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STRESSED STATE OF WELDED AND BRAZED ASSEMBLIES FROM SIMILAR MATERIALS WITH A SOFT INTERLAYER UNDER AXIAL LOADING

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Computer modeling method was used to study the stressed state in assemblies, manufactured by diffusion welding and brazing, under the impact of axial load. Cylindrical assemblies from steel with a copper interlayer are considered under loading above the copper yield point. It is shown that formation of a complex stressed state resulted in the level of equivalent stresses decreasing in the interlayer compared to the applied axial load, and increasing in a small zone of base metal near the outer surface at the butt joint with the interlayer that causes the effect of hardening (unloading) of the interlayer and softening (overloading) of base metal. Quantitative dependencies of the degree of interlayer hardening and base metal softening on more load magnitude were derived. It is found that at the elastoplastic stage of assembly loading base metal softening is external pronounced, than at the elastic stage. Degree of interlayer hardening at the elastic stage of its work does not depend on the magnitude of external load, and at the elastoplastic stage it is increased in proportion to the load. 9 Ref., 5 Figures.

Keywords: *welded and brazed assemblies, soft interlayer, computer modeling, stressed state, force loading*

New composite materials and assemblies that cannot be joined by fusion welding are ever wider applied in modern engineering. In these cases brazing or solid-phase welding, for instance vacuum diffusion welding (VDW), is used. At VDW interlayers are often used for formation of guaranteed contact of the surfaces being joined over the entire area. Copper, aluminium and nickel are used as interlayers. Brazed seam often is an interlayer in brazing.

Stressed state and performance of joints with a soft interlayer were studied in works [1–3], but the capabilities of analytical methods are limited. They do not allow taking into account all the features of the materials, loading types and structural factors, including the kinetics of formation of the stressed state (SS).

Modern computer equipment and developed program packages open up broad possibilities for such studies. In this work SS modeling was performed with application of ANSYS program package, based on finite element method, which we also applied in previous work [4–7].

In [6] it was established that in assemblies with a soft interlayer at loading by axial load SS in the joint zone becomes volumetric, equivalent stresses in interlayer material are reduced, and in the stronger base material they increase, on the contrary, i.e. so-called effect of soft interlayer hardening [1–3] is manifested, which is associated with joint SS. Here just one variant was modeled, when applied load (40 MPa) is close to the yield point (38 MPa) of interlayer material.

The objective of this work was studying SS of welded and brazed assemblies from similar materials with a soft interlayer at uniaxial compressive loading, at which axial stresses from applied load noticeably exceed interlayer material yield point, both during joint formation and when working in tension.

An interlayer is called soft, when its yield point is lower than that of base metal ($\sigma_{T_{int}} < \sigma_{T_{BM}}$).

SSS of cylindrical assemblies at joining similar material (steel + steel) through a soft copper interlayer 50 μm thick (relative thickness $s/d = 0.0025$) was studied.

In view of sample asymmetry relative to interlayer mid-thickness, SS of the upper half of the sample was modelled with appropiate assembly fastening on the model lower edge.

Model dimensions were as follows: cylinder of diameter $d = 20$ mm, and height $h = 20$ mm, half of interlayer thickness $s/2 = 25$ μm. Figure 1 gives the schematic of splitting into finite elements (FE) of the model as a whole and region adjacent to the interlayer.

Properties of the materials being joined and the interlayer: steel with modulus of elasticity $E = 2\cdot10^5$ MPa, yield point — 250 MPa, Poisson's ratio — 0.3, modulus of hardening at plastic deformation — $2\cdot10^3$ MPa; copper with modulus of elasticity $E = 1\cdot10^5$ MPa, yield point — 100 MPa, Poisson's

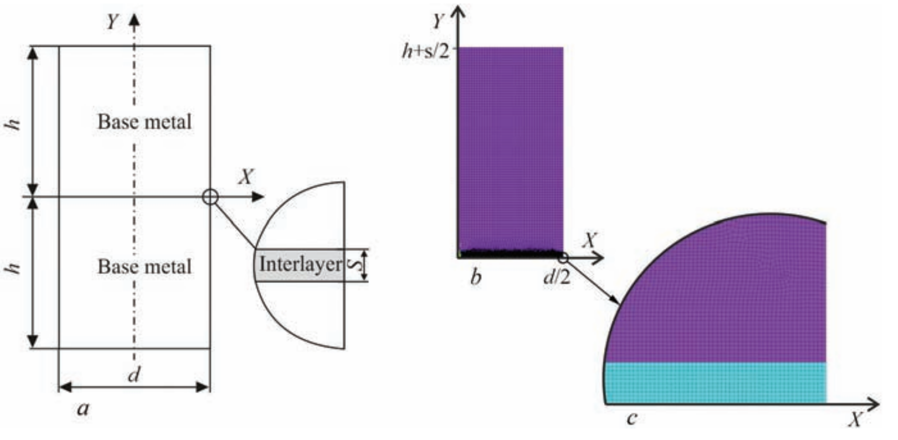

Figure 1. General view of the sample with the interlayer (*a*), section of axisymmetric finite element model (*b*) and zone of interlayer mating with the metal being joined (*c*)

ratio — 0.34; modulus of hardening at plastic deformation — $1\cdot10^3$ MPa.

Model was loaded by axial compressive load, the value of stress from which changed from 100 up to 200 MPa, i.e. maximum stresses exceeded the interlayer yield point up to two times, so that the process of interlayer material deformation occurred both at the elastic and plastic stages. At replacement of compression (during joint formation) by tension (in operation) the signs of stresses and strains will change for reverse ones without the change of their values and nature of distribution.

SS influence on mechanical properties of materials in the joint zone was assessed using stress stiffness factor equal to the ratio of stresses σ_y applied to the assembly to equivalent stresses σ_{eq} in this material: $K_{stif} = \sigma_y/\sigma_{eq}$ [8]. The magnitude of this factor determines the effect of softening (equivalent stresses exceed applied load, $K_{stif} > 1$) or hardening (equivalent stresses below the applied ones, $K_{stif} < 1$) of material in a particular narrow zone of the assembly, compared to linear stressed state, in which standard mechanical testing of material for strength is conducted. At $K_{stif} < 1$, strength, i.e. ability to resist plastic deformation, decreases and its ductility, i.e. ability to plastically deform without fracture, increases. At $K_{stif} > 1$, contrarily, strength increases and ductility decreases.

Analysis of the fields of all the components and equivalent stresses in the assemblies at axial loading showed that alongside axial stresses all the other components, namely radial, circumferential normal and tangential stresses are manifested in the small zone of the joint, namely, in the interlayer material and adjacent base metal regions, of the width of about two thicknesses of the interlayer, i.e. SS becomes volumetric. As a result, in this zone of the assembly equivalent stresses differ from applied axial stresses σ_y, exceeding them in the base metal, and decreasing in interlayer material. Here, at increase of the load the nature of the fields practically does not change, just the stress level rises in proportion to the load.

Analysis of equivalent stress curves (Figure 2), determining material behaviour at loading (purely elastic or elastoplastic deformation), showed that practically constant stress level is preserved both in the materials being joined, and in the interlayer on greater part of its length (up to 80–90 %).

Here, equivalent stresses are equal to applied load in base metal (Figure 2, *a*, *b*), and in the interlayer they change from 71 up to 100 MPa (elastic loading) at load change from 100 up to 130 MPa, and remain practically unchanged at the yield point level (about 100 MPa) at the load from 140 up to 200 MPa (elastoplastic loading) (Figure 2, *b*, *d*).

In the immediate vicinity from the butt joint edge, they somewhat increase both in the base metal, and in the interlayer material at the elastic stage of its work. The width of increased stress zone is not higher than 1–2 mm (10–20 % of sample radius). This leads to a change of stress stiffness factor K_{stif} in this region, and somewhat changes the effect of softening or hardening, compared to the linear stressed state.

For analysis and comparison with stronger interlayers having a higher yield point, the notion of «interlayer overloading coefficient» was used, which is equal to the ratio of stresses from applied axial load to interlayer yield point $K_{over} = \sigma_l/\sigma_{y_{int}}$. In our case, at elastic loading of the interlayer it changed in the range from 1.0 (100 MPa loading) to 1.3 (130 MPa), and at elastoplastic loading from 1.4 (140 MPa) to 2.0 (200 MPa).

With load increase from 100 to 130 MPa (degree of interlayer overloading from 1.0 to 1.3) maximum equivalent stresses in the base metal near the butt joint edge increase from 108 to 141 MPa (Figure 2, *a*) by the linear law. Coefficient of softening (stress stiffness factor) of base metal near the butt joint edge here remains practically unchanged at the level of about 0.92, respectively.

At further increase of load from 140 to 200 MPa, when plastic deformations develop in the interlayer, maximum stresses, similar to elastic loading, increase from 155 up to 241 MPa (Figure 2, *c*) also practically by a linear law, which is described by equation $\sigma_{eq} = 141K_{over}$, differing somewhat from elastic stage $\sigma_{eq} = 110\,K_{over} - 2$. Accordingly, reduction of stress stiff-

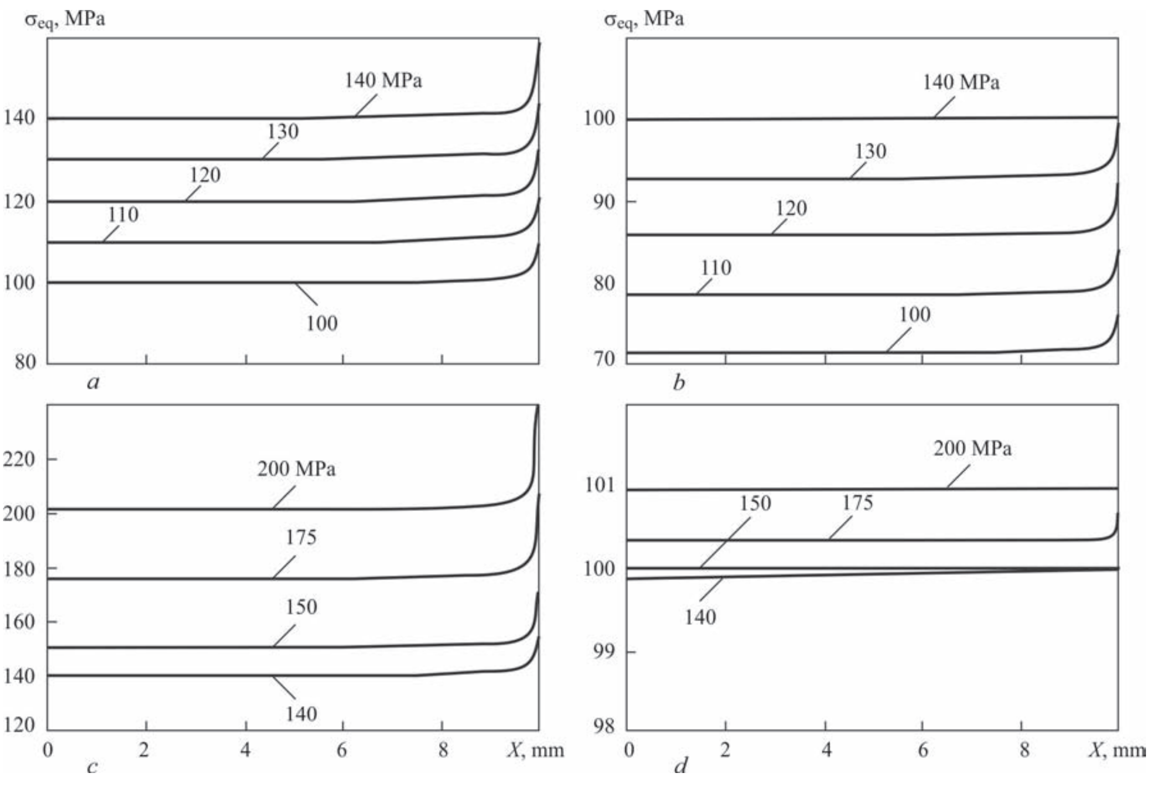

Figure 2. Curves of equivalent stresses in the butt joint on steel (*a*, *c*) and in the interlayer (*b*, *d*) at different axial loads

ness factor in the base metal at butt joint edge from 0.90 at 140 MPa load, causing plastic deformations in the interlayer, to 0.83 at the pressure of 200 MPa.

Lowering of stressed state stiffness causes the effect of softening of base metal at the assembly surface, expressed in that the maximum equivalent stresses at butt joint edge exceed those from applied axial load.

Thus, while at the elastic stage of soft interlayer deformation, stress stiffness factor, and degree of base metal softening, accordingly, depend only on the ratio of modules of elasticity and Poisson's ratios of base metal and interlayer, and do not depend on the magnitude of applied axial load, at the plastic stage dependence on the degree of interlayer overloading is also manifested.

For convenience of comparison of the two loading stages, Figure 3 gives the dependence of softening coefficient in the entire loading range, including the elastic and plastic stages of interlayer work, with the change of the extent of interlayer overloading from 1.0 up to 2.0.

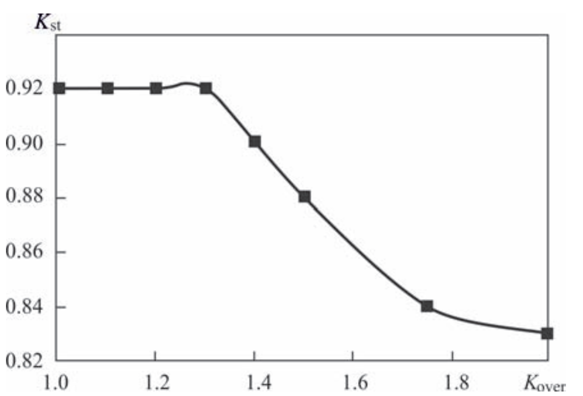

Figure 3. Dependence of softening coefficient and stress stiffness factor K_{stif} respectively of base metal near the butt joint edge on degree of soft interlayer overloading K_{over}

One can clearly see from Figure 3 that in the second (elastoplastic) stage of assembly loading base metal softening is more pronounced, that is attributable to noticeable increase of Poisson's ratio (up to 0.5) and small coefficient of interlayer material hardening at its plastic deformation. Moreover, while at the elastic stage base metal softening is determined only by the ratio of base metal and interlayer properties, at the plastic stage it depends also on the magnitude of load (degree of interlayer overloading).

In interlayer material equivalent stresses (Figure 2, *b*) remain constant at the level below the yield point (100 MPa), somewhat increasing at the edge only at up to 130 MPa load. At load increase from 100 up to 130 MPa, equivalent stresses in the interlayer increase linearly from 71 up to 93 MPa on greater part of its length and from 75 up to 98 MPa on the edge (Figure 2, *b*). At the load from 140 up to 200 MPa, equivalent stresses in the interlayer on the entire length of the butt joint, including the edge, remain on the same level, close to interlayer yield point (100 MPa). This confirms that interlayer material with the yield point of 100 MPa, is hardened due to increase of stressed state stiffness at the elastic stage, and it starts plastically deforming only at the load above 130 MPa.

Coefficient of interlayer hardening (stressed state stiffness) changes accordingly. At the load from 100 up to 130 MPa, it remains practically constant at the level of 1.4 on greater part of the butt joint and of 1.33 near its edge. At the load above 140 MPa, it, unlike elastic loading, grows linearly, and reaches the value of 1.97 at 200 MPa. Its dependence on the degree of interlayer overloading in this load range is linear, and is described by equation of regression $K_{stif} = 0.98K_{over} + 0.03$, i.e. stress stiffness factor (hardening coefficient) of the interlayer is practically equal to its overloading degree ($K_{stif} = K_{over}$) (Figure 4).

Analysis of the curves of tangential stresses along the butt joint showed that they are equal to zero on greater part of the butt joint (about 95 %), appearing and increasing up to 12–17 MPa only near its edge, at the distance of about two thicknesses of the interlayer (about 0.1 mm) from the outer surface. This is indicative of low effectiveness of purely force loading from the viewpoint of activation of the process of plastic deformation and joint formation by the traditional technology of diffusion welding.

Nature of axial stress distribution along the assembly generatrix (outer surface) is practically the same at all the loading variants. They are nonuniformly distributed along the assembly generatrix (outer surface) near the interlayer, in a zone of the width of up to two thicknesses of the interlayer, changing in the range of 70 to 120 MPa in the interlayer and 100–170 MPa in the base metal at elastic loading of the interlayer (see Figure 5, *a*) and 85–120 and 140–255 MPa at elastoplastic loading, respectively (Figure 5, *b*). Here, the peak (maximum) of axial stresses, noticeably exceeding the level of stresses from the applied external load, is located in the base metal in the immediate vicinity of the butt joint with the interlayer.

This is indicative of the fact that in the case of sufficient hardening of the soft interlayer, fracture can run through the stronger base metal at the butt joint with the interlayer, where softening (lowering of the yield point) of the material being joined is combined with an increase of axial stresses. In keeping with experimental data derived on Armco-iron samples brazed using copper, given in [9], at copper interlayer thickness of about 0.05 mm, fracture at tensile testing ran through iron at up to 325–350 MPa stresses in the assembly that is more than 1.5 times higher than copper yield point.

The established general regularities of SS formation in assemblies with a soft interlayer, expressed in increase

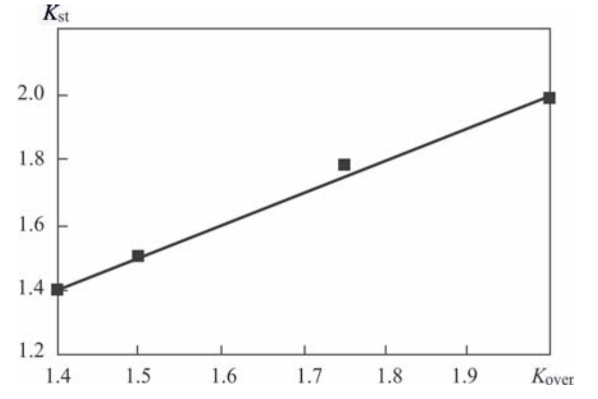

Figure 4. Dependence of hardening coefficient (stress stiffness factor K_{stif}) of the interlayer on the degree of «soft» interlayer overloading K_{over}

of stressed state stiffness, soft interlayer hardening, decrease of SS stiffness in base metal near the interlayer and its strength lowering (softening), are preserved both at elastic and at plastic loading in a broad load range.

A variant of the interlayer with a higher yield point of 150 MPa was also considered, in order to determine the influence of the level of interlayer yield point on the established regularities.

Axial load of 150 MPa, i.e. equal to interlayer yield point, 200 and 250 MPa, exceeding interlayer yield point (degree of overload), 1.33 and 1.67 times, respectively, was applied.

Analysis of equivalent stress curves along the butt joint under such loading conditions and their comparison with the previous variant of the assembly (interlayer yield point of 100 MPa) showed that the shape of the curves is preserved both in the base material, and in the interlayer. Equivalent stresses do not change in the base material on greater part of the butt joint, remaining on the level of stresses from the applied load. At the butt joint edge they rise up to 163, 220 and 295 MPa at 150, 200 and 250 MPa loading, respectively. Stress stiffness factors remain on 1.0 level in the base metal on greater part of the butt joint, and at the butt joint edge at 150 MPa loading (degree of interlayer overloading $K_{over} = 1.0$) base metal stress stiffness factor $K_{stif} = \sigma_y/\sigma_{eq} = 150/163 = 0.92$ that fully coincides with the variant of the assembly with 100 MPa yield point at the

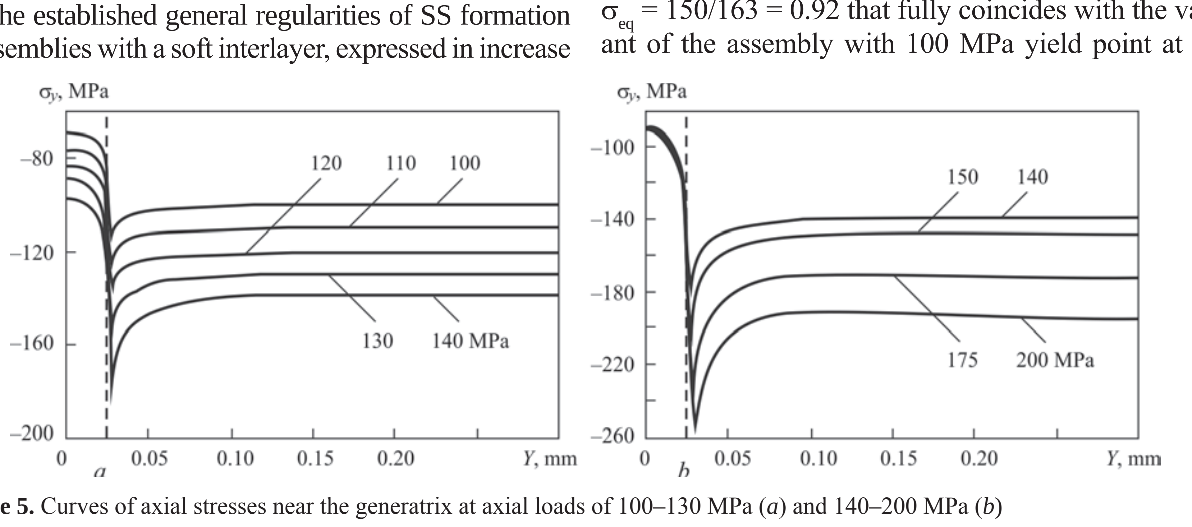

Figure 5. Curves of axial stresses near the generatrix at axial loads of 100–130 MPa (*a*) and 140–200 MPa (*b*)

same overload level. Similar results were obtained also at overloads of 200 and 250 MPa.

In the interlayer, equivalent stresses also remain constant on greater part of the butt joint on the level below the yield point (107 and 143 MPa) at the degree of interlayer overloading of 1.0 and 1.33 and on yield point level (150 MPa) at interlayer overloading degree of 1.67.

At 150 MPa load (degree of interlayer overloading K_{over} = 1.0), stress stiffness factor of the interlayer K_{stif} = 150/107 = 1.40 that practically coincides with 1.41 result, obtained for an assembly with an interlayer with 100 MPa yield point. The pattern is similar also at 200 and 250 MPa loads, at which K_{stif} = = 200/143 = 1.40 and K_{st} = 250/150 = 1.67, respectively, that fully coincides with the results obtained for the assembly with an interlayer with 100 MPa yield point.

At butt joint edge at a small degree of interlayer overloading (overloading degree of 1.0 and 1.33), when the interlayer is elastically deformed, equivalent stresses rise to 113 and 150 MPa, and stress stiffness factor increases to K_{stif} = 150/113 = 1.33 and K_{stif} = = 200/150 = 1.33, accordingly, that also completely coincides with the elastic stage of the work of interlayer with yield point of 100 MPa.

One should bear in mind that the derived regularities remain in force only under the condition of base metal working at the elastic stage. For this purpose, it should have the yield point above the maximum axial load applied to the assembly. The required degree of excess depends on the degree of soft interlayer overloading and corresponding coefficient of base metal softening. By the data of this work at the degree of interlayer overloading equal to 2.0, base metal softening coefficient is equal to 0.83, i.e. base metal yield point should be higher than 200/0.83 = 241 MPa to ensure its elastic work, i.e. it should be not less than 2.4 times higher than interlayer yield point (100 MPa). At greater load plastic deformations develop in the base metal, and their influence on assemblies SS requires a separate study.

Thus, at quantitative assessment of the behaviour of assemblies with soft interlayers with different yield point values at different levels of axial loads, it is convenient to apply the notion of the degree of interlayer overloading, which is equal to the ratio of the value of axial load to interlayer material yield point ($K_{over} = \sigma_y/\sigma_{y_{int}}$).

At sufficiently high base material yield point, exceeding the level of stresses from applied load, when just the soft interlayer undergoes elastoplastic deformation, the derived regularities of base metal softening and soft interlayer hardening remain in force both at the elastic and at the plastic stages of interlayer material work at different levels of its yield point and applied axial load.

Conclusions

1. At loading of the assembly with a soft interlayer volumetric SS forms in the interlayer material and in the small zone of base metal, adjacent to the interlayer near its edge. This accounts for the change of the parameters of metal strength and ductility, determined under the conditions of linear stressed state, i.e. hardening or softening of base metal and interlayer.

2. It is found that stress stiffness factor, determining the degree of hardening or softening of the interlayer and base metal, is constant in the interlayer material at the elastic stage, and is equal to 1.35 for the assumed variants of combination of elastic properties. At the plastic stage K_{stif} grows linearly, reaching the value of 1.97 at the load two times higher than the interlayer material yield point at standard testing.

3. Coefficient of base metal softening near the edge of the butt joint with the interlayer depends not only on interlayer properties, but also on the degree of its overload. For the considered variants it gradually, from 0.925 at elastic deformation of the interlayer, approaches 0.83 at increase of its overload coefficient to 2.0.

4. Maximum axial stresses, noticeably exceeding the level of stresses from applied external load, arise on assembly generatrix in the base metal in the immediate vicinity of the butt joint with the interlayer. In the case of sufficient hardening of the soft interlayer, fracture may run through stronger base metal, where softening of the material being joined is combined with increase of axial stresses.

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