Influence of the residual thickness of the interlayer on the stress-strain state in the nodes with soft interlayer

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Abstract. Ni3Al-based superalloys have excellent mechanical properties which have been widely used in civilian and military Fifield. In this study, the influence of the residual thickness of the interlayer on the stress-strain state in the nodes with soft interlayer was investigated by computer simulation. To establish the general patterns of SSS formation when loading cylindrical nodes with interlayers of soft rigidity and checking the adequacy of the simulation, thickness of interlayer (0.01, 0.03, 0.05, 0.08mm) were calculated. The result shows that in all the thicknesses of the interlayer, both in the main material and in the interlayers, the nature of the distribution and the magnitude of the stiffness coefficients of the stressed state kstiff are practically identical. In the base metal, over most of the joint length, this coefficient is close to 1, decreasing to 0.88 in the nodes with "soft". This corresponds to the general laws of mechanics and confirms the adequacy of the results of computer simulation.

1. Introduction
Composite and intermetallic materials, including those based on Ni3Al, are increasingly used in modern gas turbine construction[1]. Solid phase diffusion welding does not produce large macro deformation, the joint has high strength and good thermal stability, which has great potential in the welding manufacture of engine superalloy structure[2,3]. In aviation industry, intermediate layer materials are often used in diffusion bonding of Ni3Al based superalloy materials in order to improve the bonding condition of Ni3Al based superalloy materials[4,5], remove constraints and eliminate or weaken the mismatch between residual stress and properties.

It was shown that when a node with a soft interlayer is loaded with an axial load in the material of the interlayer and in a small zone of the base metal adjacent to the interlayer near its edge, a volumetric stress state is formed[6,7]. At the same time, the plastic flow of the intermediate layer material is limited by the constraint of the high strength matrix, the joint still has a higher strength, the restraint degree is related to the thickness of the intermediate layer material[8,9]. The smaller the thickness of intermediate layer, the greater the constraint is limited. Many experimental results shows that the thickness of the interlayer material has great influence on the mechanical properties of the welded joint[10,11]. However, there is little research on the effect of the thickness of IC10 directionally solidified high temperature interlayer on stress-strain state in the nodes of IC10 joints.
For the purpose of examination the influence of the material thickness of the intermediate layer on the stress-strain state of the soft interlayer joint is examined. The four models of the thickness ratio of the intermediate layer to the base metal are compared, and the influence of the thickness of the intermediate layer on the stress-strain state of the joint is investigated.

2. Computational Methods and Variants of the investigated models

2.1. Computational Methods

Using the software complex ANSYS, the stress-strain state under compression loading (force loading) and temperature change (thermal loading) of cylindrical samples (joints) of the joint of the base material (alloy + alloy) through a layer of crystallized solder was investigated.

Due to the symmetry of the sample relative to the middle of the thickness of the interlayer, the model was constructed for the upper half of the sample (the upper cylinder and half the thickness of the interlayer) with the corresponding fastening of the nodes at the lower edge of the model. Dimensions of the model: cylinder diameter \( d = 20 \text{ mm} \) and height \( h = 20 \text{ mm} \), half the thickness of the interlayer \( s/2 \).

The general view of the sample and the scheme for breaking down into finite elements (FE) of the model as a whole and the region adjacent to the interlayer are shown in Fig. 1.

Taking into account the specificity of the node, the presence of large stress gradients in a narrow zone near the interlayer, a gradient breakdown with variable dimensions of the FE was used. At the same time, the dimensions of the FE in the joint zone were chosen so that there were at least 10 of them in the thickness of the interlayer. The FE of PLANE type 183 and PLANE 182 were used [12,13].

![Figure 1. General view of the sample with interlayer (a), Section of an axisymmetric finite-element model (b) and Zone of interface of the interlayer with the metal to be joined (c).](image)

The nodes on the Y axis of the model were fixed in the direction of the X axis, and on the lower edge in the direction of the Y axis. The model was loaded with a longitudinal (along the vertical Y axis) uniformly distributed at the end of the compressive load or a decrease in temperature. A comparison of the solutions of these and similar problems in tension or heating showed that in the elastic stage of deformation when the compression is compressed by stretching or cooling by heating, the nature of the SSS does not change, only the signs of stresses and deformations change, which corresponds to the general principles of mechanics.

2.2. Variants of the investigated models

The effect of the thickness of the interlayer was investigated on the models given in Fig. 1. The calculation was carried out for four thickness variants, as with "soft" (variants 1-4), interlayers (Table 1). In all the variants, the modulus of elasticity of the base metal were assumed to be the same \( E_{bm} = 1.673 \times 10^5 \text{ MPa} \), the Poisson ratio of both the base material and the interlayer was assumed to be 0.3. At
the same time, the "soft" interlayers had a modulus of elasticity that was almost 2 times smaller than that of the base metal, while the "hard" interlayers had a modulus of 2 times higher, respectively.

The node was loaded with an axial compressive load of 10 MPa. Proceeding from the general laws of mechanics, and as it was confirmed by the results of computer simulation, with the change (decrease or increase) in the load in the elastic stage, the magnitude of all component stresses also varies proportionally. When loading with a tensile load, the nature of the SSS and the magnitude of the stresses are preserved, only their sign changes.

| No. of var | E_{bm}, 10^5 MPa | Thickness of interlayer, s, mm | Relative thickness (degree of elongation) of the interlayer, s/d |
|-----------|------------------|-------------------------------|-------------------------------------------------------------|
| 1         | 0.84             | 0.01                          | 0.0005                                                      |
| 2         | 0.84             | 0.03                          | 0.0015                                                      |
| 3         | 0.84             | 0.05                          | 0.0025                                                      |
| 4         | 0.84             | 0.08                          | 0.0040                                                      |

3. Results and discussion

3.1. The stress fields in small areas near the interlayer and the base metal

Fig.2 to Fig.7 show the stress fields in small areas near the interlayer and the outer edge of the node, where the SSS becomes volumetric. For the convenience of their comparison and clarity, they are shown in different scales, inversely proportional to the thickness of the interlayer.

Comparison of the fields of all components and equivalent voltages of the volumetric SSS zone located at the joint edge shows that the thickness of the interlayer in the investigated range of elongation (s/d = 0.0005–0.0040) practically does not affect the nature of the SSS or on the magnitude of the stresses. When the thickness of the interlayer changes, only the dimensions of this zone vary in direct proportion. The width of the zone of volumetric SSS in the main material is commensurable with the thickness of the interlayer. The length from the external surface of the assembly, both in the main material and in the interlayer, at all thicknesses is about 5 times the thickness of the interlayer.

**Figure 2.** The fields of radial $\sigma_r$ stresses near the interlayer near the outer surface of the node.
Figure 3. The fields of axial $\sigma_y$ stresses near the interlayer near the outer surface of the node.

Figure 4. The fields of maximal main $\sigma_3$ stresses near the interlayer near the outer surface of the node.
Figure 5. The fields of circumferential $\sigma_z$ stresses near the interlayer near the outer surface of the node.

Figure 6. The fields of tangential $\tau_{xy}$ stresses near the interlayer near the outer surface of the node.

Figure 7. The fields of equivalent $\sigma_{eq}$ stresses near the interlayer near the outer surface of the node in variants 1 (a), 2 (b), 3 (c) 4 (d).
Outside this zone, the radial, circumferential and tangential stresses become negligibly small, the SSS remains practically linear, with axial, maximum principal and equivalent stresses equal to the applied axial load.

3.2. Analysis of the diagrams of individual components and equivalent stresses

Analysis of the diagrams of individual components and equivalent stresses (Fig. 8–11) confirmed that, in both the jointed materials and in the interlayer, in all the thickness variants, for the greater part of the width of the node (more than 90%), a practically constant level of stress remains, in a small area at the edge of the joint.

Radial stresses in the base metal are tensile (Fig. 8, a). While remaining close to zero on most of the joint, they reach 1.6 MPa in all variants at the joint edge, which is 16% of the applied axial ones. In the material of the interlayer, radial stresses, on the contrary, are compressive. On the majority of the joint, they are about -2.1 MPa in all thickness variants and decrease to -0.85 MPa, that is, more than 2 times, at the joint edge (Fig. 8, b).

Figure 8. Diagrams of radial stress along the joint in the base metal (a) and interlayer (b) and near its outer edge.

Thus, the maximum radial stresses are about 16% of the applied load in the base metal, 21% on most of the interlayer and 11% at the outer edge of the joint.

The axial compressive stresses along most of the joint, both in the main material and the interlayer, remain at the level of the applied load, that is, -10 MPa (Fig. 9, a) and decrease at the joint edge to -9.08 MPa in all variants. The maximum principal stresses are similarly distributed (Fig. 9, b), and their level is almost the same: about -9.16 MPa.

Figure 9. Diagrams of the axial (a) and main maximum (b) stresses along the joint of the base metal and the interlayer near its edge.
The circumferential stresses, both in the main material and the interlayer along the joint, are distributed similarly to the radial stresses. In the main metal, they are equal to zero on most of the joint and appear only at its outer edge. Here they, like the radial ones, are tensile, but their level is 2 times lower (Fig.10,a): 0.8 MPa in all variants.

![Figure 10](image1.png)

**Figure 10.** Diagrams of circumferential stresses along the joint in the base metal (a) and interlayer (b) and near its outer edge.

In the material of the interlayer, the circumferential stresses are compressive, they remain at the level of -2.15 MPa for the majority of the joint and decrease at the outer edge to -1.3 MPa, that is, almost 1.5 times, in all variants (Fig.10, b).

Tangential stresses are absent on most of the joint length (about 95%), and appear and increase only at its edge up to 1 MPa in all variants (Fig.11). That is, the maximum tangential stresses are about 10% of the applied axial stresses.

![Figure 11](image2.png)

**Figure 11.** Diagrams of tangential stresses along the joint of the base metal and the interlayer near its outer edge.
In accordance with the individual components, equivalent stresses are also distributed (Fig. 12). Along the greater part of the joint they are constant, in the base material at a level close to the applied load of 10 MPa in all variants (Fig. 12, a). In the interlayer, the stress level in this zone is about 7.85 MPa, that is, less than in the main metal, by more than 20% (Fig. 12, b). Only in the immediate vicinity of the edge of the joint, at a distance of about 10 interlayer thicknesses, the equivalent stresses increase somewhat, reaching 10.64 MPa in the base metal and 8.2 MPa in the interlayer.

To estimate the effect of volumetric SSS on the strength of a material, we use the stiffness coefficient of the stress state equal to the ratio of the maximum principal stresses (when the node is stretched \( \sigma_1 \), and at compression \( -\sigma_3 \)) to the equivalent \( K_{\text{stiff}} = \frac{\sigma_1 / 3}{\sigma_{\text{eq}}} \) [14,15].

**Figure 12.** Diagrams for equivalent stresses \( \sigma_{\text{eq}} \) along the joint of the main metal (a, b) and interlayer (c, d) along the entire length of the joint (a, c) and near its edge (b, d).

In Fig. 13 are graphs of the change in the stiffness coefficient in the joint zone in the main material (a, b) and the interlayer (c, d) along the entire joint (a, c) and near its edge (b, d). Analysis of the curves shows that in all variants of the nodes, both in the main material and in the interlayers, the character of the distribution of the stiffness coefficients \( K_{\text{stiff}} = \frac{\sigma_1 / 3}{\sigma_{\text{eq}}} \) is practically the same. In this case, in the base metal, for most of the joint length, this coefficient is close to 1. That is, the SSS arising in the joint zone practically does not affect the strength of the base metal over the majority of the joint length and leads to its softening only near the outer surface[16], where the stiffness coefficient decreases to 0.88 (Fig. 13, b).
Figure 13. Changing the Stiffness Coefficients of the Stress State $K_{s\text{iff}}$ along the joint in the base metal (a, b) and interlayer (c, d) along the entire length of the joint (a, c) and near its edge (b, d).

In the interlayer, the picture is different, the metal is hardened over the entire length of the joint, the stiffness coefficient here rises to 1.273. And only at the edge of the joint it is somewhat lower: 1.13 (Fig. 13, d). Such SSS also does not contribute to the formation of a joint in DW by traditional technology.

The nature of the distribution of the axial, principal maximum and equivalent stresses along the generatrix (external surface) of the site is very close in all variants (Fig. 14). The axial and maximum principal stresses are practically identical in all variants and vary in the range from 7.7 to 10 MPa in the interlayer and from 10 to 11.1 MPa in the base metal in a zone commensurate with the thickness of the interlayer (Fig.14,a and b). The diagrams of equivalent stresses along the generatrix are similar in character to the axial and maximum principal stresses (Fig.14, c). Their level varies from 7.3 to 10 MPa in the interlayer and from 10 to 10.7–10.8 MPa in the base metal.
Figure 14. Diagrams of axial $\sigma_y$ (a), principal maximum $\sigma_3$ (b) and equivalent (c) stresses along the geneatrix of the node in variant of interlayer.

The distribution of the stiffness coefficient of the stress state along the geneatrix near the joint is shown in Fig.15.

Figure 15. Changing the Stiffness Coefficients of the Stress State $K_{stiff} = \sigma_3/\sigma_{eq}$ along the generatrix of the node in the variants of the interlayer.

Analysis of the figure shows that on the external surface of the node the nature of the SSS is somewhat more favorable than inside the joint near its edge[17]. Here, only in variant 1 (0.01 mm thick), the stiffness coefficient increases to 1.08 in the main material and decreases to 0.973 in the base metal, while within the joint they are 1.13 and 0.88, respectively. That is, the metal of the interlayer is strengthened, and the base metal is softened to a lesser degree. In versions 2, 3 and 4, the interlayer on the surface is hardened even less, here the stiffness coefficient is about 1.05. In the main metal on the surface there is no softening, the stiffness coefficient is close to 1.03.

4. Conclusion
The width of the zone of volumetric SSS in the main material is commensurable with the thickness of the interlayer. The length from the outer surface of the node, both in the main material and in the interlayer, at all thicknesses and both stiffnesses, is about 5 times the thickness of the interlayer.

1. Axial compressive stresses along the majority of the joint, both in the main material and the interlayer, remain at the level of the applied load and vary only at the joint edge in all thicknesses of the interlayer: at nodes with a "soft" interlayer decrease by 10%.

2. Circumferential stresses, both in the main material and in the interlayer, along the joint are distributed similarly to the radial ones. In the main metal, they are equal to zero on most of the joint and appear only at its outer edge. Like radial ones - in the nodes with a "soft" interlayer tensile, but its level
is lower in all thickness variants. In the material of the interlayer, the circumferential stresses are compressive in "soft" layer.

3. In accordance with the individual components, equivalent stresses are also distributed. Along most of the joint they are constant, in the main material at a level close to the applied load of 10 MPa in all variants. In the layer, the stress level in this zone in nodes with a "soft" interlayer is lower than in the main metal by more than 20%. Only in the immediate vicinity of the joint edge, at a distance of about 10 interlayer thicknesses, equivalent stresses increase slightly, about 6% in the base metal and 3% in the "soft" layer.

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