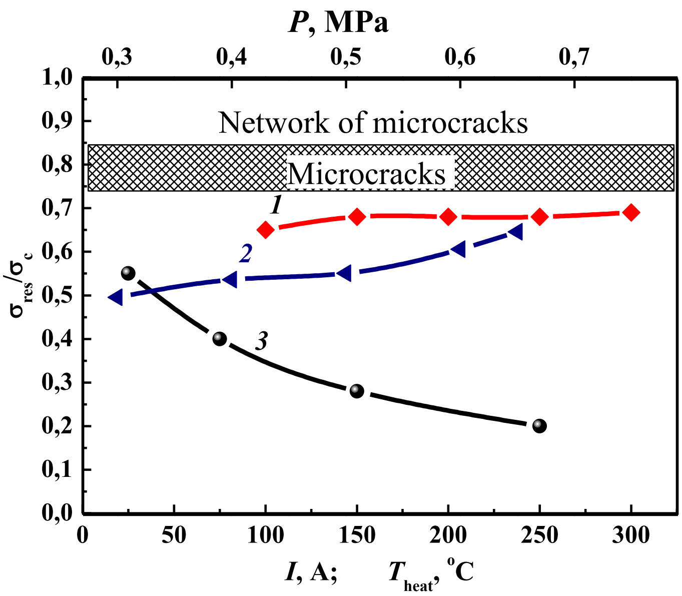


Figure 8. The ratio of residual stresses and cohesive strength σ_{res}/σ_c in the ASC with CW 150Cr10B5MnSi depending on the parameters of its spraying: current *I* (1), air jet pressure *P* (2) and sample heating temperature before spraying T_{heat} (3).

The correctness of the obtained patterns regarding the influence of residual stresses on the abrasive wear resistance of ASC was checked on coatings sprayed with CW 150Cr10B5MnSi and CW 150Ti10B5MnSi. It was established that heating the samples to 200°C before spraying and tempering at a temperature of 550°C for 2 hours after spraying significantly reduces the residual tensile stresses in the coatings of both options (Table 1). Thus, in the ASC with CW 150Ti10B5MnSi, heating the substrate before spraying caused a fourfold decrease in the residual tensile stresses. Two-hour tempering at a temperature of 550°C eliminated the tensile stresses in ASC, and even residual compressive stresses (~10 MPa) were recorded in the coating. The positive effect of heating the substrate and tempering was somewhat smaller in the ASC with CW 150Cr10B5MnSi coating. Still, the general tendency to reduce the residual stresses in the coating during their application was also preserved in this case.

The change in residual stresses in ASC after additional thermal exposure before or after their application positively affected the abrasive wear resistance of such coatings, which increased several times (Table 2).

In particular, the abrasive wear resistance of the ASC with CW 150Ti10B5MnSi, sprayed without pre-heating, was 30% worse than that of the prototype (ShKh15 steel with a hardness of 62 HRC). Pre-heating the substrate to 200°C made it possible to increase its abrasion resistance twice (compared to the prototype). After tempering, the abrasive wear resistance in the conditions of the fixed abrasive of such a coating increased as much as 5 times. The positive effect of both variants of heat exposure on the abrasive wear resistance of the ASC with CW 150Cr10B5MnSi turned out to be much smaller, but the more than twofold increase in performance compared to the prototype with high hardness is also an excellent result. It was assumed that tempering of the ASC had a striking effect due to the release of finely dispersed titanium-doped iron borides from amorphous boron particles, which contributed to the coating's dispersion strengthening and increased its abrasive wear resistance.

Table 1. Effect of heat treatment on the level of residual stresses in ASC.

CW type	Residual stresses in ASC σ_{res}, MPa		
	Without heating the steel substrate before spraying	With the heating of the steel substrate to 200°C before spraying	Post-tempering of a ASC at 550°C for 2 hours
CW 150Ti10B5MnSi	160	40	-10
CW 150Cr10B5MnSi	120	50	-5

Table 2. The effect of heat treatment on the abrasive wear resistance of ASC.

CW type	The abrasive wear resistance of ASCs relative to the standard for comparison (ShKh15 steel with a hardness of 62 HRC)		
	Without heating the steel substrate before spraying	With the heating of the steel substrate to 200°C before spraying	Post-tempering of a ASC at 550°C for 2 hours
CW 150Ti10B5MnSi	0,7	2,0	5
CW 150Cr10B5MnSi	1.3	2.3	2.2

The results obtained in this way prove the appropriate use of tempering for ASC with the proposed CW for appreciable reduction of tensile residual stresses in coatings, promotion of separation of dispersed carbides and borides in their structure, and, as a result, a significant increase of their abrasive wear resistance in conditions of fixed abrasive.

4. CONCLUSIONS

- In the structure of the ASC with CW 150Ti10B5MnSi dopped by (Ti + B_4C), the allocation of amorphous boron with a size of 20...40 µm with a rim of iron borides Fe_2B was detected. This is due to the decomposition of B_4C at temperatures above 2450°C. When tempered at 550°C, amorphous boron particles form iron borides alloyed with titanium, which contribute to a five-fold increase in the abrasive wear resistance of the coating compared to ShKh15 steel with a hardness of 62 HRC.
- An empirical formula for determining the residual stresses σ_{res} in ASC is proposed, which takes into account the experimentally obtained dependences on the influence of the phase composition and carbon content in ASC on σ_{res}
- The ratio of residual stresses in coatings σ_{res} to their cohesive strength σ_c is proposed to be used as an indicator of coating resistance to cracking. Based on the analysis of the obtained coatings, it is shown that cracks begin to form in coatings for which the index $\sigma_{res}/\sigma_c > 0.75$, while for $\sigma_{res}/\sigma_c > 0.85$, a network of cracks appears in the coatings.
- It was established that pre-heating the samples and post-tempering reduce the residual tensile stresses, promotes the separation of dispersed carbides and borides in their structure, and significantly increases their abrasive wear resistance.

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