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FLUX-CORED WIRE FOR RESTORATION SURFACING OF WORN SURFACES OF RAILWAY WHEELS*

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Research was performed and flux-cored wire of PP-AN180MN/98 grade was developed for restoration surfacing of worn areas of advanced higher-strength railway wheels. A set of physicomechanical properties of the deposited metal was determined. It is found that at application of PP-AN180MN/98 wire for surfacing higher-strength wheels, irrespective of preheating temperature and number of deposited layers, deposited metal hardness is optimum (0.94–1.0 of rail hardness). Here, a comparatively homogeneous bainite-martensite structure forms in all the joint areas (in the deposited metal, fusion zone and overheating area of HAZ metal). The deposited metal features a high level of resistance to brittle fracture and wear at sliding friction in contact with rail steel. Obtained research results lead to the conclusion that at application of flux-cored wire PP-AN180MN/98 for surfacing, the restored wheels will have a high reliability, and traffic safety will be ensured under the conditions of increasing operating loads. 17 Ref., 5 Tables, 4 Figures.

Keywords: *electric arc surfacing, railway wheel, flux-cored wire, structure, mechanical properties, brittle fracture, wear*

At present freight car wheels are made in Ukraine from high-strength steel of grade 2, with carbon content of 0.55–0.65 %. This steel ensures quite high values of mechanical properties of wheel metal — ultimate strength σ_t = 930–1130 MPa, wheel rim hardness $HB \geq 2500$ MPa [1, 2]. Wheels made from such steel have quite high reliability in operation at a relatively low cost. The level of load on the axle of freight car wheel pair in operation in the railways of Ukraine and CIS countries is up to 23.5 t.

During operation the wheels wear on rolling profile. Because of the features of work of «wheel–rail» friction-rolling pair, the working surface of the wheel flange wears more intensively, and defects of the type of «nicks» often form on the wheel rolling surface. Flange wear occurs as a result of mechanical friction, and at development of «nicks» the thermomechanical nature of defect initiation is realized as a result of quenching structure formation in subsurface layer of wheel metal [3–5].

Surfacing technologies are traditionally applied at restoration of worn wheel flanges, which is cost-effective. Restoration of flange wear by surfacing allows reducing the rim metal wastes at mechanical turning along the wheel rolling profile, as well as lowering the flange wear due to deposition of metal with specified properties on its surface [6, 7]. Nowadays the wheels with «nicks» are not restored by surfacing, but they are treated by turning up to complete removal of the defects.

At present application of solid wires of Sv-08KhM, Sv-08KhMF and Sv-10KhN2GSMFTYu types, as well as flux-cored wire of PP-AN180MN/90 grade (10KhNMGSFT alloying system), is recommended for surfacing the railway wheel flanges. Surfacing with solid wires is performed as submerged-arc process, and surfacing with flux-cored wire is conducted both using flux and in shielding gas atmosphere. Metal, deposited with application of these welding consumables, matches the level of strength and hardness of railway wheels, made from wheel steel of grade 2, and also features higher wear resistance.

Modern tendencies in development of domestic main railway transport are aimed at increasing the axle load up to 27.5 t and freight train speed up to 150 km/h that requires application of higher strength wheels, the metal of which would have sufficiently high level of crack and wear resistance. In this connection, today in Ukraine, new wheel steels are developed on the base of wheel steel of grade 2, in which improvement of physicomechanical properties is achieved by their microalloying by carbide- and nitride-forming elements [8–10].

It is obvious that the recommended welding consumables cannot be used for restoration surfacing of the developed higher strength wheels. Therefore, the

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Table 1. Chemical composition of deposited metal of test flux-cored wires, wt.%

PP-AN180MN/90 wire	C	Si	Mn	Cr	Ni	Ti	V	S	P
I	0.07	0.42	0.8	0.8	0.5	0.018	0.08	0.01	0.025
II	0.14	0.62	1.3	1.1	0.7	0.028	0.10	0.02	0.025
III (PP-AN180MN/98)	0.12	0.48	1.15	0.96	0.7	0.022	0.10	0.02	0.03
IV	0.067	0.45	1.02	0.32	0.4	0.016	0.10	0.01	0.01

objective of this work was development of the new welding consumable, with application of which the deposited metal would correspond to the set of properties of higher strength wheel metal. This will allow an essential extension of the operating life of new wheels and ensuring traffic safety at increase of operating loads.

Experimental procedures. The new welding consumable was developed with application of physical testing methods for evaluation of strength, ductile and impact toughness properties of the deposited metal according to GOST 1497 and GOST 9454. Wear resistance was determined in keeping with the accepted methods of wear testing at «friction-sliding» of the contacting surfaces of metal products [11, 12]. Deposited metal resistance to brittle fracture was assessed at three-point bending using fracture mechanics criteria [13, 14]. Traditional optical microscopy methods were used to study structural changes in the metal.

The object of study was metal deposited with PP-AN-180MN/90 wire and with the new developed welding consumable. In some experiments, wires of Sv-08KhM and Sv-10KhN2GSMFTYu grades were used for comparison.

Development of welding consumable. Flux-cored wire of PP-AN180MH/90 (10KhNMGSFT) grade was taken as the base for development of the new consumable. $CaO–MgO–CaF_2–SiO_2$ system, which is traditionally used in a number of wires of PP-AN180MN type, was selected as the slag system for the new flux-cored wire. Test compositions of deposited metal obtained during development of the new wire are shown in Table 1.

Hardness is one of the main indices of mechanical characteristics of the deposited metal, which is responsible for its operating properties. In order to determine the hardness values of the deposited metal, comparative single-, two- and three-layer deposits in shielding gases at energy input of 8.5–10 kJ/cm^2 were made on 200×100×20 mm samples of wheel steel of grade 2 (0.58 % C) at the first stage of wire development. Preheating temperature was equal to 150 °C, as in surfacing the railway wheel flanges. Hardness was determined on the deposit surface with application of hardness meter of TK grade in *HRC* units with subsequent conversion to *HB* units. Hardness measurement results are given in Table 2.

As one can see, hardness of the 1st, 2nd and 3rd layers of the metal, deposited with test flux-cored wire II, is higher than that of rail steel ($HB \geq 3200$ MPa). Optimized alloying and slag systems of test flux-cored wire III ensure stable values of hardness of the 2nd and 3rd layers of the deposited metal (on the level of 3000–3200 MPa). Molybdenum was removed from the alloying system of the flux-cored wire without lowering of the mechanical and technological characteristics. Test sample of flux-cored wire PP-AN180MN/90 (III) was taken as the base and was assigned the working grade PP-AN180MN/98.

Deposited metal structure at application of PP-AN180MN/90 and PP-AN180MN/98 wires is characterized as bainite-martensite. At deposition with PP-AN180MN/90 wire without preheating the ratio of bainite and martensite structural components is equal to 55/45, at 100 °C preheating it is 70/30. At deposition under similar conditions with PP-AN180MN/98 wire, the ratio of bainite and martensite is equal to 50/50 and 65/35, respectively. Microhardness of bainite structural component changes, depending on preheating temperature, in the range from 2820 up to 3090 MPa, that of martensite — from 3290 up to 3660 MPa. In the fusion zone and in coarse-grain area in the HAZ, the fraction of bainite rises up to 75 %. Characteristic structures of the joint metal at surfacing with PP-AN180MN/98 wire are shown in Figure 1.

At the second stage, the level of deposited metal hardness at surfacing a wheel pair from steel 2 with preheating to 250 °C was evaluated. Such a tempera-

Table 2. Deposited metal hardness, depending on composition and number of deposit layers (T_{pr} = 150 °C)

PP-AN180MN/90 wire	Number of deposited layers	*HB*, MPa
I	1	2500–2700
	2	2300–2500
	3	2000–2300
II	1	3200–3700
	2	3500–3600
	3	3400–3500
III (AN180MN /98)	1	3200–3500
	2	3000–3200
	3	2800–3100
IV	1	2400–2700
	2	2200–2400
	3	2000–2200

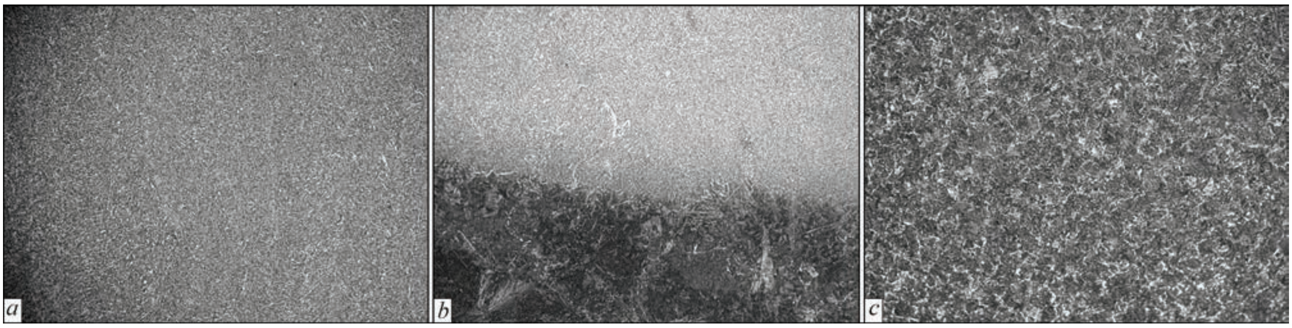

Figure 1. Microstructure (×200) of single-layer deposit made with PP-AN180MN/98 wire at energy input of 8.9 kJ/cm at T_{pr} = 100 °C: *a* — deposited metal; *b* — fusion zone; *c* — HAZ overheating zone

ture of metal is characteristic for the wheel rim after the 5th pass at continuous process of flange surfacing. Investigation results are given in Figure 2. For comparison the Figure also gives the data on hardness values of the metal deposited with other materials. The dash-dotted line marks the hardness level of higher strength wheels. As one can see, flux-cored wire PP-AN180MN/98 provides stable high results on deposited metal hardness even at such a temperature.

Flux-cored wire PP-AN180MN/98 belongs to wires with low-slag base (less than 6 % of slag-forming components), that allows elimination of the negative effect of charge component separation in wire manufacture on its welding-technological properties and ensuring stability of deposited metal properties. The ratio of components, making up the slag base, guarantees high parameters of welding-technological properties in terms of slag crust separation, deposited metal spreading, bead surface formation and smooth transitions between the beads and base metal. The slag base of the wire ensures high resistance to porosity at low consumption of shielding gas (8–10 l/min) and low level of diffusible hydrogen in the deposited metal (0.3–0.5 cm^3/100 g), that is indicative of high resistance of the deposited metal to cold cracking.

The alloying base of the welding wire includes such components as chromium, nickel, manganese and titanium, ensuring high enough hardness of the deposited metal (Table 3) at the required level of mechanical characteristics. Mechanical properties of the metal deposited with PP-AN180MN/98 wire are given in Table 4.

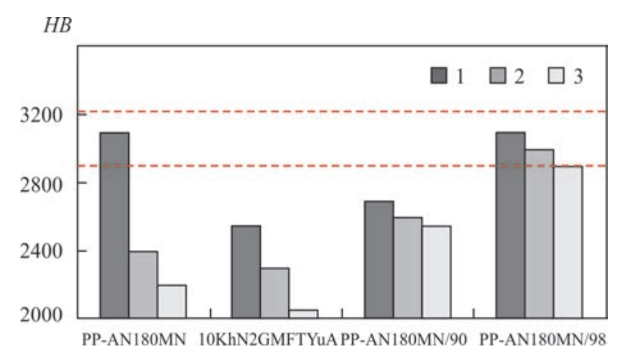

Figure 2. Deposited metal hardness at T_{pr} = 250 °C: *1* — 1st layer; *2* — 2nd layer; *3* — 3rd layer

Thus, the optimized alloying system of flux-cored wire PP-AN180MN/98 provides higher and more stable indices of deposited metal hardness (on the level of 3000–3200 MPa), than in deposition with other consumables. These values are optimum both at single-layer, and at multilayer surfacing of railway wheels. As shown by further studies, the metal deposited with flux-cored wire PP-AN180MN/98 also has higher brittle fracture resistance.

Brittle fracture resistance of deposited metal. It is known that deposited metal resistance to cracking under the impact of external loading, depends on its structural condition, which is determined by its chemical composition and cooling rate. Presence of diffusible hydrogen in the deposited metal also significantly affects crack initiation and propagation. Amount of diffusible hydrogen in the deposited metal is determined by welding method and modes, and the degree of its diffusion — by the metal chemical composition and temperature.

Deposited metal samples for testing were cut out of multilayer joints, which were made in the groove of a butt joint with 10 mm gap in the root. Deposits were

Table 3. Metal hardness at surfacing with PP-AN180MN/98 wire (T_{pr} = 50 °C)

Surfacing method	Surfacing energy input, kJ/cm	Number of deposited layers, pcs	*HB*, MPa
In CO_2	8.5–10	1	3200–3500
		2	3100–3150
		3	3000–3200
Under a layer of AN-60 flux	9–11	1	3200–3500
		2	3000–3200
		3	2800–3100

Table 4. Mechanical properties of metal at surfacing with PP-AN180MN/98 wire (T_{pr} = 150 °C, CO_2 surfacing method)

$\sigma_{0.2}$, MPa	σ_t, MPa	δ_5, %	ψ, %	*KCU*, J/cm²			*HB*, MPa
				+20	–40	–60	
800	890	10.7	54.3	96.0	76.8	66.5	3000–3200

Table 5. Brittle fracture resistance of deposited metal

Welding consumable	T_{pr}, °C	Deposited metal structure	K_{1c}, MPa√m	
			20 °C	–40 °C
Sv-08KhM	–	Bainite	97.9	88.5
	100	Bainite-pearlite	86.4	69.8
PP-AN180MN/90	–	Bainite-martensite 55/45	105.6	92.2
	100	Bainite-martensite 70/30	110.3	97.7
PP-AN180MN/98	–	Bainite-martensite 50/50	104.2	90.6
	100	Bainite-martensite 65/35	109.8	96.2

made by submerged-arc process using AN-60 flux. The following welding consumables were used: 3 mm solid wire Sv-08KhM and 2 mm flux-cored wires PP-AN180MN/90 and PP-AN180MN/98. Surfacing energy input was in the range of 9–11 kJ/cm. Surfacing was performed with and without metal preheating to temperature T_{pr} = 100 °C. Diffusible hydrogen content in the deposited metal, which was determined by pencil test, was equal to 3.5–3.8 ml/100 g in surfacing with Sv-08KhM wire and 2.2–2.4 ml/100 g at application of PP-AN180MN/90 and PP-AN180MN/98 wires.

A fatigue crack 3.0 mm deep was pre-grown in the samples. Then the samples were tested by three-point bending. The criterion for evaluation of deposited metal brittle fracture resistance was the critical stress intensity factor K_{1c}, at fracture of samples, which was calculated according to standard procedures of fracture mechanics [15]. Results of deposited metal testing for brittle fracture are generalized in Table 5.

It is found that without preheating brittle fracture resistance of the deposited metal at application of flux-cored wires PP-AN180MN/90 and PP-AN180MN/98 is approximately 10 % higher, than at surfacing with Sv-08KhM wire. This difference becomes greater at preheating up to the temperature of 100 °C. Increase of the critical stress intensity factor is already equal to 22 % at testing temperature of 20 °C and to 40 % at –40 °C. Here, deposited metal fracture, irrespective of the surfacing method and preheating temperature, occurs in the brittle mode at development of the main crack.

It should be also noted that brittle fracture resistance of the metal deposited with Sv-08KhM wire, decreases by 12 % with preheating at testing temperature of 20 °C and by 21 % at –40 °C. At surfacing with flux-cored wires, contrarily, brittle fracture resistance of weld metal rises by approximately 4 % at application of preheating up to the temperature of 100 °C.

Established changes in brittle fracture resistance of the deposited metal, depending on alloying system of the welding consumable and preheating temperature, are attributable to joint action of two factors. First, diffusible hydrogen content in the metal deposited with flux-cored wires is almost 1.5 times lower than at surfacing with Sv-08KhM wire (2.3 compared to 3.65 ml/100 g). Secondly, this is a structural factor. Quenched metal, which has a mixed bainite-martensite structure, has higher resistance to brittle fracture than metal with just the bainite structure, or with the structure having a fraction of pearlite component [14, 16].

Deposited metal wear resistance. Wear resistance is one of the main indices of operational strength of railway wheels restored by surfacing. Wear resistance of deposited metal was assessed at «friction-sliding» of model samples. Testing was performed in keeping with the accepted research methods [12, 17]. According to this method, the deposited metal sample of 25×15×3 mm dimensions was pressed to the counterbody from rail steel of M-76 grade, which rotated at a constant speed (Figure 3). The sample pressing force

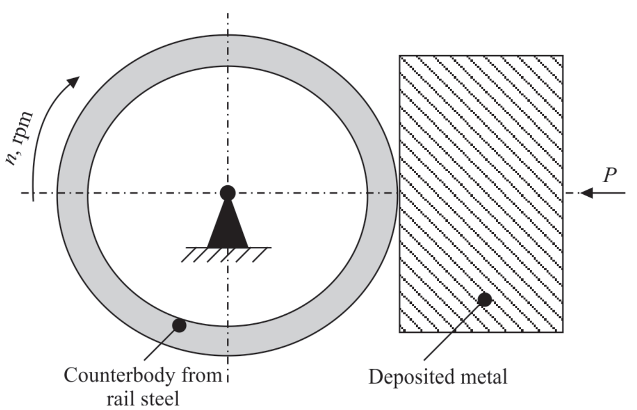

Figure 3. Schematic diagram at testing deposited metal samples at «friction–sliding»

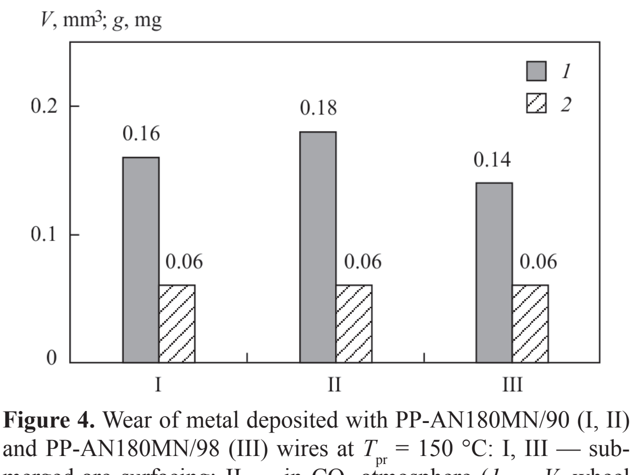

Figure 4. Wear of metal deposited with PP-AN180MN/90 (I, II) and PP-AN180MN/98 (III) wires at T_{pr} = 150 °C: I, III — submerged-arc surfacing; II — in CO_2 atmosphere (*1* — *V*, wheel steel); *2* — *q*, rail steel)

was equal to 81.3 N, counterbody rotation speed was 30 rpm, and testing time was equal to 30 min.

Contact of deposited metal sample and counterbody from rail steel resulted in wear of metals — a pit of constant depth formed on the sample, and a ring-shaped groove appeared on the counterbody surface. The extent of counterbody wear by weight (g, mg) was determined by weighing before and after loading in analytical scales (accuracy of 0.0005 g), and sample wear was determined by pit volume (V, mm^3). Generalized testing results of deposited metal of different alloying systems are given in Figure 4.

As is seen from the given data, at gas-shielded surfacing with PP-AN180MN/90 wire, unlike submerged-arc surfacing, deposited metal wear resistance decreases by approximately 11 % (pos. 1 and 2). This is related to the features of running of metallurgical processes at different surfacing methods. At CO_2 surfacing, partial burnout of titanium from the metal runs more intensively. At submerged-arc surfacing with PP-AN180MN/98 wire (pos. 3) deposited metal wear resistance rises by approximately 12.5 %.

Conclusions

1. New flux-cored wire PP-AN180MN/98 (12GSKhNFT) was developed on the base of flux-cored wire PP-AN180MN/90, due to optimization of alloying system (10GSKhNFT) and low-slag base (CaF_2–$CaCO_3$–MgO–SiO_2), which is not prone to separation.

2. At application of PP-AN180MN/98 wire for surfacing higher strength wheels, irrespective of preheating temperature and number of deposited layers, deposited metal hardness is optimum and equal to *HB* 3000–3200 MPa (rail hardness $HB \geq 3200$ MPa). Here, comparatively homogeneous bainite-martensite structure forms in all the joint areas (in the deposited metal, fusion zone and in the overheating area of the HAZ metal).

3. Metal deposited with PP-AN180MN/98 wire has a high wear resistance at «friction-sliding» at contact with the rail. Wear resistance of metal, deposited with PP-AN180MN/98 wire, is 12.5 % higher than in surfacing with PP-AN180MN/90 wire. Here, rail wear is not increased.

4. Deposited metal has a high level of brittle fracture resistance that allows recommending PP-AN180MN/98 wire for application for surfacing higher strength wheels. Restored wheels will have a high reliability, and traffic safety will be ensured under the conditions of increasing operating loads.

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