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STRUCTURE AND PROPERTIES OF WELDED JOINTS OF Ni_3Al INTERMETALLIC

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ABSTRACT

Welded specimens of Ni_3Al intermetallic are the main strengthening phase of heat-resistant nickel alloys were taken as an example to define the main problems arising in fusion welding of this class of materials. Features of weld formation, structural and phase changes, and mechanical properties of the welded joints are considered. Conditions of crack initiation and methods to prevent them are determined. The effect of welding modes and heat treatment on the structure, strength and ductility characteristics was studied. Mechanical properties of welded joints in the temperature range of 20–1200 °C are assessed. Schemes and modes of welding and heat treatment are proposed, which allow preventing cracking and ensure an equal strength of welded joints and base metal at improvement of their ductility.

KEYWORDS: Ni_3Al intermetallic, welded joints, structure, mechanical properties, crack resistance, welding and heat treatment modes

INTRODUCTION

Today, in the creation of high-temperature industrial structures, including parts of a hot path in gas turbine engines, installations, multicomponent heat-resistant nickel alloys (HNA) based on the intermetallic Ni_3Al compound remain the most widely used materials. The volume fraction of Ni_3Al in the alloy can reach 85–90 % (for example, alloys of VKNA type), which provides its high serviceability and heat resistance of up to 1250 °C. The advantage of using intermetallics as a phase base of HNA is provided by its unique capabilities, such as high values of strength and elasticity, structural stability, that does not degrade when the temperature is increased, as well as limited rate of creep, recrystallization and corrosion [1–4]. At the same time, some of the mentioned advantages and features of the physical and mechanical characteristics contribute to deterioration of the alloy manufacturability, especially its weldability. Thus, high strength and modulus of elasticity, low ductility close to high temperatures, high coefficient of thermal expansion, low thermal conductivity contribute to the formation of significant welding stresses and cracks arising.

Considering the wide use of HNA in the aircraft, power, nuclear, metallurgical and other branches of industrial production, the problem of developing scientific and technological fundamentals of welding of modern perspective high alloys is acute.

Taking into account the predominant role of Ni_3Al intermetallic as the main strengthening phase of HNA, the study of structural-phase changes and mechanical properties as a result of thermodeformation effect during welding will help to establish the physical fundamentals of weldability and strength in order to reasonably approach the development of technologies of welding industrial HNA.

RESEARCH METHODS

The studies were carried out with the use of plane specimens of Ni_3A1 intermetallic, produced by the method of rapid cooling from the liquid state by pouring into a massive copper mold in a protective inert atmosphere.

In addition to the reasons mentioned above, the choice of the studied material — Ni_3A1 intermetallic is predetermined by the need in excluding excitation of crystallization processes and phase transformations due to alloying elements of typical HNA. The need in a clear fixation of the intermetallic phase due to a high (~ 10^3 °C/s) cooling rate of the melt determined the method of producing specimens.

The experiments were performed by electron beam welding (EBW) in vacuum, taking into account the advantages of EBW, in particular, possibilities of a wide control of heat input and heat distribution in the welding pool.

The specimens with a thickness of 1.5–2.0 mm and a size of 50×40 mm were welded. The specimens for welding and investigations were cut with the use of electric spark method and a subsequent grinding of cut places. The welding mode parameters were chosen from the standpoint of providing high-quality welds with a full

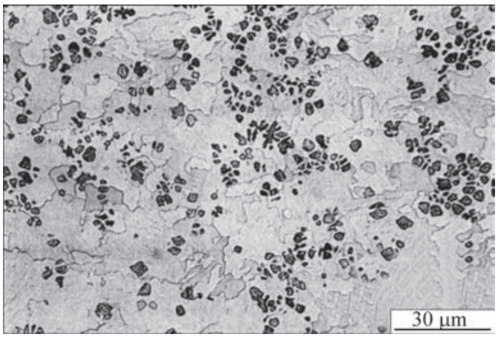

Figure 1. Microstructure of the initial material (Ni_3Al intermetallic), obtained by the method of hardening from the melt

penetration, taking into account the possibility of controlling thermal deformation processes in view of their effect on the tendency to crack formation.

The welding speed in the experiments varied in the range of 5–60 m/h. In order to limit the formation of cracks, preheating of the specimens with a beam was used. The range of heating temperatures during the studies was 400–800 °C.

The structure of the welded joints was detected by ion bombardment of the surface of the sections in an argon atmosphere with the further examination in the optical (NEOPHOT-32) and the electron scanning microscope (Jeol Superprob 733) with an X-ray analyzer. The phase composition of the specimens was determined in the DRON-UMI diffractometer in a monochromatic CuKα-radiation. The degree of a distant order η was evaluated from the ratio of integral intensities of diffraction peaks corresponding to the disordered face centered cubic lattice of a solid solution to the ordered one.

The mechanical characteristics were evaluated by the method of microindentation (“hot and cold”), testing of the plane specimens on three-point bending at room and elevated temperatures in the range of 200–1200 °C in the installation of the type INSTRON. The values of strength σ_t, yield $\sigma_{0.2}$ and ductility δ were determined during the destruction of upper fibers on the plane specimens with a section of 4×1.5 mm at a distance between the supports of 18 mm [5].

Microhardness at room temperature was determined using the PMT-3 hardness tester at a load of 2 N, at elevated temperatures (200–900 °C) in vacuum of 10^{-3} Pa in a modernized BIM-1C installation [6].

RESEARCH RESULTS

The initial material under study — Ni_3Al intermetallic produced by the method of hardening from the melt, is characterized by an equiaxial grain structure with a fine dendritic filling and the presence of separate metastable concentration configurations of a dendritic morphology (Figure 1). The performed micro-X-ray spectral analysis revealed a nonuniform distribution

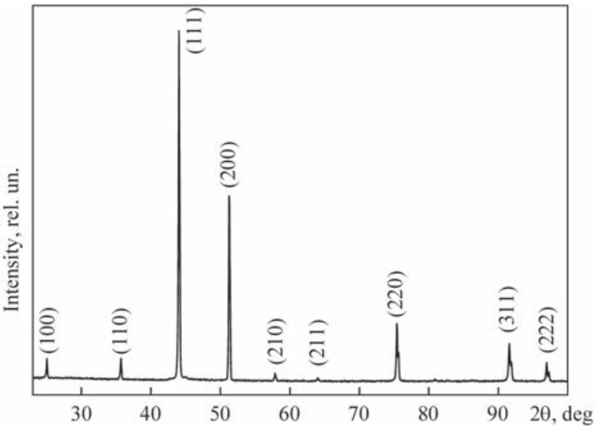

Figure 2. X-ray pattern from the surface of the specimen of Ni_3Al intermetallic in the initial state

of chemical components, which is most likely related to the mismatch in the process of cast formation of a peritectic point of the equilibrium diagram (Ni–Al) [7] with the region of the stoichiometric composition of Ni_3Al. The presence of such formations is associated with structural, mechanical and chemical heterogeneity, a significant discrepancy of microhardness values: from 2000–2500 MPa for the matrix to 3000–4000 MPa for the formations; low ductility of the material.

The X-ray analysis showed that in the initial material, both the presence of the ordered γ′-phase of Ni_3Al (Figure 2), as well as the disordered γ-phase, which was confirmed during fractographic examination of the specimens after plastic bending deformation (Figure 3).

Low ductility and toughness of fracture of intermetallic at low temperatures in combination with cast and welding stresses, chemical and structural heterogeneity, which contributes to an increased tendency to crack formation, is a well-known disadvantage of intermetallic alloys of a structural type $L1_2$, which include the investigated Ni_3A1. In welding of Ni_3Al specimens (as well as heat-resistant alloys on their base), the primary task is to prevent their arising.

One of the first methods of reducing the probability of crack formation is a preliminary heat treatment

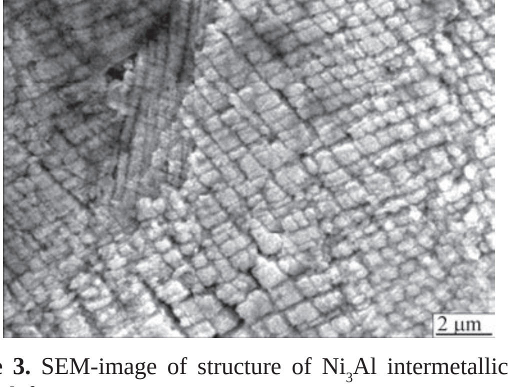

Figure 3. SEM-image of structure of Ni_3Al intermetallic after plastic deformation

Table 1. Mechanical properties during tests on bending of Ni_3Al intermetallic in the initial state and after heat treatment

State of the material	$\sigma_{0.02}$, MPa	$\sigma_{0.2}$, MPa	σ_t, MPa	δ, %	H_v, MPa
Initial	510	Brittle fracture	595	0,08	2450
Heat treatment of 1150 °C, 2 h	243	270	394	1,75	2100

Table 2. Temperature and time parameters of cooling of weld metal of HNA with the content of Ni_3Al of more than 65 % for different welding speeds

v_w, m/h	$G \times R$, °C/s		R, mm/s	
	FL	Weld axis	FL	Weld axis
17	$3 \cdot 10^3$	25	0,4	5
40	$49 \cdot 10^3$	54	1	8
53	10^5	300	1,3	11

Note. *R* — rate of crystallization of weld pool metal; $G \times R$ — cooling rate; FL — area of the weld metal on the fusion line.

of welded metal, aimed at improving its ductility. The studies of the effect of heat treatment on the structure and properties of Ni_3Al showed that the optimal heat treatment (at 1150 °C during 2 h) led to an increase in the ductility due to an increase in the grain size (from 7 to 17 μm), and also contributed to dissolution of concentration configuration formations in the structure. The method of X-ray structural analysis revealed that this heat treatment leads to the maximum increase in the degree of orderness of Ni_3Al solid solution. Thus, a satisfactory complex (optimal ratio of strength and ductility) of mechanical properties of intermetallic at room temperature (Table 1) was obtained [8].

In [8] it is shown that when testing the specimens in a temperature range of 400–800 °C, the ductility δ is sharply reduced, almost to zero, which can be negatively manifested under unfavourable conditions, when the rise in welding stresses occur at the specified temperature interval, in maintaining or increasing the tendency to crack formation. Thus, preliminary heat treatment does not radically solve the problem of preventing cracking in welding of Ni_3Al intermetallic. The previous calculations [9] showed that in welding HNA at a speed of about 55 m/h, namely in this temperature range, a rise in welding stresses is observed.

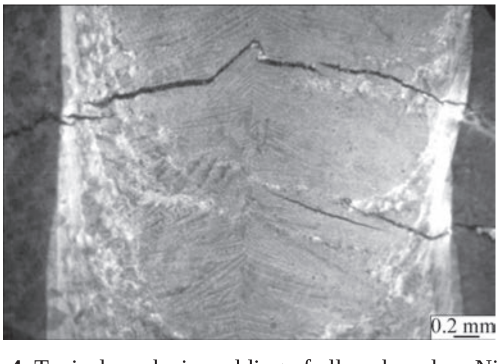

Figure 4. Typical cracks in welding of alloys based on Ni_3Al intermetallic

The best result from the standpoint of preventing cracking is achieved as a result of control of the thermal cycle of welding, the value and nature of heat input and rigidity of welded joint. Technologically, this is performed by preheating, choosing the welding speed and concentration of welding beam energy as a result of its focusing and scanning. The thermometering of welding process revealed that the rate of cooling of the weld metal in the temperature range of ductility failure (400–800 °C) is mainly determined by the welding speed and is approximately 300 °C/s at 12 m/h; 600 °C/s at 40 m/h; 155 °C/s at 53 m/h at the width of the weld, respectively 5.8; 4.6 and 2.8 mm.

The temperature and time parameters of cooling of the weld metal during crystallization and subsequent cooling vary throughout the cross-section and can reach approximately 10^5 °C/s depending on the conditions and parameters of the welding mode, which is shown on the example of variation in the rate from 17 to 53 m/h (Table 2).

Depending on the size and a certain combination of the mentioned thermal characteristics, both main longitudinal as well as transverse cracks may arise in the weld metal. More typical transverse cracks (Figure 4) arise at elevated (55–90 m/h) welding speeds, high specific power of the heating source in the welds of a small width. A decrease in the tendency to their formation due to an increased width of the weld is limited by the occurrence of the burn-throughs and the formation of axial crystallization cracks.

There is a narrow range of mode parameters and welding conditions, at which a high quality formation of welds without defects and the absence of cracks of both types are provided.

For the considered specimens, the realization of such conditions is achieved at a preheating of up to 600 °C, welding speed of 12–17 m/h, focusing and current of the welding beam, at which quality weld forma-

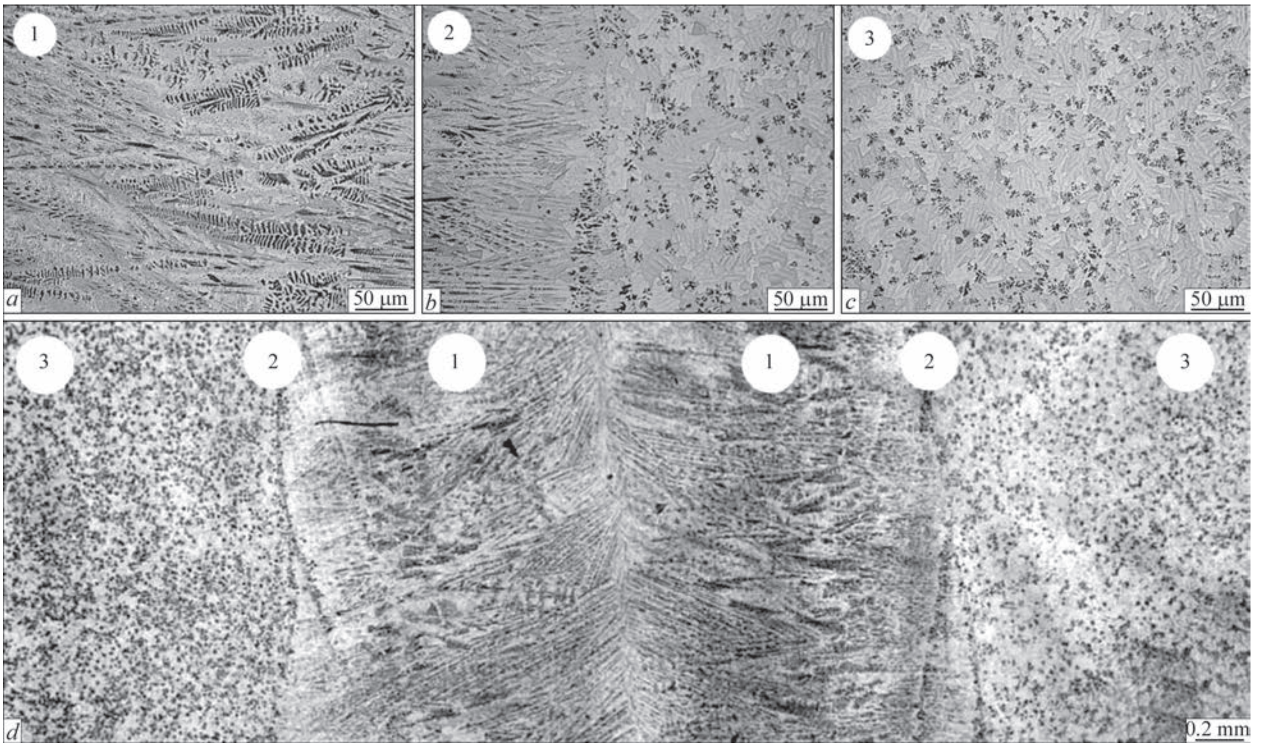

Figure 5. Microstructure of welded joint and individual areas of Ni_3Al intermetallic: *a* — weld metal (*1*); *b* — fusion zone (*2*); *c* — base metal (3); *d* — macrosection of welded joint

tion with a through penetration of 2.8–3.8 mm width is provided. Obviously, under such conditions, there is a low rate of increment, level and a uniform distribution of welding deformations and stresses, as well as the formation of a more homogeneous structure.

Taken into account a rather low ductility of intermetallics, the stochasticity of the influence of EBW parameters on the interaction of beam and welded metal, formation of a temperature field, the obtained conclusions require correcting regarding each case of thickness, geometry of welded material, requirements to joint, etc. Thus, in welding of Ni_3Al intermetallic specimens of 1.5 mm thickness with preheating at a weld width of about 4 mm, produced at a welding speed of 12 m/h, longitudinal axial cracks and at 55 m/h, numerous transverse cracks arise. At the same time, at a thickness of 2 mm, welding speed of 12 m/h and weld width of about 4 mm, cracks were not observed.

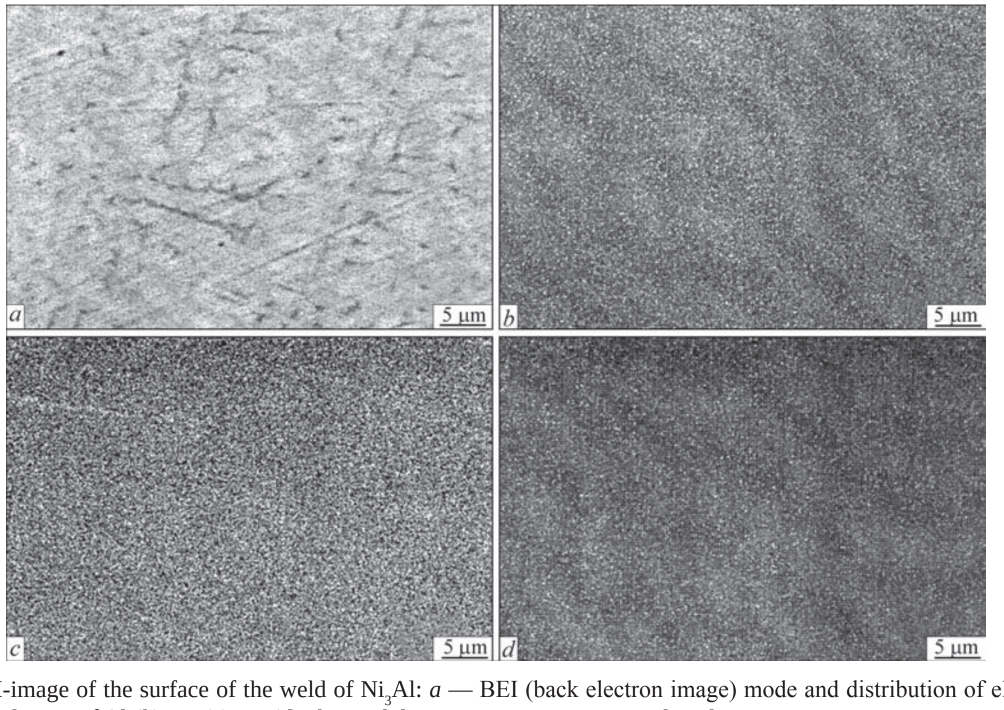

Figure 6. SEM-image of the surface of the weld of Ni_3Al: *a* — BEI (back electron image) mode and distribution of elements in the characteristic radiation of Al (*b*), Ni (*c*), Fe (*d*) obtained during micro- X-ray spectral analysis

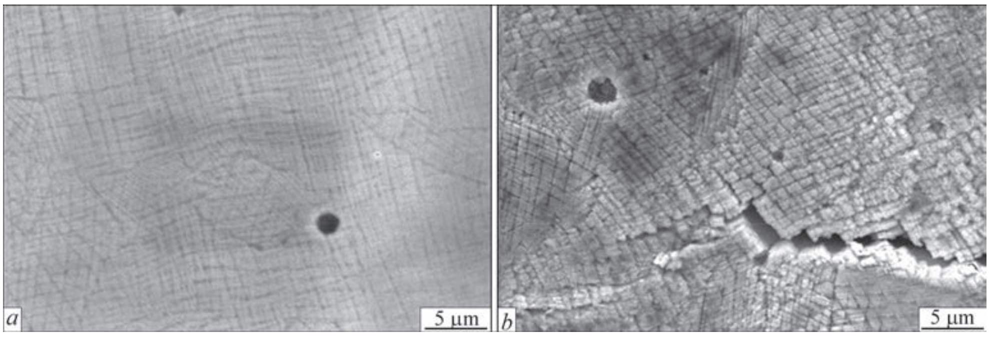

Figure 7. SEM-image of initial metal of Ni_3Al (*a*) and the surface of fracture of welded joint (*b*)

Table 3. Influence of heat treatment on mechanical properties (bending tests) of welded joints of Ni_3Al intermetallic. Welding in as-delivery state

Heat treatment	$\sigma_{0.02}$, MPa	$\sigma_{0,2}$, MPa	σ_t, MPa	δ, %	H_v, MPa	*E*, MPa
Without heat treatment	430	Brittle fracture	504	0,09	2500	2275
1100 °C, 2 h	323	Same	395	0,07	2270	–
1150 °C, 2 h	310	–”–	385	0,17	2300	–
1200 °C, 2 h	160	–”–	164	0,1	–	1714

Note. *E*, H_v — for heat-treated welded joints were not determined, and for welded joints in the initial state, the modulus and hardness were determined by the measurements of instrumental hardness; $\sigma_{0.02}$ is not a standard mechanical characteristics, that characterizes microductility and is determined by deformation of 0.02 % for comparing the materials subjected to brittle fracture; $\sigma_{0.2}$ is a standard characteristics at deformation of 0.2 % — yield strength, which cannot be determined from the diagram of our intermetallics, because the specimens are subjected to brittle fracture.

The structure of the welded joint of 2 mm thickness, produced maintaining the specified favourable conditions, is presented in Figure 5.

The X-ray spectral analysis of the weld metal showed that in the initial state of the material, the weld represents mainly an ordered intermetallic phase of Ni_3Al. The results of examinations by scanning electron microscopy with an X-ray microanalyzer showed that the main components and admixtures of the weld material are uniformly distributed (Figure 6). The size of the matrix and morphology of the γ′-phase are little different from the initial ones (Figure 7). A characteristic feature of the structure of the weld metal are columnar dendrites of a variable size (see Figure 5), orthogonally directed to the crystallization front of the welding pool, which in turn consist of small cellular elements. The difference in the crystallization rates (see Table 2) and the temperature gradient over the cross-section of the welding pool leads to significant changes both in their sizes and morphology. Thus, near the fusion line, the distance between dendrites λ is 3–8, and near the axis of the weld is 5–9 µm. The difference between the morphology and sizes of the elements of the structure of the weld and the initial metal is mainly determined by the direction and intensity of heat removal in the process of crystallization. When forming a cast (initial metal), the heat removal is directed perpendicularly to its thickness; in crystallization of the weld it is directed orthogonally to the isotherm of the welding pool crystallization in the plane of the specimen. An increased dispersion of the structure of the base metal is associated with a higher rate of crystallization, and a change in the dispersion over the cross-section of the weld is associated with a change in the crystallization rate: from high near the fusion line to minimal, close to welding speed along the weld axis.

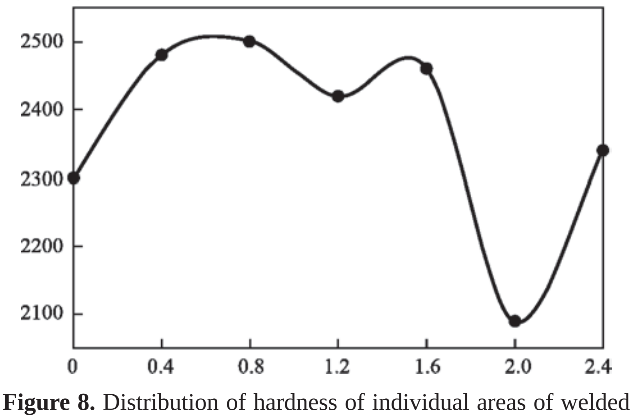

Figure 8. Distribution of hardness of individual areas of welded joint of Ni_3Al intermetallic

The considered peculiarities of the structure of welded joints are manifested in the certain way while determining the mechanical characteristics. Thus, the bending tests at room temperature (Tables 1, 3) indicate some reduction in strength and ductility as compared to intermetallic in the state of delivery.

The effect of the structural factor is also noticeable when evaluating the hardness of individual areas in the welded joint: base metal, heat-affected zone, areas of epitaxial growth, transitional area and near the weld axis (Figure 8).

Table 4. Influence of heat treatment after preliminary stabilizing annealing of 1150 °C, 2 h and welding on mechanical properties (bending tests) of welded joints of Ni_3Al intermetallic

No.	Heat treatment	$\sigma_{0.02}$, MPa	$\sigma_{0.2}$, MPa	σ_t, MPa	δ, %
1*	1150 °C, 2 h	270	304	325	0.35
2	1150 °C, 5 h	–	290	345	1.2
3*	1150 °C, 10 h	245	270	310	1.58
*Material of other melting					

At the same time, the methods of instrumental hardness showed that the integral values of ductility, hardness and Young modulus for the mentioned zones are close to each other [10].

When the test temperature rises up to 900 °C, the hardness of the weld (2.1–2.4 GPa) is much exceeding the one for the base metal (1.6–1.8 GPa). As well as for the initial metal, the growth of H_v is also observed in the region of 600 °C (Figure 9).

Thus, as a result of welding, a less dispersed structure is formed, that varies over the weld width, which is also manifested in the reduction of its mechanical characteristics; here, the ductility index remains at the same low level as in the initial metal (see Tables 1, 3), i.e., the dispersion and morphology of the strucutre of the weld metal of Ni_3Al intermetallic is not optimal.

In view of these results, when studying welding of Ni_3Al intermetallic and alloys on its base, more attention should be paid to local changes in the structure of the weld metal, especially when studying the mechanism of crack formation, which are also most frequently originated in the areas of the weld with high hardness and dispersion of the structure (see Figure 5). The need in a separate consideration of the influence of structural changes in welding on the nature, mechanism of deformation and fracture of welded joints is also obvious.

In order to improve the indices of the structure, to obtain a satisfactory ratio of strength and ductility characteristics and to reduce residual stresses, a comprehensive study of the effect of heat treatment on the properties of welded joints was conducted. In this case, the heat treatment was carried out the same as for the initial metal in the temperature range of 800–1300 °C for 1–10 h.

As is seen from the results of mechanical tests (see Table 4, Figure 10), a satisfactory combination of values of σ_t, $\sigma_{0.2}$ and δ is achieved at annealing temperatures of 1150 °C. The optimal duration of heat treatment at the mentioned temperatures is 5 h (Figure 10). An increase in the duration to 10 h leads to a further growth in the ductility, but the strength characteristics begin to decrease more significantly. A more significant increase in the ductility of the welded joint as a result of heat treatment is achieved on the specimens,

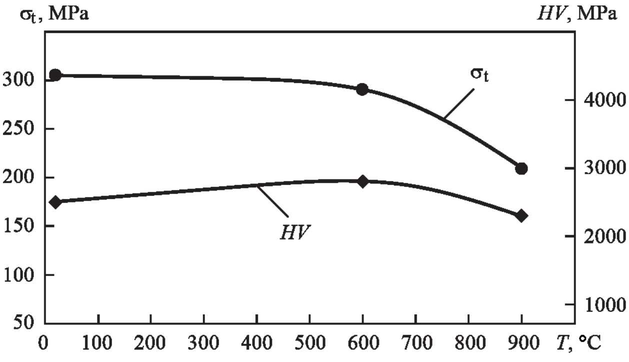

Figure 9. Influence of test temperature on tensile strength σ_t and hardness H_v of the weld of Ni_3Al intermetallic

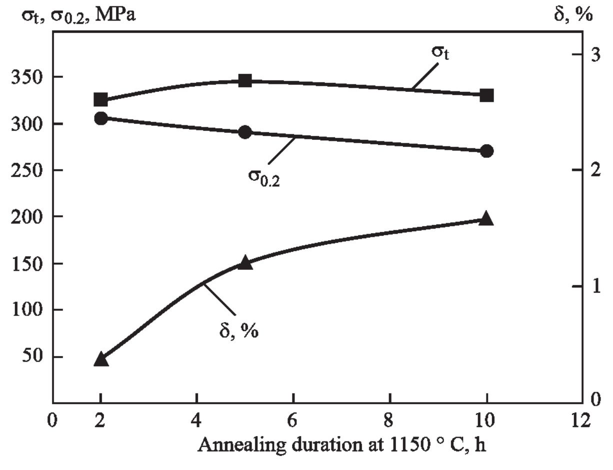

Figure 10. Influence of annealing duration at 1150 °C on mechanical characteristics of welded joint of Ni_3Al intermetallic. Test temperature is 20 °C

which were preliminary treated before welding on the mode of 1150 °C during 2 h (Figure 10).

Thus, the implementation of the research results and proposed technological solutions in welding Ni_3Al intermetallic specimens allows preventing cracking and providing mechanical properties of welds at the level of the initial ones at a simultaneous increase in their ductility.

CONCLUSIONS

1. Ni_3Al intermetallic, which is the base of most modern HNA, is featured by an extremely low ductility and a high tendency to crack formation in fusion welding.

2. Prevention of crack formation in EBW of Ni_3Al intermetallic is achieved by combining the following technological means: heat treatment and preliminary heating of welded specimens, through penetration, reducing the rigidity of the joint, welding speed and heating concentrations. For specimens of 1.5–2.5 mm thickness, this is achieved at a preliminary annealing of 1150 °C during 2 h, preheating to about 600 °C, welding speed of 12–17 m/h and the welding beam current of ~ 15–20 mA in its sharp focusing, which provides a uniform through penetration and a high-quality formation of welds of ~ 3.0 mm width.

3. An increase in the ductility of welded joints while maintaining σ_t, $\sigma_{0.2}$, H_v and E at the level of the initial material is provided while maintaining the mentioned technological means of preventing crack formation, the use of postweld heat treatment of 1150 °C for 2 h. This provides the formation of the structure of 15–17 μm, which is close to the equiaxial grain with ordered quasi-cubic particles of the γ′-phase with the size of about 0.5–0.7 μm and the preservation of the stoichiometric composition of Ni_3Al intermetallic.

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CONFLICT OF INTEREST
The Authors declare no conflict of interest

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DEVELOPED in PWI

EQUIPMENT AND TECHNOLOGY FOR HIGH-SPEED HYBRID LASER-PLASMA WELDING

Hybrid laser-plasma welding implements the process of joint action of two heat sources (laser beam and plasma arc) into one weld pool, which increases the efficiency of absorption of laser beam energy by the welded metal. The equipment is designed to produce welded joints from aluminum and magnesium alloys, titanium, nickel and copper and other alloys, as well as low-alloy and alloy steels without and with filler wire feed.