Welding International 2006 **20** (6) 483–487
Selected from Svarochnoe Proizvodstvo 2006 **59** (1) 17–22; Reference SP/06/01/17; Translation 3647

Flux-cored wire for the deposition of alloys based on nickel aluminide

doi:10.1533/wint.2006.3647

S N TSURIKHIN, G N SOKOLOV, V I LYSAK, I V ZORIN and E I LEBEDEV
Volgograd State Technical University

Creep-resisting surface in alloys for the hardening of metallurgical equipment (pressing dies, jigs for pipe-rolling mills, blades for cutting hot-rolled stock and other components, subjected to the cyclic temperature–force effect in heating temperatures above 800 ºC) are characterised mainly by the nickel base and contain, in addition to the refractory alloying elements (tungsten, molybdenum, tantalum) also low-melting components, for example, aluminium. In this case, the highest efficiency is shown by complexly alloyed alloys based on nickel aluminide Ni_3Al-ZhS6U-NK, VKNA-1V-NK,[1,2] and foreign analogues of these alloys WAZ-16, NX188, TAZ-8B, TRW.[3] The production of Ni_3Al is possible because of the stoichiometric ratio of the content of nickel and aluminium in these alloys. In this case, the content of aluminium in alloy may reach 10–12% of the total content of the heavy refractory components (Cr, Ta, W, Mo) of up to 20%.

The problem of deposition of alloys with similar alloying is based on the difficulties in producing the physically and chemically homogeneous deposited metal because of the nonuniform melting of the metallic components, present in the surfacing materials, and characterised by different melting points, and also because of the separation of heavy and light metallic fractions in the charge of the flux-cored wires, coatings of the electrodes and other materials.[4]

The aim of the present work is the development of a composition of a flux-cored wire (CFCW) resulting in the formation of the deposited creep-resisting alloy based on Ni_3Al, and the examination of its structure-phase composition and high-temperature properties.

The flux-cored wire was produced from nickel NP-2 strip (GOST 2170) with the size of 0.6 × 16 mm for the outer layer of the shell, and the strip of A97 aluminium alloy (GOST 7871), size 0.12 × 12 mm, for the internal layer of the shell. The filler was in the form of a wire of commercial purity metals (Ta, W, Mo) with a diameter of 0.6 mm each, and also Np-Kh20N80 nichrome with the diameter of 1 mm and a charge of a mixture of metallic powders of aluminium, nickel, zirconium and GSP graphite.

The microstructure of the deposited metal was investigated in an Olympus BX61 Digital microscope. The phase composition of the metal was determined by X-ray diffraction analysis in copper radiation in a DRON-3M diffractometer, with the speed of movement of the counter of 1°/min and the range of the angles of reflection $2\theta = 20 \div 120°$. The hardness of the deposited metal at higher temperatures, up to 1100 ºC, was determined in equipment TSh-2 using a hard-alloy beryllium-coated ball with a diameter of 5 mm, the load 7.35 kN, holding time 10 s.

The wear resistance of the deposited metal was evaluated by the method of high-temperature hardness measurements at 850, 950 and 1050 ºC.[5] The criterion of wear resistance was the ratio:

$$I = \frac{I}{V_d}, \qquad [1]$$

where V_d is the volume of the metal deformed by a conical diamond indentor over the length of $l = 10$ mm.

The load on the indentor was 0.6 N, with the movement in relation to the tested specimen at a speed of 4 mm/s. This test procedure makes it possible to ensure of the correlation of the experimental data with the high-temperature hardness of the investigated alloys and determine the alloys with the highest wear resistance for the given working temperature range of the alloys.

The flux-cored wire consists of a two-layer shell, in which the outer layer is produced from nickel, and the inner layer from aluminium. Inside the shell, the metallic wire cores are made of tungsten, molybdenum, nichrome and tantalum, and the remaining volume of the shell is filled with the mixture of the metallic powders of nickel, aluminium and zirconium. The distribution of the electrically conducting powders of nickel and aluminium in the charge and introduction into the charge of refractory heavy metals into the charge of the wires reduces the extent of separation of the components in the charge of the wire and makes it possible to reduce the general resistance of the wire. This design of the flux-cored wire results in relatively uniform density of welding current in the cross-section. This leads to the more uniform melting of the components of the flux-cored wire both in electroslag surfacing and in the arc process, and improves the welding-technological properties and homogeneity of the deposited metal.

To produce the matrix of deposited metal on the basis of Ni_3Al, the mass of the nickel and aluminium, introduced into the flux-cored wire was selected from the stoichiometric ratio:

$$\frac{Ni_c + Ni_{sh}}{Al_c + Al_{sh}} = 6.52, \qquad [2]$$

where Ni_c, Ni_{sh}, Al_c, Al_{sh} is the content of nickel and aluminium respectively in the charge and in the nickel and aluminium layers of the composite flux-cored wire,%.

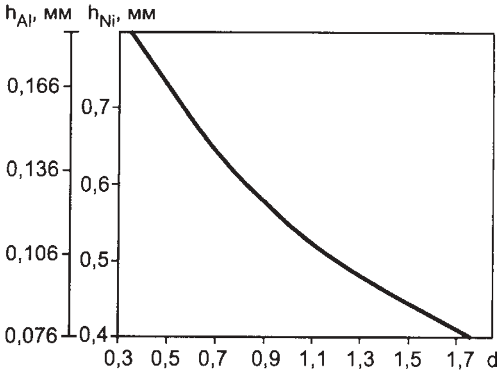
In order to ensure this ratio of the content of aluminium and nickel in the flux-cored wire in production, the thickness of the external h_{Ni} and internal h_{Al} layers of the shell was selected in the range 0.4–0.8 and 0.0 76–0.185 mm, respectively (Fig. 1). The nickel and aluminium content of the charge depends on the coefficient *d* which takes into account the ratio of the content of nickel in the charge and in the shell of the wire or the aluminium content in the charge of the wire and in the shell. The coefficient was calculated from the following relationship on the basis of the selected thickness of the nickel and aluminium layers of the shell (Fig. 1):

$$d = \frac{Ni_c}{Ni_{sh}} = \frac{Al_c}{Al_{sh}}. \qquad [3]$$

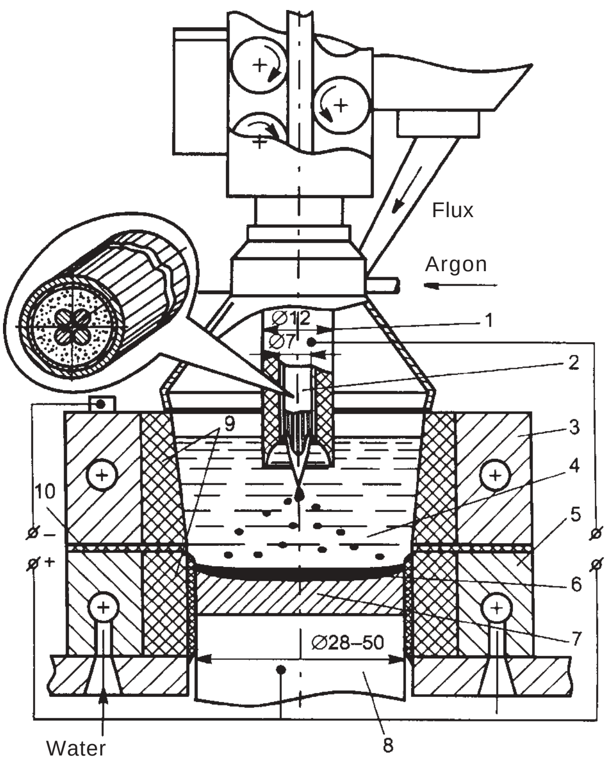
Taking into account the values of d, calculations were carried out to determine the mass of the nickel and aluminium shells, and also the required content of nickel and aluminium in the charge of the wire. As the thickness of the layers of the shell increases, the value of the coefficient d decreases and, consequently, the aluminium and nickel content of the charge also decreases. The content of other elements in the flux-cored wire was calculated on the basis of the values obtained in the production of the standard creep-resisting alloy.[1] The limits of the selected thickness values of the layers of the shell of the flux-cored wire are determined by the narrow range of the possible diameters of the wires, 4–5 mm. The manufacture of the flux-cored wire with the diameter smaller than 4 mm is not rational because of two reasons: the decrease of the filling factor of the flux-cored wire and restricting the possibility of alloying the metal, and the increase in the probability of breaking in the drawing process because of the low deformation capacity of high-strength wires made of refractory metals.

In the process of drawing the starting components filled with the wire and powder components, the filling factor K_f was 0.83. In the calculation of the factor K_f, the mass of the charge was calculated taking into account the mass of the wire components. In the fabrication of the flux-cored wire with the diameter of 5 mm in a single-drum wire mill, the U-shaped profile of the wire, produced from the aluminium strip, was filled with the charge prior to compression. The charge contained powders of the ductile metals (Al, Ni) and, consequently, it was possible to close the cavities between the wire components positioned in the coaxial direction in relation to the shell. No breaking of the wires was detected in drawing.

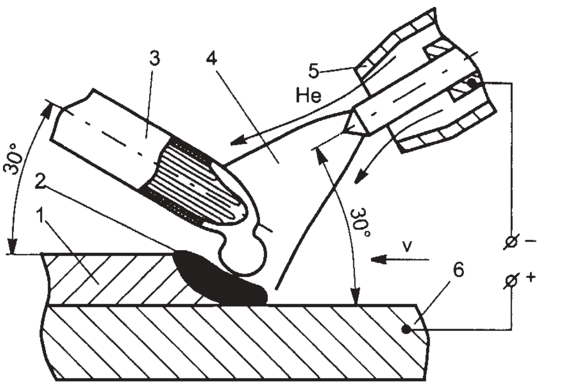
Experimental surfacing with the developed material was carried out using a new method of electroslag surfacing with ANF-6 flux in a sectional current-conducting solidification mould (SM) with a hollow graphite electrode[4] with the two-circuit system of supplying direct current to the slag pool (Fig. 2). This process makes it possible to concentrate, in the region below the electrode, the thermal power of the slag pool with the temperature of the slag up to 3500 °C, resulting in the rapid and uniform melting of the components of the flux-cored wire and in the formation of a homogeneous melt of metallic droplets. The diameter of the electrode and the diameter of the hole in the electrode were determined on the basis of calculations to obtain a stable electroslag process for



1 *The dependence of the ratio of thickness of layers of the shell of the composite flux-cored wire on the coefficient d.*



2 *The diagram of electroslag surfacing in a sectional solidification mould: 1) hollow electrode; 2) the composite flux-cored wire; 3) current-supplying section of the solidification mould; 4) the slag pool; 5) the shaping section of the solidification mould; 6) the metal pool; 7) the deposited metal; 8) the components; 9) graphite insert; 10) the insulator.*



3 *Diagram of helium-arc surfacing: 1) the deposited metal; 2) the weld pool; 3) the composite flux-cored wire; 4) the arc; 5) the torch; 6) parent metal.*

the given (up to 100 ml) volume of the slag pool. In surfacing, the voltage and straight polarity direct current were equal to: in the slag in the solidification mould 20 V and 150 A, in the hollow electrode 23 V and 200 A, the consumption of cooling water in the solidification mould 1.2 l/min, the rate of supply of the flux-cored wire into the slag through the hole in the electrode 5 mm/s. Argon was blown on the surface of the slag.

The melting rate of every wire component of the flux-cored wire was evaluated by the amount of metal melted in unit time. The optimum conditions of the electroslag surfacing with the flux-cored wires corresponded to the surfacing conditions in which the difference in the melting rate of the wire components was minimum. In the experiments, the current from the hollow electrode was varied in the range 120–250 A. At currents exceeding these values, the process of electroslag surfacing is unstable for small solidification moulds (diameter up to 50 mm).

To compare the quality of melting of the flux-cored wire with electroslag surfacing in the solidification mould, helium-arc surfacing was carried out on steel 40Kh with a direct current of 40 A, reversed polarity, at a voltage 40 V, the helium flow rate 5 l/min (Fig. 3).

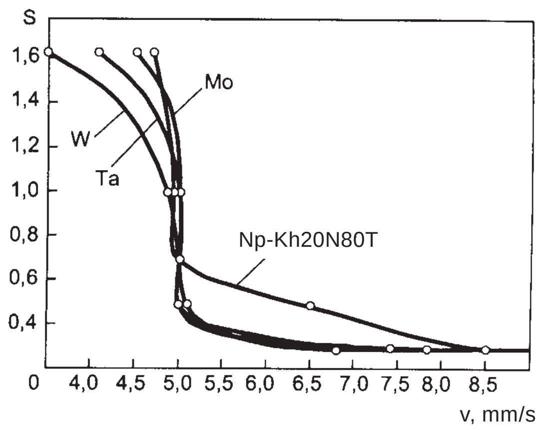
Various experimental compositions of the deposited metal were investigated. The structure and properties of the alloys were compared with the properties of the basic composition of the metal (%): 0.15 C, 11.0 Al; 4.4 Cr; 3.0 W; 3.0 Mo; 0.03 V; Ni–balance. To increase the resistance of the metal to high-temperature loading, the metal was additionally allied with carbon, tantalum and zirconium (Table 1). The simultaneous variation of the zirconium and tantalum content of the alloys is caused by differences in the effect of these elements on the phase composition of the positive metal with Ni_3Al-base. It is well known that the zirconium 6 may be included in the composition of the intermetallic phase $Ni_{77}Al_{22.65}Zr_{0.25}$ for the æ-phase CrNiMoZr, and tantalum is characterised by the formation of carbides Ta_2C with high resistance to dissolution.

The experimental results show that the uniformity of melting of the components of the flux-cored wire depends mostly on the ratio of currents:

$$S = \frac{I_s}{I_e}, \qquad [4]$$

where I_s is the current in the slag in the current-conducting section of the solidification mould; I_e is the current in the hollow graphite electrode.

If $S = 0.8 \div 1.0$, the temperature of the slag in the region below the hollow electrode increases to 3300–3500 °C, and the wire components of the flux-cored wire melt uniformly with the shell at a rate of 4.8–5.2 mm/s (Fig. 4). Therefore, high-quality deposited metal may be produced. At S <0.8, the slag pool rapidly boils followed by splashing and the rate of melting of the wire rapidly increases. At S > 1.0 the temperature of the slag in the region below the electrode becomes comparable with the temperature of the slag pool in the solidification mould (2100 °C), and the melting rate of the components of the flux-cored

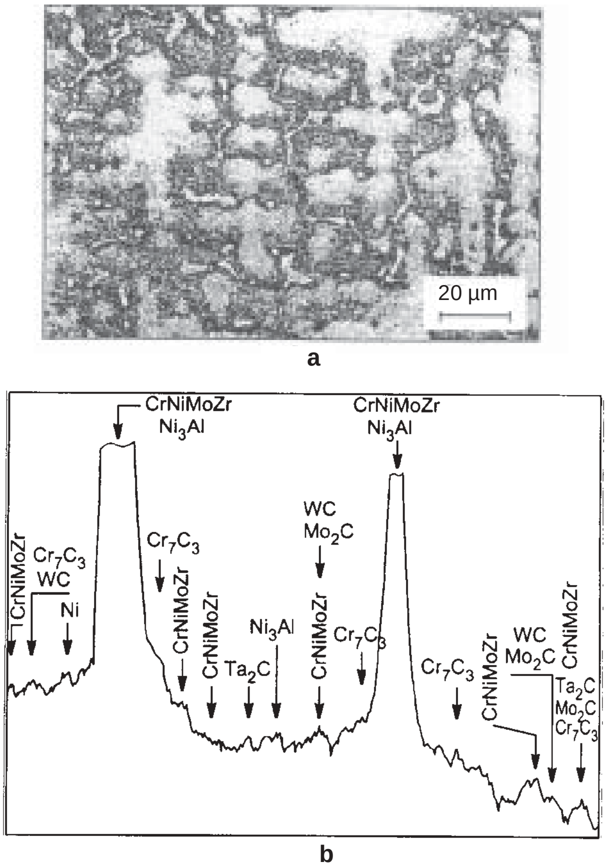


4 *The dependence of the melting rate of wire components of flux-cored wire in electroslag surfacing on the ratio of current in the current-contacting section and the hollow electrode.*

Table 1

Number of alloys	Content of element, %			Hardness (HV), MPa, at temperature, °C	
	C	Ta	Zr	25	1100
Basic 1	0.15	0	0	3700	280
2	0.30	0.5	0.5	3900	340
3	0.50	1.0	1.0	4150	390
4	0.60	1.5	1.5	4500	430
5	0.70	2.0	2.0	5000	450
6	0.80	2.5	2.5	5900	470

Content of impurities (%): 0.15–0.25 Si; 0.1–0.2 Mn; 0.01–0.012 S; 0.004–0.005 P; 2.5–3.5 Fe.



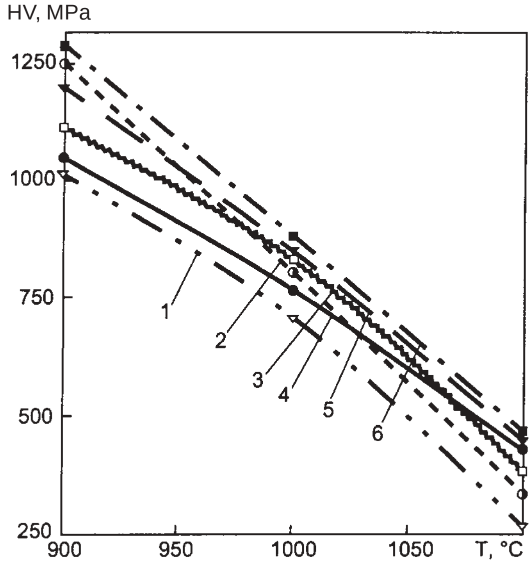
5 *The microstructure (× 500) (**a**) and the phase composition (**b**) of the deposited metal based on the alloyed nickel aluminide Ni_3Al.*

wire differs.

In helium-arc surfacing the rate of melting of the components of the flux-cored wire in the active zone was higher in comparison with electroslag surfacing, with satisfactory formation of the deposited metal and the minimum (0.5–1%) penetration (0.5–1%) of the steel substrate made of steel 40Kh.

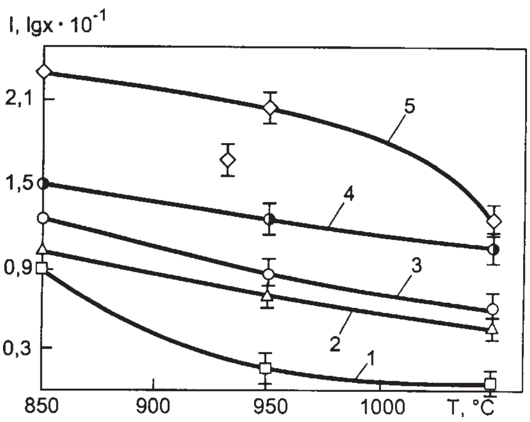
The experimental results also show that in the condition after surfacing, the structure of deposited metal (Fig. 5**a**) consists mainly of the alloyed intermetallic compound γ'-Ni_3Al (up to 70%). The regions between the dendrites contain the precipitates of the γ-phase CrNiMoZr (up to 15–20%) and up to 5–7% of the ductile structure of the component of the γ-phase (disordered solid solution of aluminium in equal). There are also precipitates of γ'-Ni_3Al and the carbides WC, Mo_2C, Ta_2C and Cr_7C_3 (Fig. 5**b**). With the increase of the tantalum and zirconium content in the deposited metal from 0.5 to 2.5%, the hardness of the deposited metal and high temperatures increases (Fig. 6). This may be explained by the large increase of the content of the hardening phases (up to 40%) of the structure of alloy No. 6. The increase in the content of carbon (above 0.80%) and tantalum and zirconium (above 2.5%) in the deposited metal increases the fraction of the hardening phases in the structure precipitated at the grain boundaries. This reduces the resistance of the metal to the formation of thermal fatigue cracks.

In sclerometric testing of the deposited specimens it



6 *The dependence of the hardness of deposited metal at high-temperature on the tantalum and zirconium content: 1) without Ta and Zr; 2–6) the Ta and Zr content respectively 0.5, 1.0, 1.5, 2.0 and 2.5% each.*

was established that the wear resistance parameter *I* decreases with the increase of the test temperature, and for different alloys the magnitude of this decrease differs. This is associated with differences in the structure and properties affecting the resistance of metal to high-temperature deformation (Fig. 7). The best results ($I \geq 1.1$ at 1050°C) were obtained for the experimental alloys on the basis of the complexly alloyed intermetallic compound Ni_3Al and the nickel-based industrial alloy (240N65Kh26M4B2). The smaller volume of the deformed metal for the alloy based on Ni_3Al corresponding to I = 1.8 at a temperature of 1050°C indicates the high deformation resistance of the metal at working temperatures and high thermal stability of the heterogeneous structure as a result of the increased content of the hardening phases, uniformly distributed in the matrix: carbides Ta_2C, WC, Mo_2C, and complex intermetallic compound CrNiMoZr, i.e. the æ-phase.



7 *Dependence of the criterion of wear resistance of metal on the temperature of sclerometric testing: 1) 25Kh5FMS; 2) 30Kh3V9SF; 3) 20Kh28M6N25; 4) 240Kh25N65M4B2; 5) metal based on alloyed Ni_3Al.*

Comparison of the results of measurement of high-temperature hardness and high-temperature sclerometric tests resulted in a correlation between them with a coefficient of $k = 450$.

Conclusions

1 The new composite flux-cored wire with the two-layer structure ensures the required strength and reliable sealing of the charge, and the composition of the wire guarantees the formation of the high-quality creep-resisting deposited metal based on nickel aluminide Ni_3Al.

2 A creep-resisting alloy containing up to 70% Ni_3Al was obtained for the first time in the deposited condition. In comparison with the currently available surfacing alloys, this new alloy is characterised by high plastic deformation resistance at a temperature of up to 1100°C.

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