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INFLUENCE OF THE PHYSICAL AND MECHANICAL PROPERTIES OF INTERLAYERS ON THE STRESS-STRAIN STATE OF JOINTS AT DIFFUSION WELDING AND BRAZING OF HEAT-RESISTANT ALLOYS BASED ON INTERMETALLIDE Ni_3Al

Investigated the stress-strain state (SSS) during slow cooling (for 600 s) of cylindrical assemblies of Ni3Al - based alloy with a "soft" interlayer having a lower (0.85) yield strength and a lower than the base metal by 15 and 30% creep resistance. It was found that in a small zone of the base metal near the outer surface at the joint with the interlayer is created a complex SSS arises, which reduces stresses in the interlayer due to plastic creep deformations. The stress stiffness coefficients and, accordingly, the degree of hardening or softening of the metal during slow cooling change in small (about 5 interlayer thicknesses) areas near the joint edge. [dx.doi.org/10.29010/88.7]

Keywords: *computer modeling; plastic deformations; stress stiffness coefficient; diffusion welding; high-temperature brazing; heat-resistant alloy.*

Introduction

The main objective of modern gas turbine construction is to increase the efficiency and resource of turbines. An increase in engine efficiency is achieved by increasing the gas temperature in front of the turbine. This requires materials with higher heat-resistance. New design solutions are also being applied.

The main structural materials in gas turbine construction are heat-resistant nickel alloys [1]. The metal science of these alloys is developing successfully. Strategic directions for the development of materials and technologies are considered in [2]. The materials of the new generation are intermetallic alloys based on Ni3Al alloyed with rhenium and tantalum [1–3].

Diffusion welding of cast heat-resistant nickel alloys and alloys, based on Ni_3Al, does not give positive results. Therefore, the main methods of their connection are solid-state welding, for example, diffusion welding in vacuum, friction welding and brazing [4, 5]. Diffusion welding can be performed without interlayers or with intermediate interlayers, which can be non-meltable or meltable. When regulating the thickness of the meltable and remaining at the joint of the interlayer, such a process is called a transient liquid phase bonding (TLP), compound in foreign literature. When brazing with a layer in the joint, a brazed seam is formed, which properties influence on the properties of joint.

Formulation of the problem

As it was established back in [6,7], the presence of interlayers in the compound significantly affects the SSS and its performance, but at that time analytical methods were used that did not allow taking into account the dynamics of the process and all factors affecting the SSS of nodes, in particular plastic deformation metal during thermal loading while cooling. The development of computer modeling and software systems allow conducting intensive research on the formation of SSS compounds with intermediate layers during diffusion welding and brazing of heat-resistant alloy based on Ni_3Al intermetallic metal, operating at temperatures up to 1200 °C. Since the proper stresses and the level of deformations determine the performance of welded and brazed assemblies, studies regarding the formation of the stress-strain state of joints are relevant.

In this work, the SSS simulation was performed by the finite element method using the ANSYS software package [8.9], which we used in previous works [10–12]. In [13], the stresses formed in the process of joining the workpieces during welding and brazing of units of homogeneous materials with a "soft" layer under axial load were determined. During cooling, self-stresses are generated in the nodes.

The aim of this work is to study the effect of a combination of thermal coefficients linear expansion (TCLE), creep resistance of the interlayer material and the base metal during delayed cooling on the formation of SSS during diffusion welding and brazing of cylinder-cylinder-type assemblies.

Materials and research methods

The influence of the combination of the properties of the interlayer and the base metal was studied on cylindrical models (Fig. 1) with a height and diameter $h = d = 20$ mm, with an interlayer thickness $s = 0.08$ mm. We studied the SSS of nodes under thermal loading by lowering the temperature from 1270 to 1100 °C, taking into account creep.

The properties of the base metal, in addition to the yield strength, in all cases were assumed to be the same, constant in the range of cooling temperatures: elastic modulus $E_{om} = 0.5 \cdot 10^5$ MPa, Poisson's ratio $\mu = 0.4$, hardening coefficient during plastic deformation of the material $K_{pd} = 0.5 \cdot 10^2$ MPa, thermal coefficient of linear expansion TCLE = $21 \cdot 10^{-6}$ 1/°C. The creep rate was calculated using the Norton equation:

$$\dot{\varepsilon}_{cr} = C_1 \cdot \sigma^{C_2} \cdot e^{-C_3/T},$$

where σ is stress, Pa, T is temperature, K.

The yield strength $\sigma_{p0.2}$ (conditional) for the base metal is assumed to be linearly decreasing from 150 MPa at 1100 °C to 0 at a temperature of 1270 °C.

Creep coefficients C1, C2 and C3 for the base metal were obtained based on the processing of creep curves (alloy based on Ni_3Al): C1 = $4.524 \cdot 10^{-29}$, C2 = 6.51, C3 = 92840.8.

Variants of nodes with interlayers having physical and mechanical properties other than those of the base metal were considered: TCLE less than 2 times ($10.5 \cdot 10^{-6}$ 1/°C) and more than 2 times ($42 \cdot 10^{-6}$ 1/°C) than that of the base metal; with a lower yield strength (0.85 of the yield strength of the base metal), with a lower creep resistance than the base metal by 15 and 30%.

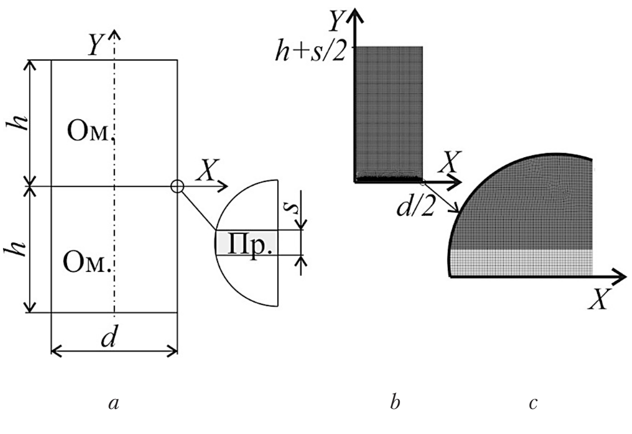

Fig. 1. General view of the sample with the interlayer (*a*), the cross section of the finite element model (*b*) and the interface zone of the interlayer with the joining metal (*c*)

The creep rate of the interlayer material was calculated according to the same equation as in the base metal, while the C1 coefficients increased taking into account the decrease in creep resistance and were taken equal to $5.203 \cdot 10^{-29}$ and $5.881 \cdot 10^{-29}$, respectively. The elastic modulus of the interlayer material and the Poisson's ratio in all cases were assumed to be the same with the base metal: $E_{pr} = 0.5 \cdot 105$ MPa and $\mu = 0.4$.

The investigated variants of nodes with different properties (TCLE and creep resistance) of the interlayer are given in table 1.

Table 1

Variants of material properties of the interlayer of the researched nodes

Var.	TCLE, 10^{-6} 1/°C	Creep resistance with respect to the base metal	Cooling time, s
1	10,5	-	0
2	10,5	0,85	600
3	10,5	0,7	600
4	42	-	0
5	42	0,85	600
6	42	0,7	600

Thermal loading was carried out by a slow decrease of temperature for 600 seconds. The results were compared with fast cooling options without creep (options 1 and 4). In this case, the possibility of plastic deformation of both the interlayer and the base metal was taken into account.

Statement of the main matter

An analysis of the fields of all components and equivalent stresses showed that their character is preserved in all variants, only their magnitude changes somewhat. As with rapid cooling (options 1 and 4), the stresses are large over most of the assembly, and only in a small area located near the interlayer at the joint edge (at the outer surface of the cylinder), and in the interlayer itself, a complex SSS is created due to difference TCLE of the connected metal and the interlayer. At the same time, the stress level in options with slow cooling is slightly lower than with fast cooling.

Slow cooling for 600 s reduces stresses in the interlayer and in a small zone of the base metal near its edge due to creep deformations in the interlayer. Moreover, the degree of creep resistance of the interlayer in comparison with the base metal in the accepted range (0.85 or 0.7) practically does not play a role. The resulting creep strains have little effect on the character of the stress field. Options 1 ... 3 (with an interlayer with a small

TCLE) differ from options 4 ... 6 (with an interlayer with a large TCLE) only in level and opposite sign of stresses.

A slightly different pattern of change in the fields of plastic deformations, both short-term (instantaneous) and creep.

In variants 1, 2 and 3 with a smaller difference in the TCLE of the interlayer and the base metal ($10.5 \cdot 10^{-5}$ 1/°C) and, accordingly, with a lower level of stresses, short-term plastic deformations are small, they arise only in a small area at the joint edge. Moreover, they noticeably decrease in options 2 and 3 as a result of a decrease in stress due to creep.

In variants 4, 5 and 6, due to the doubled difference in the TCLE of the interlayer and the base metal ($21 \cdot 10^{-5}$ 1/°C) and, correspondingly, a higher level of stresses, short-term plastic deformations noticeably increase and are distributed along the entire length of the interlayer. In variants with slow cooling (var. 5 and 6) they also noticeably decrease due to creep.

Fields of plastic creep deformations show a slight increase in their level in var. 3 and 6 compared to var. 2 and 5 with a decrease in the creep resistance of the interlayer material (about 10%), and a noticeable increase (up to 3 times) with an increase in the level of stresses in the assembly due to the greater difference in the TCLE of the interlayer and the base metal.

A graphic representation of the nature of the distribution and the level of all components and equivalent stresses in the base metal and the interlayer gives diagrams (Fig. 2 ... 4).

Analysis of stress diagrams along the joint shows that all stress components and equivalent stresses in the base metal are practically absent in most of the joint and only increase in a small area near the outer surface, with a length of about 10 thicknesses of the interlayer. Radial (Fig. 2, *a*) to 67 and -102 MPa with rapid cooling (options 1 and 4) and to -55 MPa (options 2 and 3) and -73 MPa (options 5 and 6) with slow. Similarly, axial increase to 68, 46 and 45 MPa in options 1, 2 and 3 and -69, -59 and -58 MPa in options 4, 5 and 6 (Fig. 3, *a*). The circumferential ones change in the same way as radial to 54, 40.5 and 40 MPa in options 1, 2 and 3 and -69, -56 and -54 MPa in options 4, 5 and 6. The tangents at the very edge of the joint increase to -44, -34 and -33 MPa in options 1, 2 and 3 and 51, 42 and 41.5 MPa in options 4, 5 and 6 (Fig. 3, *b*).

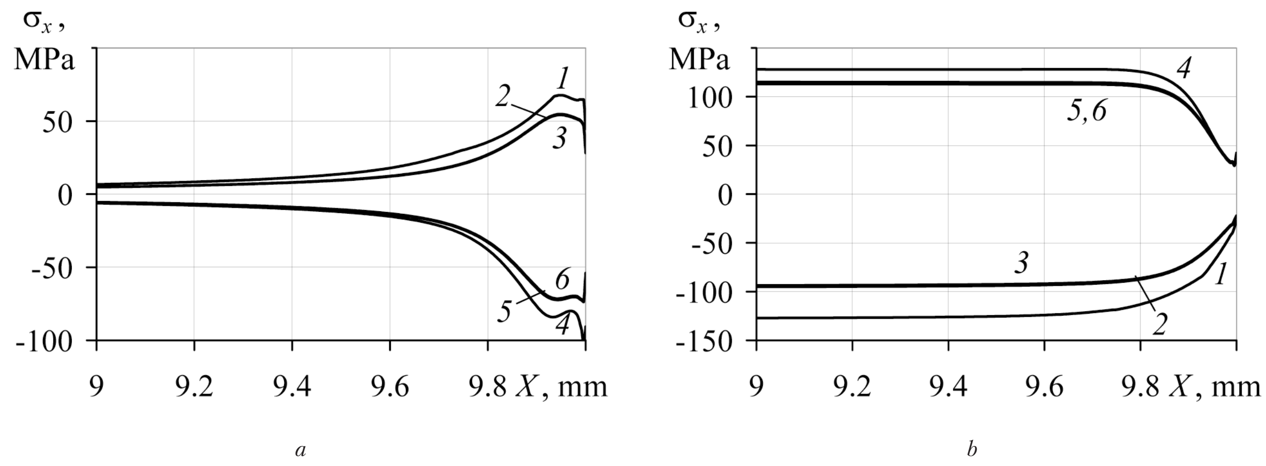

Fig. 2. Plots of radial stresses σ_x at the joint in the base metal (*a*) and the interlayer (*b*) near its outer edge, options 1 ... 6

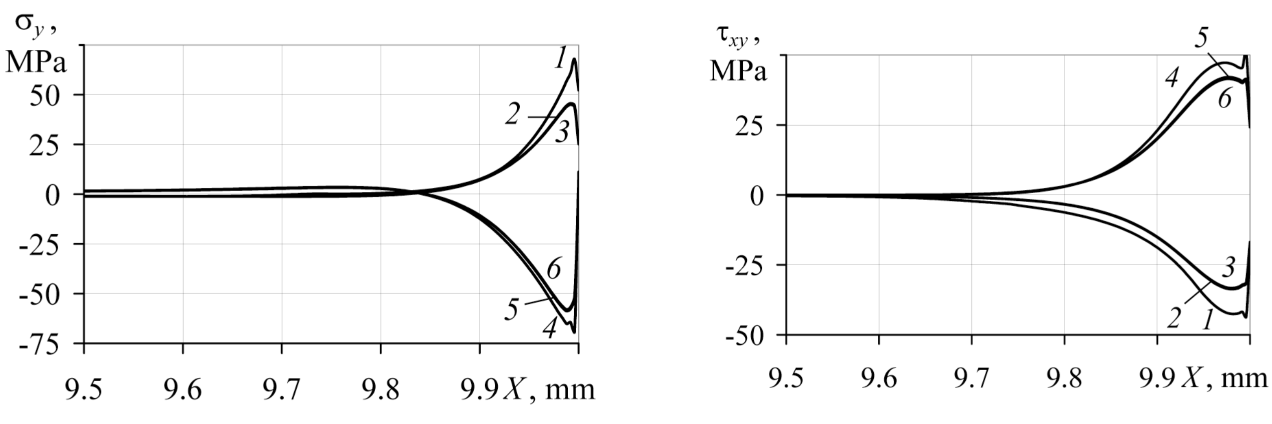

Fig. 3. Plots of axial σ_y (*a*) and tangential τ_{xy} (*b*) stresses at the joint of the base metal and the interlayer near its outer edge, options 1 ... 6

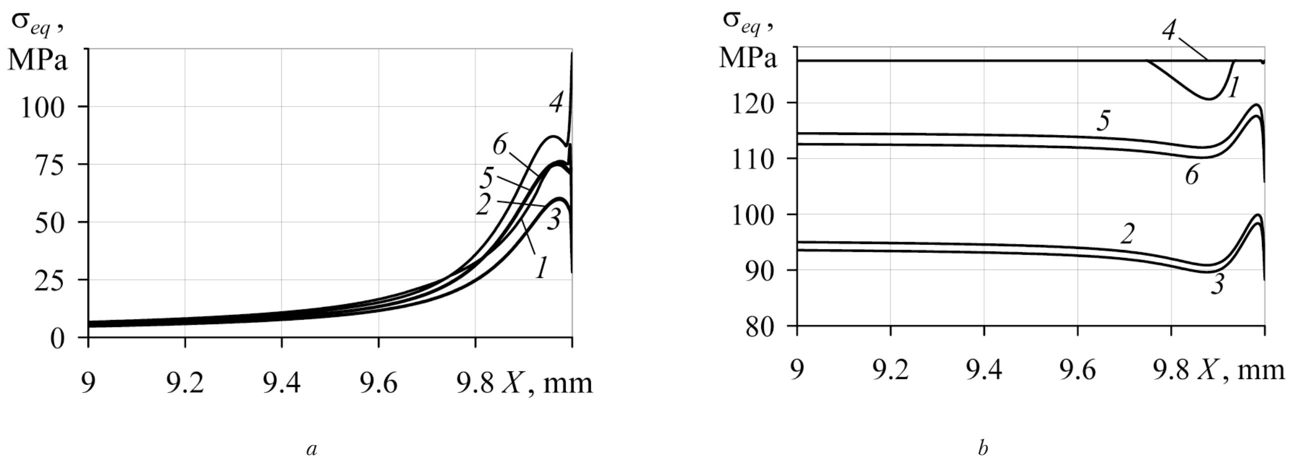

Fig. 4. Plots of equivalent stresses σ_{eq} at the joint in the base metal (*a*) and the interlayer (*b*) of the nodes, options 1 ... 6

As can be seen from a comparison of the diagrams, the signs of the component stresses are opposite in nodes with an interlayer with a smaller (options 1 ... 3) and large (options 4 ... 6) TCLE compared to the base metal. Moreover, due to creep, they are slightly reduced in options 2, 3 and 5, 6 compared with rapid cooling (options 1 and 4).

Equivalent stresses are also distributed in accordance with the individual components; at the edge of joint, they increase from 76, 60 and 60 MPa in options 1, 2 and 3 and 87, 76 and 75 MPa in options 4, 5 and 6 (Fig. 4, *a*), that is, remaining well below the yield strength of the base metal (150 MPa). For comparison, with elastic deformation (without taking into account the plastic deformation of the interlayer) of similar nodes, they amounted to 100 and 200 MPa in the nodes with interlayers with small and large TCLEs, respectively. That is, plastic deformations of the interlayer material reduce equivalent stresses in the most loaded zone of the base metal, unloading and preventing plastic deformations in it.

In the interlayer, the axial and tangential stresses are identical with the base metal, they are also absent for most of the joint length (Fig. 3, *a* and *b*) and only near the edge, appear and sharply increase at a distance of about 5 thicknesses, axial stresses up to 68, 46, 45 MPa in options 1, 2, 3 and -69, -59, -58 MPa in options 4, 5, 6, and tangents up to -44, -34, -33 MPa and 51, 42, 41.5 MPa, respectively.

The radial stresses over most of the joint length in the interlayer, in contrast to the base metal, are quite large, distributed uniformly at the level of -128, -96, -94.5 MPa (options 1, 2, 3) and 128, 115, 113 MPa (options 4, 5, 6), that is, they are close to the yield strength (128 MPa) of the interlayer material at 1100 °C (Fig. 2, *b*). Circumferential stresses are similarly distributed.

Thus, a comparison of different options shows that creep deformations slightly reduce the level of components stresses, both in the base metal and in the interlayer. In this case, a change in the creep resistance of the interlayer material within the accepted limits (0.8 and 0.75 from the base metal) practically does not affect the level of reduction of components stresses.

In accordance with the change in the components stresses, equivalent stresses in the interlayer are also distributed (Fig. 4, *b*). For the greater part of the joint length, they are reduced due to the creep of the interlayer material and remain constant over almost the entire length of the joint: in options 1, 2 and 3 at the level of 128, 96 and 94 MPa, and in options 4, 5 and 6 at the level of 128, 115 and 113 MPa.

In accordance with equivalent stresses, plastic deformations in the interlayer are also distributed (Fig. 5).

Equivalent short-term plastic deformations (Fig. 5, *a*) over most of the joint length are constant, close to 0 (0.047 ... 0.011%) in options 1 ... 3 and are 0.404, 0.151 and 0.146% in options 4, 5 and 6. That is, they significantly increase with an increase in the TCLE coefficient of the interlayer and the base metal and decrease with the appearance of creep deformations and a decrease in the creep resistance of the interlayer material (Fig. 5, *a*).

Near the outer edge of the joint, they first decrease slightly and then again increase to 0.11, 0.028 and 0.027% (var. 1, 2 and 3) and 0.57, 0.234 and 0.226% (var. 4, 5 and 6).

Similarly distributed are creep strains (Fig. 5, b). With rapid cooling (var. 1 and 4), they are naturally absent, in the remaining versions remaining at a constant level over most of the joint (from 0.114 and 0.284% in var. 2 and 5 to 0.118 and 0.294% in var. 3 and 6), they near the edge first slightly decrease, and then increase to 0.081 and 0.15% in var. 2 and 3, up to 0.343 and 0.358% in var. 5 and 6.

A graphic representation of the change in the level of deformations in the joint zone with a change in the

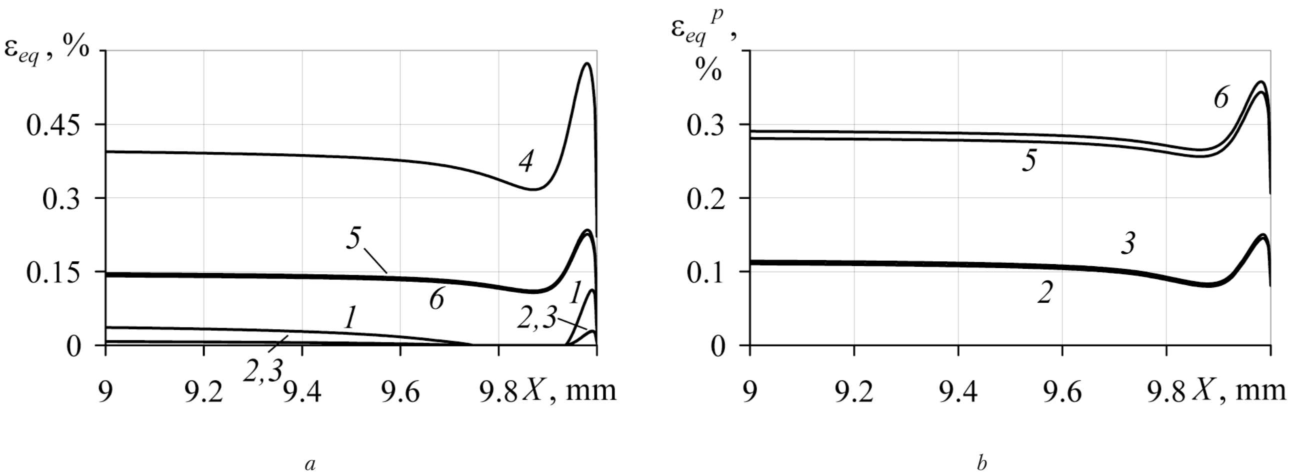

Fig. 5. Plots of equivalent short-term plastic deformation ε_{eq} (*a*) and creep strains ε_{eq}^{p}(*b*) at the joint in the interlayer material near its outer edge, options 1... 6

properties of the interlayer (its yield strength, creep resistance and TCLE) gives a diagram (Fig. 6).

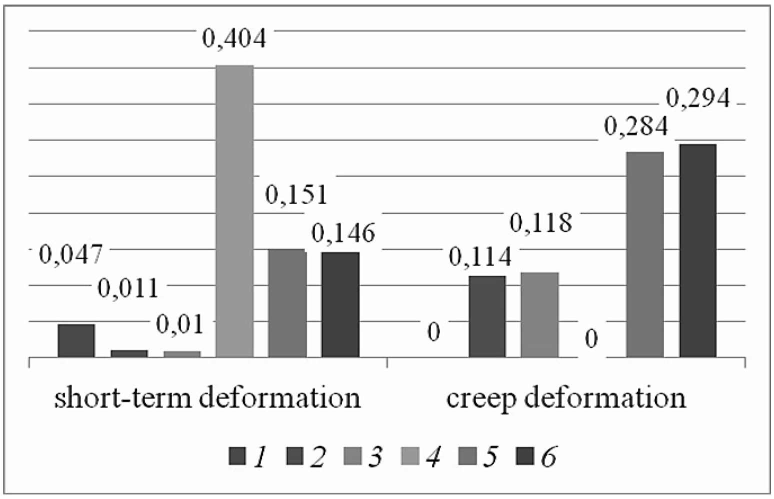

Fig. 6. Plastic deformations in the interlayer (%) on most of the joint, options *1, 2, 3, 4, 5,* and *6*

Short-term plastic deformations in the layer due to creep are reduced from 0.047% in var. 1 to 0.011 and 0.01% in var. 2 and 3 and from 0.404 in var. 4 to 0.151 and 0.146% in var. 5 and 6, respectively. In this case, creep deformations increase from 0 to var. 1 and 4 to 0.114 and 0.118% in var. 2 and 3 and up to 0.284 and 0.294% in var. 5 and 6, significantly exceeding the level of short-term strains.

An important feature of the volumetric stress state as compared to the linear one is the change in the characteristics of strength (yield strength) and ductility (elongation) of the metal, which are determined experimentally under uniaxial tension. Under the conditions of volumetric stress state, hardening (increase in strength and decrease in ductility) or softening (decrease in strength and increase in ductility) of metal occurs. As a quantitative characteristic of this change, the stress stiffness coefficient k_s is used, which is equal to the ratio of the maximum (modulo) principal stresses (σ_1 or σ_3) to equivalent σ_{eq} [14]. The main stresses are also defined in the work.

An analysis of the results of modeling the SSS under temperature loading showed that the appearance of plastic deformations in the interlayer has little effect on the stiffness coefficient and the degree of hardening or softening of both the base metal and the interlayer material (Fig. 7).

In the base metal near the axis of the node, it is 0.68, gradually increasing as it approaches the outer surface to 1 at a distance of about 1 mm from it and to 1.4 ... 1.5 near the surface. In the interlayer, it remains equal to 1 for the most part of the joint length (90%) and only at the surface itself it first slightly increases (to 1.05), and then sharply decreases to 0.6 ... 0.8 (0.85 ... 0.75 in var. 1 ... 3 and 0.65 ... 0.6 in var. 4 ... 6).

Comparison of stress diagrams with similar ones obtained in solving the elastic problem showed that their nature and level, both in the base metal and in the interlayer, vary insignificantly, mainly in small areas near the joint edge. Here, the stiffness coefficient in the base metal increases to 1.5, i.e., the metal is hardened somewhat more than in the elastic stage (1.35).

In the interlayer, the stiffness coefficient decreases to 0.5, i.e., the metal softens more than when solving the problem, taking into account only the elastic deformation of the metal (0.6). Thus, plastic deformations in the interlayer slightly increase the effect of hardening and softening of the base metal and the interlayer only on the outer surface of the assembly. The increase in the strength of the metal, as well as

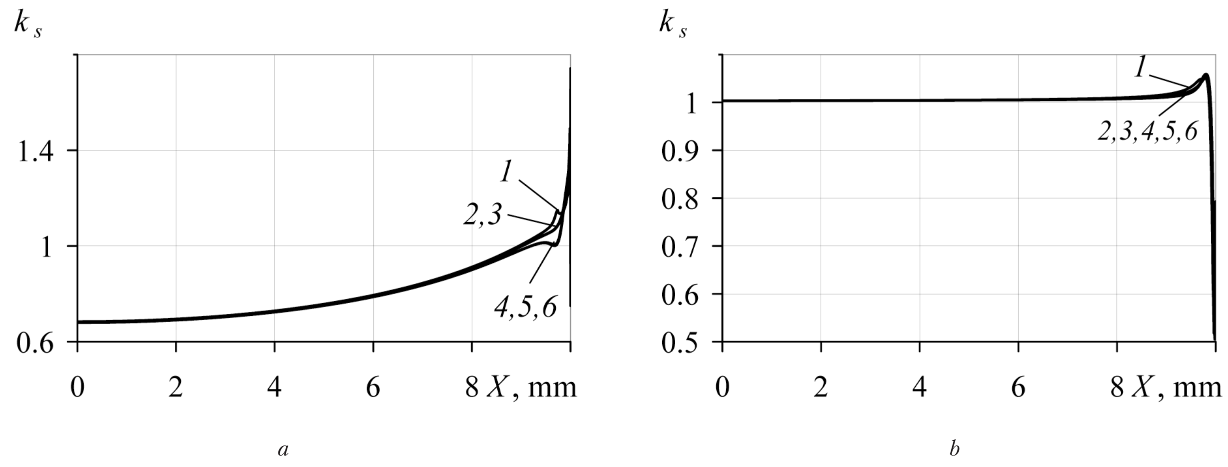

Fig. 7. Changes in stress stiffness coefficients $ks = \sigma_{1(3)}/\sigma_{eq}$ at the joint in the base metal (*a*) and interlayer (*b*), options 1 ... 6

its softening is caused by a change in the nature of the stress-strain state.

Conclusions

1. During thermal loading by slow cooling of units with a soft interlayer in a small zone located near the interlayer at the joint edge (at the outer surface of the cylinder), and in the interlayer itself, a complex SSS is created due to the difference in the TCLE values of the joined metal and the interlayer. At the same time, the stress level in options with slow cooling is slightly lower than with fast cooling.

2. Slow cooling for 600 s reduces the stress in the interlayer and in a small zone of the base metal near its edge due to creep deformations in the interlayer. Moreover, the degree of creep resistance of the interlayer in comparison with the base metal in the accepted range (0.85 or 0.7) practically does not play a role. The resulting creep strains have little effect on the nature of the stress fields.

3. In variants with a smaller difference in the TCLE of the interlayer and the base metal ($10.5 \cdot 10^{-5}$ 1/°C) and, accordingly, with a lower level of stresses, short-term plastic deformations are small, they arise only in a small area of the interlayer at the edge of the joint. At the same time, they noticeably decrease as a result of stress reduction due to creep.

4. In variants with a greater difference in the TCLE of the interlayer and the base metal ($21 \cdot 10^{-5}$ 1/°C) and, correspondingly, a higher level of stresses, short-term plastic deformations noticeably increase and are distributed along the entire length of the interlayer. In variants with slow cooling (var. 5 and 6), they also noticeably decrease due to creep.

5. Creep deformations during slow cooling noticeably increase with an increase in the difference in the TCLE of the interlayer and the base metal, changing slightly with a change in the creep resistance of the interlayer within the accepted limits.

6. The stiffness coefficients of the stress-strain state, and, accordingly, the degree of hardening and softening of the metal in the joint zone, with slow cooling, both in the base metal and in the interlayer, change slightly, mainly in small areas near the joint edge.

Abbreviations

SSS — stress-strain state;
TCLE — thermal coefficients of linear expansion.

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ВЛИЯНИЕ ФИЗИКО-МЕХАНИЧЕСКИХ СВОЙСТВ ПРОСЛОЙКИ НА НАПРЯЖЕННО-ДЕФОРМИРОВАННОЕ СОСТОЯНИЕ ПРИ ДИФФУЗИОННОЙ СВАРКЕ И ПАЙКЕ ЖАРОПРОЧНОГО СПЛАВА НА ОСНОВЕ ИНТЕРМЕТАЛЛИДА Ni_3Al

Методом конечных элементов исследовано напряженно-деформированное состояние (НДС) при медленном охлаждении (в течение 600 с) цилиндрических узлов из сплава на основе Ni3Al с «мягкой» прослойкой, имеющей меньшей (0,85) по сравнению с основным металлом пределом текучести и с меньшим, чем у основного металла на 15 и 30 % сопротивлением ползучести. Установлено, что в небольшой зоне основного металла вблизи внешней поверхности у стыка с прослойкой возникает сложное НДС, которое снижает напряжения в прослойке вследствие пластических деформаций ползучести. Коэффициенты жесткости напряжений, а соответственно, и степень упрочнения или разупрочнения металла при медленном охлаждении изменяются на небольших (около 5 толщин прослойки) участках вблизи кромки стыка. [dx.doi.org/10.29010/88.7]

Keywords: *компьютерное моделирование; пластические деформации; коэффициент жесткости напряжений, диффузионная сварка, высокотемпературная пайка, жаропрочный сплав.*

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