Piercing mandrel strengthening by surfacing with nickel aluminide-based alloy

I V Zorin, Yu N Dubtsov, G N Sokolov A A Artem'ev, V I Lysak and S N Elsukov
Volgograd State Technical University, 28, Lenina ave., Volgograd, 400005, Russia
E-mail: kewa991@yandex.ru

Abstract. Electrode composite wire (CW) was used for argon-arc surfacing of a thermal-resisting nickel aluminide-based alloy (Ni-Al-Cr-W-Mo-Ta system) on the butt-end surface of the non-water-cooled piercing mandrel. It was shown that multipassing surfacing forms a defect-free deposited metal based on the $\gamma'$-Ni$_3$Al phase of various structural origins. Using high-temperature sclerometry and thermal fatigue testing methods, the metal deposited with CW containing ultrafine particle of 0.3–0.4 % wt. WC carbide features increased resistance to thermal and force effects at temperatures up to 1200 °C.

1. Introduction
It is known that in the temperature range of 1100-1200 °C, the most efficient alloys are heat-resistant $\gamma'$-Ni$_3$Al phase-based alloys produced by casting with high-gradient directed crystallisation with a specified structure throughout the whole workpiece [1-3]. This approach is not always possible or efficient when it is necessary to strengthen the most stressed areas of the metallurgical tools (piercing mandrels, pressing tools). Their intensive wear is due to the metal deformation in temperature-force cycling up to 1200 °C. Such operation conditions are the most common for large non-water-cooled mandrels, piercing the workpieces of difficult-to-form heat-resistant and corrosion-resisting steels and alloys [4, 5]. This increases the relevance of the technologically flexible processes of surfacing of such mandrels with $\gamma'$-Ni$_3$Al-based materials, featuring high deformation resistance of the deposited metal at temperature up to 1200 °C. One way to increase the strength properties of Ni$_3$Al-based metal is microalloying with rare-earth (La, Y, Ce) metals (REM) [6, 7]. This makes it possible to stabilise the structure with nanosized (up to 70 nm) endogenous phases due to their low solubility in $\gamma'$+$\gamma$ solid solutions [7]. At the same time, due to their surface activity, REMs decrease the melt surface tension and influence the energy required for nucleation centers, which increases their amount [8]. Such a mechanism can also be employed with refractory thermally stable compounds when introducing them into the weld pool melt in the form of exogenous ultrafine particles [9], as well as with REMs with high surface energy.

The objective of this paper is to increase the deposited metal wear resistance under the thermal-force action using CW containing ultrafine components, as well as to study their effect on the structure formation of nickel aluminide $\gamma'$-Ni$_3$Al-based metal.

2. Materials and methods
The composite wire was produced by an accumulative mechanical 4x drawing through the hard-alloy
die of the shell that was made of nickel strand and filler; components were metal wires of aluminium, tungsten, molybdenum as well as tantalum foil and chrome metal powder. The composite wire produced in that way represented a leak-free shell structure 2.5 mm in diameter, ensuring the stable arc [10]. The rated chemical composition ensured the production of the deposited metal on the basis of alloyed nickel aluminide: (wt. %) 0.3 C; 3.0 W; 2.5 Mo; 4.2 Cr; 1.9 Ta; 11 Al; and Ni-remaining element. The CW composition also included 0.3-0.4 % wt. of nickel micropowder with implanted ultrafine (less than 80 nm) particles of WC carbide. The nickel micropowder and ultrafine carbide ratio was 1:1.

The deposited metal structure was studied with the inverted digital microscope Zeiss Axiovert 40 MAT and the scanning electron microscope Versa 3D (FEI Company, USA).

The deposited metal deformation resistance within a temperature range of 800-1200 °C was appraised by the sclerometer tests of experimental samples 50×5×8 mm in size, which was produced from the metal deposited on the mandrel. During the testing in argon, the Rockwell indenter travelled on the polished surface of the sample, and heated with the passing current at the rate of 0.8-1.0 mm/sec, and with load on the indenter 0.55 N (Pat. RF 87018). The criterion of the metal’s resistance to large deformation at a normal load was \( k \) indicator, inversely related to the total volume \( V_d \) of the metal deformed by the spherical surface of the Rockwell cone. The specified volume was calculated on the basis of the analysis (with Image Analysis software) of the geometrical parameters (width and height) of the 10 mm tracks’ cross-sectional profiles. The tracks' profiles were acquired by scanning the deformed metal surface with the scanning probe microscope Solver Pro (NT-MDT, Russia).

The deposited metal was tested for resistance to the formation of thermal fatigue cracks by the developed procedure-heating the sample with the plasma spray up to 1200 °C and subsequent water cooling up to 50-60 °C at the rate of 140-150 °C/sec. The length of one heating-cooling cycle was 1 min. These testing conditions created higher thermal stresses in the Ni3Al-based metal, and the time to the appearance of the first fatigue crack was reduced in comparison with the iron-nickel alloys. The criterion of the deposited metal resistance to thermal fatigue was the amount of heating-cooling cycles before the cracks were visible at 4x optical magnification appeared on the sample surface.

3. Technological characteristics of surfacing

The surfacing object was a non-water-cooled large mandrel of the piercing mill 156 mm in diameter, made of 34CrNiMo6 steel (EN 1.6582). In order to reduce the influence of the base metal carbon on the rated chemical composition of the deposited metal, the 2.5 mm high undercoat of the nickel alloy HN60VT grade (Russian grade abbreviation GOST 5632-2014; 0.1 C; 26 Cr; 16 W; 1.0 Ti+Al; Ni-remaining element) was first formed on the mandrel butt-end surface.

The automatic argon-arc surfacing was conducted with two separate beads with a lateral motion of the electrode CW at the rate of ~ 108 m/h. This helped to level the thermal field in the mandrel, which prevented the formation of deposited metal cracks due to the low thermal relaxation capability of nickel aluminide. To prevent the mandrel butt-end surface overheating and the related defects of the deposited metal formation, the duration of surfacing for each passing was limited to 4-5 seconds. The surfacing was performed with the direct current of reverse polarity. The key characteristics of the arc surfacing mode (Table 1) ensured the high-quality formation of the deposited metal and the absence of thermal cracks in the range of the surfacing energy input rate of 800–850 kJ/m. The mandrels were first heated to 400 °C.

| Welding current rate (A) | Arc voltage (V) | Welding speed (m/h) | Oscillation range (mm) |
|-------------------------|-----------------|---------------------|------------------------|
| 270-290                 | 26-28           | 25-30               | 20-25                  |
4. The study of the structure and properties of deposited metal

The study of well-formed 10 mm high metal (Figure 1 a) deposited on the mandrel butt-end surface revealed that its fir-tree structure is represented by the solid solution on the γ'-phase, produced as a result of the eutectic and peritectic reactions involving the γ-solidsolution. This corresponds to the stoichiometry area for the Ni$_3$Al intermetallic compound on the Ni-Al state diagram. The transition area between the alloy HN60VT undercoat and the nickel aluminide-based deposited metal is small (20-30 µm) (Figure 1 b). It does not have any carbide line precipitations or diffusive and crystallisation layers. The basic phase in the transition area structure are dendrites based on the γ-solid solution which contains γ'-Ni$_3$Al phase, the size of which smoothly decreases through the deposited metal layer height (Figure 1 b), and the alloying elements' content in this area corresponds to their rated values.

![Figure 1. The structure of the deposited butt-end surface of the mandrel (a) and the transition section (b) between the deposited alloy HN60VT (2) and the alloy on the basis of alloyed nickel aluminide (3): (1) ~ 34CrNiMo6 steel.](image)

It is demonstrated Figure 2 a that the alloy deposited with CW containing microgranules with ultrafine particles has the highest deformation resistance at temperature up to 1200 °C. One possible reason for this is the formation of new crystallisation centre due to WC nanoparticles, which results in the redistribution of molybdenum, tantalum and tungsten in the volume of γ' and γ phases of the forming dendrite; this helps with the strengthening of the solid solution of the γ'-phase with these elements. The specified peculiarities of the γ'+γ structure formation determine the 1.5-1.7 times increase of the $k$ indicator of large deformation resistance of the metal in the temperature range of 800-1200 °C against the alloy deposited without ultrafine particles Figure 2. The data provided for comparison on the large deformation resistance of alloy HN60VT shows that despite the content of up to 16 % wt. of tungsten and up to 26 % wt. of chrome, the operating temperature range of this deposited metal type is limited to 800-900 °C.

The study of the deposited metal thermal resistance revealed its high sensitivity to the thermal stress level, which manifests itself in a relatively small number of cycles before the first fatigue crack appears Figure 2 b. The lowest resistance to the thermal fatigue cracks under the considered conditions is characteristic of metal on the basis of high nickel alloy. A considerable increase of the nickel aluminide-based metal thermal resistance is attributable to the higher thermal stability of its structure provided by a high concentration (up to 85 % wt.) of γ'-phase of various structural origin. In the metal deposited with ultrafine WC particles, the fatigue crack nucleation is less intensive, and its opening width is 4-6 times less, and the crack development is blocked in the concentration area of the γ'$_{eut.}$ phase particles.

Obviously, the formation of the fatigue cracks in the metal deposited without ultrafine particles can be connected with the critical amount of the TCP phases of the form (Ni, Ta) (W, Mo, Cr) attained during the thermal cycling. In the metal alloyed with the ultrafine particles, during the thermal cycling these phases assume cubic shape, which is less active stress concentrator than the plate-like one.
Provided that the coherent bond with the alloy matrix is preserved, the cubic particles are able to hinder the dislocation migration. At high temperature this factor will prevent the deposited metal softening.

![Figure 2](image)

**Figure 2.** Comparative analysis of the indicator $k$ of the deposited metal's plastic resistance at sclerometry (a) and thermal fatigue tests (b): 1 – HN60VT alloy; nickel aluminide-based metal alloyed with carbide WC ultrafine particles (3) and without them (2). $N$ – amount of heating-cooling cycles before the crack.

5. Conclusion
The high-quality formation of multiple-bead deposited metal on the butt-end surface of the piercing mandrel is ensured under the conditions of argon-arc surfacing, with the electrode composite wire featuring a small energy input rate and process duration.

The obtained results allow us to consider microalloying with ultrafine refractory particles as one possible way to modify the alloys with a $\gamma' + \gamma$ structure in order to improve their strength and thermal fatigue properties at temperature up to 1200 °C.

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