Stress-strain State in Elastic Phase in Ni3Al superalloy with soft interlayer

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Abstract. In this study, the stress-strain State in elastic phase of cylinder-cylinder joint in Ni3Al superalloy with "soft" elastic modulus ratios 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, three load cases were calculated: -5 (var.1), -20 (var.2) and -40 (var.3) MPa. The result shows that regardless of the magnitude of the axial load (in all load cases) in the nodes, with "soft" interlayers, 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 node is not more than 5~10 thickness of the interlayer; the nature of the SSS in the elastic stage of the material is completely only the level of stresses is directly proportional to the magnitude of the external load. This corresponds to the general laws of mechanics and confirms the adequacy of the results of computer simulation.

1. Introduction

Ni-Al alloys, especially Ni-Al single crystal alloys, have been widely applied as structural materials and functional materials in civilian and military fields, due to their high strength, high temperature stability, corrosion and oxidation resistances in aggressive environments [1, 2]. As the most promising and valued Ni-Al alloys, Ni3Al-based single crystal alloys are well known as superalloys because of their excellent mechanical properties at high temperature, which have been extensively used for the hot components of gas turbines[3,4].

Vacuum diffusion welding has been widely used in the connection of superalloys, high melting point metals, stone, ceramics and heterogeneous materials [5]. It plays an important role in aviation and spaceflight. In aviation industry, interlayer materials are often used in diffusion bonding of Ni3Al superalloy in order to improve the bonding condition between Ni3Al superalloy, remove the beam, eliminate or reduce the mismatch between residual stress and properties [6, 7]. Intermediate layer generally adopts similar composition to the base metal, to obtain welds similar to the base composition of the base metal.

Many experimental results show that the thickness of interlayer material has a great effect on the mechanical properties of welded joints [8, 9]. Therefore, the influence of the thickness of the interlayer material on the stress distribution and fracture mechanism of the joint has been studied [8, 9]. The existing work mainly focuses on the study of interface normal stress. However, the influence of different
elastic modulus of interlayer on the mechanical properties of joints is rarely reported. In order to investigate the effect of interlayer on the stress-strain state of elastic phase in Ni3Al superalloy cylinder-cylinder joints with different elastic modulus ratios. In this paper, the software complex ANSYS was used to investigated the stress-strain state (SSS) 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 ("soft" interlayer material).

2. Preliminary analysis of the base alloy

2.1. The coefficient of linear thermal expansion (TCLE) in different alloy temperature ranges

The coefficient of linear thermal expansion (TCLE) in different alloy temperature ranges is given in Table 1. A comparison of the data along and across the crystal shows that they coincide with a sufficient accuracy for practical calculations, so in subsequent calculations they are assumed to be the same (average) [10, 11].

Table 1. Average coefficient of linear expansion (10^−6 1/°C) ranges along and across the crystal in accordance.

| T°C | 20-100 | 20-200 | 20-300 | 20-400 | 20-500 | 20-600 | 20-700 | 20-800 | 20-900 | 20-1000 | 20-1100 |
|-----|--------|--------|--------|--------|--------|--------|--------|--------|--------|---------|---------|
|     |        |        |        |        |        |        |        |        |        |         |         |
|     | 11.7   | 11.8   | 12.2   | 12.6   | 13.1   | 13.5   | 13.9   | 14.4   | 14.8   | 15.3    | 15.7    |
| longwise | 11.7   | 12.0   | 12.3   | 12.7   | 13.2   | 13.6   | 14.0   | 14.4   | 14.8   | 15.3    | 15.7    |
| crosswise | 11.7   | 12.0   | 12.3   | 12.7   | 13.2   | 13.6   | 14.0   | 14.4   | 14.8   | 15.3    | 15.7    |

For the convenience of analysis of the temperature dependence, the values for the mid-points of the respective temperature ranges are given in Table 2.

The obtained dependence (Fig.1) is linear in character and is described with sufficient accuracy by the regression equation (0.0086T+10.934) • 10^-6, whose extrapolation allows to determine the TCLE at higher temperatures (from 620 to 1200°C). In particular, for a temperature of 1185°C, the TCLE will be 21.25.

Table 2. Coefficients of linear temperature expansion (10^-6 1/°C) in the middle part of the corresponding temperature ranges.

| T°C | 60 | 110 | 160 | 210 | 260 | 310 | 360 | 410 | 460 | 510 | 560 | 610 |
|-----|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| TCLE| 11.7 | 11.9 | 12.25 | 12.65 | 13.15 | 13.55 | 13.95 | 14.4 | 14.8 | 15.3 | 15.7 | 16.15 |

Figure 1. The dependence of the TCLE on the temperature (from 20 to 620°C), constructed from the average temperatures of the ranges and extrapolated to 1200°C.

2.2. The elastic modulus E and Poisson’s ratio μ

Dependence of the elastic properties of the alloy on the temperature along and across the crystal is given in Table 3. Comparison of the elastic properties along and across the crystal shows that they differ markedly. Since the butt solder joints are usually located across the crystal in the simulation of the SSS, it is advisable to use elastic properties in the direction transverse to the crystal.
Table 3. Dependence of the elastic properties of the alloy on the temperature along and across the crystal.

| T, deg ℃ | 20  | 600 | 700  | 800  | 900  | 1000 | 1100 |
|----------|-----|-----|------|------|------|------|------|
| E, hPa   |     |     |      |      |      |      |      |
| longwise | 129.6 | 119.7 | 115.0 | 107.1 | 96.3 | 86.7 | 73.2 |
| crosswise | 167.3 | 141.8 | 133.4 | 123.1 | 117.6 | 110.1 | 89.8 |
| µ        |     |     |      |      |      |      |      |
| longwise | 0.372 | 0.392 | 0.421 | 0.427 | 0.445 | 0.463 | 0.485 |
| crosswise | 0.301 | 0.320 | 0.332 | 0.343 | 0.347 | 0.354 | 0.369 |

The values of the elasticity modulus and Poisson's ratio at temperatures above 1100°C can be found by extrapolating the available data and taking into account the approximation of the elasticity modulus to zero, and the Poisson's ratio to 0.5 at the melting point of the alloy (Fig. 2 and 3).

Figure 2. Dependence of the modulus of elasticity of the alloy on temperature, used in modeling.

Figure 3. Dependence of the Poisson's ratio of the alloy on temperature, used in modeling.

2.3. Strength and plasticity of the alloy

Characteristics of the strength and plasticity of the alloy along the crystal for different temperatures after the standard heat treatment [10, 11].

Table 4. Dependence of the strength properties of the alloy on temperature.

| T /°C | 20  | 200 | 400  | 600  | 700  | 800  | 850  | 900  | 1000 | 1100 |
|-------|-----|-----|------|------|------|------|------|------|------|------|
| σ_p02/MPa | 848 | 830 | 860  | 825  | 835  | 845  | 870  | 893  | 860  | 602  | 307  | 155  |
| σ_b/MPa | 1237 | 1190 | 1150 | 1060 | 1080 | 1080 | 1120 | 1128 | 980  | 827  | 471  | 236  |
| δp/%   | 14.8 | 12  | 11   | 11   | 12   | 9.5  | 7.5  | 9.1  | 11   | 12.4 | 31.0 | 48.2 |
| ψ/%    | 17.3 | 16.5 | 14.5 | 18.5 | 13.5 | 15   | 11   | 10.6 | 15   | 14.6 | 32.7 | 52.3 |

3. Results and Discussion

3.1. Computational Methods

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 mm and height h = 20 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.4.

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 LANE type 183 and PLANE 182 were used [12,13].

Figure 4. 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).

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 [12,13].

In accordance with the laws of mechanics in the elastic stage of deformation, the stress level is directly proportional to the magnitude of the applied load. In order to establish the general patterns of SSS formation when loading cylindrical nodes with interlayers of various rigidity and checking the adequacy of the simulation, three load cases were calculated: -5 (var.1), -20 (var.2) and -40 (var.3) MPa nodes with "soft" interlayers.

3.2. Patterns in the formation of a stress-strain state at different strengths in nodes with a "soft" interlayer
In all cases, the modules of elasticity of the base metal ($E_{bm} = 2 \cdot 10^5$ MPa) [10] and the interlayer ($E_{int} = 1 \cdot 10^5$ MPa), as well as its thickness (0.1 mm) remained unchanged. The calculation was carried out on the models given in Figure.4.

The analysis of the fields of all components and equivalent stresses obtained as a result of simulation showed that in all variants for the greater part of the node the SSS remains close to linear with axial and equivalent stresses equal to the applied load. And only in a small zone of the node located near the interlayer near the edge of the joint (at the outer surface of the cylinder) is a complex SSS created due to the difference in the module of elasticity of the metal to be joined and the interlayer. The fields in this zone are shown in Fig.5 to 10 on an enlarged scale (x260). Comparison of the fields shows that the nature of SSS in all cases of loading is completely preserved, only the level of stresses is directly proportional to the magnitude of the external load (see scales a, b and c in the Figureures).

In the small joint zone adjacent to the free lateral surface, near the interlayer and in the interlayer, in addition to the axial stresses, all other components appear: radial and circumferential normal and...
tangential stresses, the stressed state becomes volumetric. As a result, equivalent stresses (Figure 10) differ from the applied axial ones, exceeding them in the base metal, and decreasing in the interlayer material.

![Figure 5. The fields of radial $\sigma_x$ stresses in variants 1(a), 2(b), 3(c).](image)

![Figure 6. The fields of axial $\sigma_y$ stresses in variants 1(a), 2(b), 3(c).](image)

![Figure 7. The fields of maximal main $\sigma_1$ stresses in variants 1(a), 2(b), 3(c).](image)

![Figure 8. The fields of circumferential $\sigma_z$ stresses in options 1(a), 2(b), 3(c).](image)

![Figure 9. The fields of tangential $\tau_{xy}$ stresses in options 1(a), 2(b), 3(c).](image)
Figure 10. The fields of equivalent $\sigma_{eq}$ stresses in variants 1(a), 2(b), 3(c) near the interlayer near the outer surface of the node.

In this case, the fields of the maximum principal stresses, under compression, are $\sigma_3$ (Fig.7), in all cases practically do not differ from the axial stress fields $\sigma_y$ (Fig.6).

The width of the zone of volumetric SSS in the main material is about 0.1 mm, that is, it 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, is no more than 0.5 mm, that is, within 5 interlayer thicknesses.

Analysis of the diagrams of individual components and equivalent stresses (Fig.11-15) confirmed that, in both the jointed materials and the interlayer, in all thickness variants the majority of the node width (up to 90%) remains practically constant, with a change only in a small area at the edge of the joint.

The maximum radial stresses in the base metal are tensile (Fig.11 (a)). Staying close to zero on most of the joint, they reach 0.8, 3.2 and 6.4 MPa in variants 1, 2 and 3, respectively, that is, they increase in direct proportion to the load (Table 5). Their dependence on the value of the compressive load $P$ with the reliability $R_2 = 1$ is described by the equation $\sigma_x = -0.16P$.

Table 5. Maximum stresses (MPa) in the main metal of the node.

| Stresses         | In the middle part of the joint | At the joint edge |
|------------------|---------------------------------|------------------|
|                  | Var. 1  | Var. 2  | Var. 3  | Var. 1  | Var. 2  | Var. 3  |
| Radial           | 0       | 0       | 0       | 0.8     | 3.2     | 6.4     |
| Axial            | -5      | -20     | -40     | -4.5    | -18     | -36     |
| Circumferential  | 0       | 0       | 0       | 0.425   | 1.7     | 3.4     |
| Tangential       | 0       | 0       | 0       | 0.5     | 2       | 4       |
| Main             | 5       | 20      | 40      | 4.5     | 18      | 36      |
| Equivalent       | 5       | 20      | 40      | 5.025   | 21      | 42      |
| Stiffness coefficient | 0.995  | 0.995  | 0.995  | 0.88    | 0.88    | 0.88    |

Table 6. Maximum stresses (MPa) in the interlayer of the node.

| Stresses         | In the middle part of the joint | At the joint edge |
|------------------|---------------------------------|------------------|
|                  | Var. 1  | Var. 2  | Var. 1  | Var. 2  | Var. 1  | Var. 2  |
| Radial           | -1.05   | -4.2    | -8.4    | -0.525  | -2.1    | -4.2    |
| Axial            | -5      | -20     | -40     | -4.5    | -18     | -36     |
| Circumferential  | -1.05   | -4.2    | -8.4    | -0.55   | -2.2    | -4.4    |
| Tangential       | 0       | 0       | 0       | 0.5     | 2       | 4       |
| Main             | 5       | 20      | 40      | 4.5     | 18      | 36      |
| Equivalent       | 4       | 16      | 32      | 4       | 16      | 32      |
| Stiffness coefficient | 1.27   | 1.27    | 1.27    | 1.13    | 1.13    | 1.13    |

In the material of the interlayer, radial stresses, on the contrary, are compressive. On the majority of the joint they are about -1.05, -4.2 and -8.4 MPa in variants 1, 2 and 3 ($\sigma_x = 0.21P$), and decrease to -0.525, -2.1 and -4.2 MPa ($\sigma_x = 0.105P$), that is, 2 times, at the joint edge (Figure.11(b), Table 5 and 6). That is, the maximum radial stresses for a given combination of the elastic properties of the base metal and the interlayer amount to 16% of the applied load in the base metal, 21% on most of the interlayer and 10.5% at its outer edge.
The axial stresses along the majority of the joint, both in the main material and the interlayer, remain at the level of the applied load, that is, 5, 20 and 40 MPa (Fig. 12(a), Table 5 and 6) and decrease at the joint edge to 4.5, 18 and 36 MPa in versions 1, 2 and 3, respectively. The maximal principal stresses are similarly distributed (Fig. 12(b), Table 5 and 6), and their level is the same: 4.5, 18 and 36 MPa. That is, the axial stresses also linearly depend on the magnitude of the applied load, at the edge of the joint this dependence is described by the equation $\sigma_y = 0.9P$.

![Figure 11](image1.png)

**Figure 11.** Diagrams of radial stresses along the joint in the base metal (a) and interlayer (b) (variants 1, 2 and 3).

![Figure 12](image2.png)

**Figure 12.** Diagrams of the axial (a) and main maximum (b) stresses on the joint of the base metal and the interlayer near its edge (variants 1, 2 and 3).

The circumferential stresses, both in the main material and 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. Here they, like the radial ones, are tensile, but their level is almost 2 times lower (Figure. 13 (a), Table 5 and 6): 0.425, 1.7 and 3.4 MPa in variants 1, 2 and 3 respectively ($\sigma_z = -0.085P$).

In the material of the interlayer, the circumferential stresses are compressive, they remain at the level of -1.05, -4.2 and -8.4 MPa ($\sigma_z = 0.21P$) on the majority of the joint and decrease at the outer edge to -0.55, -2.2 and -4.4 MPa ($\sigma_z = 0.11P$), that is, almost 2 times, in versions 1,2 and 3, respectively (Fig.13(b) and Table 6).
Figure 13. Diagrams of circumferential stresses along the joint in the base metal (a) and interlayer (b) (variants 1, 2 and 3).

Tangential stresses are absent in most of the joint length (about 95%), and sharply increase only at the very edge (Fig. 14 and Table 5) to 0.5, 2 and 4 MPa in versions 1, 2 and 3, respectively ($= 0.1P$). That is, the maximum tangential stresses are 10% of the applied axial stresses and about 50% of the maximum radial stresses.

The distribution of tangential stresses along the joint (Fig. 14) confirms the low efficiency of force loading only from the point of view of activating the process of plastic deformation and the formation of a joint under traditional diffusion welding technology (DW). When welding by loading (compression) after heating to the welding temperature, favorable conditions are created only in a narrow zone at the periphery of the joint.

Figure 14. Diagrams of tangential stresses along the joint of the base metal and the interlayer (variants 1, 2 and 3).

In accordance with the individual components, equivalent voltages are also distributed (Fig. 15). Along most of the joint, they are constant, in the main material at a level close to the applied load of 5, 20 and 40 MPa in versions 1, 2 and 3, respectively (Fig. 15(a) and Table 5).

Figure 15. Diagrams of equivalent stresses along the joint in the base metal (a) and interlayer (b) near its outer edge (variants 1, 2 and 3).
In the interlayer, the stress level in this zone is 4, 16 and 32 MPa in variants 1, 2 and 3 (σz = -0.8P), that is, less than in the main metal, by 20%. Only in the immediate vicinity of the edge of the joint, at a distance of about 0.5~1 mm, that is, 5~10 thickness of the interlayer, they increase somewhat in the base metal, reaching 5.25, 21 and 42 MPa in variants 1, 2 and 3, respectively (σeq = -1.05P), and practically do not change in the interlayer (Fig. 15(b) and Table 6).

For convenience in comparing the level of individual stress components in the interlayer in Figure 16 shows the SSS diagram in it (%) of the applied axial load. From the diagram it is clearly seen that the material of the interlayer is in a volumetric dressed state. At the same time, for the most part, the axial stresses are equal to the applied load, the radial and circumferential stresses are 21% of it. Accordingly, equivalent stresses are reduced to 80% of the applied load, which confirms the fact of hardening of the soft interlayer.

At the outer edge of the joint, the stress state of the interlayer material changes somewhat, the radial and circumferential stress components decrease 2 times, tangential appear, and the equivalent remain at 80%.

![Figure 16. Levels of constituent and equivalent stresses in the interlayer material over the majority of the joint (row 1) and at its edge (row 2).](image)

To estimate the effect of volumetric SSS on the strength and plasticity of the material of the unit, we use the stiffness coefficient of the stress state equal to the ratio of the maximum principal stresses (when the node is stretched σ1, and at compression -σ3) to the equivalent Kstiff = σ1 (3)/σeq [14, 15]. A low stiffness coefficient (Kstiff <1) causes softening effect (lowering the yield point and increasing ductility) of the material compared to a linear stress state (Kstiff = 1), under which standard mechanical strength testing is carried out [15, 16]. The increase in the stiffness coefficient (Kstiff > 1), on the contrary, causes the effect of hardening (increase in the yield point and a decrease in plasticity) of the material [17].

In Fig.17 are graphs of the change in the stiffness coefficient in the joint zone in the main material (a) and in the interlayer (b) near its edge. Analysis of the curves shows that in all the load cases, both in the main material and in the interlayers, the stiffness coefficients Kstiff = σ3 /σeq are practically the same.

In this case, in the main metal, over most of the joint length, this coefficient is close to 1 (0.995). That is, the SSS arising in the jointing 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, where the stiffness coefficient decreases to 0.88 (Fig.17(a)). This explains the well-known fact that when compressing during diffusion welding, the most favorable conditions for jointing are created at the periphery of the joint.
Figure 17. The change in the stiffness coefficients of the stress state $\kappa_{\text{stiff}} = \sigma_3 / \sigma_{\text{eq}}$ at the joint in the base metal (a) and the interlayer (b) near its outer edge (variants 1, 2 and 3).

In the interlayer, the picture is different, the metal is hardened over the entire length of the joint, the stiffness coefficient here increases to 1.27. And only on the edge of the joint it is somewhat lower: 1.13 (Fig.17(b)). That is, the metal of the "soft" layer is strengthened, reducing the effect of its "softness". Such SSS also does not contribute to the plastic deformation of the "soft" layer and the formation of a joint in diffusion welding by traditional technology.

From the point of view of reducing the overall deformations of the node with DW and its operability under axial load loading, the distribution of stress along the generatrix of the node and along its axis is also of interest.

The distribution of axial, principal and equivalent stresses along the generatrix (external surface) of the node is practically the same in all variants (Fig.18).

Figure 18. Diagrams of axial $\sigma_y$ (a), principal maximum $\sigma_3$ (b) and equivalent stresses along the generatrix of the node (variants 1, 2 and 3).

In the base metal near the interlayer, in a zone commensurate with its thickness (no more than 2 thicknesses), it is characterized by great unevenness. The axial and maximum principal stresses are
practically the same and vary within 4, 16 and 32 MPa (σy = 0.8P) in the interlayer and 5.5, 22 and 44 MPa (σy = 1.1P) in the base metal in variants 1, 2 and 3, respectively (Fig. 18 (a, b)).

The diagrams of equivalent stresses along the geneatrix in terms of character and magnitude almost completely coincide with the axial and maximum principal (Fig. 18(c)). In this case, the peak (maximum) of stresses, somewhat exceeding the level of the applied external load, is located in the material to be jointed in the immediate vicinity of the interface with the interlayer.

Obviously, in the case of sufficient hardening of the "soft" interlayer under tension, fracture can occur along a more durable base metal at the interface with the interlayer, where the softening of the material to be jointed is accompanied by an increase in the axial stresses therein. This is confirmed by the results of tensile tests of diffusion bonding of alumina to steel using soft copper interlayer [18] in the literature.

4. Conclusion
The general patterns of SSS formation when loading cylindrical nodes with interlayers of "soft" rigidity and checking the adequacy of the simulation, three load cases were calculated: -5 (var. 1), -20 (var. 2) and -40 (var. 3) MPa, the conclusion is as follows.

1. When loading axial load in the elastic stage of the material, a complex SSS is created in the node. In a small zone of the base metal adjacent to the free lateral surface of the node near the interlayer and in the interlayer itself, in addition to the axial stresses, all other components appear: radial and circumferential normal and tangential stresses, the stressed state becomes volumetric.

On the rest of the base metal, the SSS for all loads remains close to linear with axial and equivalent stresses, almost equal to the applied load.

The SSS arising in the jointing zone has practically no effect on the strength and ductility of the base metal over most of the joint length and leads to softening ("soft" interlayer) only near the outer surface, where the stiffness coefficient is 0.88.

On the generatrix (on the outer surface) of the node, the peak (maximum) of the stresses, somewhat exceeding the level of the applied external load, is located in the material to be jointed in the immediate vicinity of the joint with the "soft" interlayer. Obviously, in the case of sufficient hardening of the "soft" interlayer under tension, fracture can occur over a more durable base metal near the joint with the interlayer, where the softening of the material to be jointed is accompanied by an increase in the axial stresses in it.

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