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STRESS-STRAIN STATE OF WELDED AND BRAZED ASSEMBLIES FROM DISSIMILAR MATERIALS WITH SOFT INTERLAYER AT THERMAL LOADING

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Computer modeling by finite element method was used to study the stress-strain state in joints of homogeneous materials under axial load. The studies were carried out taking into account plastic deformations in soft interlayers, which are usually used in diffusion welding to activate surfaces and reduce residual stresses. In brazing the intermediate layer is the braze weld, that differs from the base metal in its physical and mechanical properties. It is shown that along the butt, both in the metals being joined, and in the interlayer, equivalent stresses are distributed more uniformly than during elastic deformation. Plastic deformations in the interlayer are absent in the zone of stagnation (on the axis of the cylindrical assembly) and are almost linearly increased, reaching maximum values (about 6.5 %) at the outer cylindrical surface of the assembly. A high level of plastic deformations indicates the feasibility of using thermal loading in diffusion welding of dissimilar materials with soft interlayers. The degree of «softness» of the interlayer and its effect on the stress-strain state of the assembly during plastic deformation is mainly determined by its strength (yield limit) and almost does not depend on its rigidity (moludus of elasticity). 8 Ref., 1 Table, 10 Figures.

Keywords: *welded and brazed assemblies, soft interlayer, computer modeling, stress-strain state, thermal loading*

Brazing and diffusion welding are becoming ever wider applied in modern engineering, as they allow producing assemblies from dissimilar materials, which cannot be connected by fusion welding. However, one of the problems in such components is their strength under force and thermal loading.

Stressed state and work of the joints with interlayers, in particular, with a soft interlayer, was studied in [1, 2] by analytical methods, which do not allow taking into account all the factors of the influence of stress-strain state (SSS).

ANSYS program package, based on finite element (FE) method was used in this work, which allows taking into account the design and technological factors, material features, kinds of loading, etc., as well as establishing the main regularities of SSS formation [3, 4].

In [5] it was established that in the joints with a soft interlayer, a bulk stressed state forms on the assembly generatrix and in the immediate vicinity of the butt under the impact of axial load, at which softening of the stronger and strengthening of the weaker metal is possible that influences the joint performance. The same effect can occur at cooling after welding and at the change of temperature during assembly operation. This work is timely, considering that SSS formation in the assemblies with an interlayer is little studied, and is important not only for joint formation, but also for their performance.

The objective of this work was investigation of SSS of welded and brazed assemblies from dissimilar materials, in particular, dissimilar steels with a copper-based soft interlayer under thermal loading by variation of temperature, taking into account plastic deformation of interlayer material, which was determined by Mises yield criterion.

Investigations were conducted on cylinder-cylinder (C–C) assemblies from materials of the same rigidity and strength with softer interlayers. Assembly dimensions were as follows: total height $2h = 40$ mm, diameter $d = 20$ mm and interlayer thickness $s = 0.05$ mm (Figure 1).

The materials being joined had different temperature coefficients of linear expansion (TCLE), equal to $20\cdot10^{-6}$ and $10\cdot10^{-6}$ l/deg in materials *1* and *2*, and interlayer material *3* had average TCLE value equal to $15\cdot10^{-6}$ and $10\cdot10^{-6}$ l/deg (Table).

As is seen from Table, in variants *1′* and *2′* joined are the materials having the same moduli of elasticity and yield limits, but the joint is made through a «soft» interlayer, having a lower yield limit, than the materials being joined, and lower (variant *1′*) or the same (variant *2′*) modulus of elasticity. Yield limit values of the base materials and interlayer in this variant were selected so that only the interlayer material was plastically deformed, and base material deformed only elastically. The strengthening coefficient at plastic deformation of interlayer material was taken to be equal to $1\cdot10^3$ MPa for variant *1′* and $2\cdot10^3$ MPa for variant *2′*. Comparison of the variants allows isolating the ef-

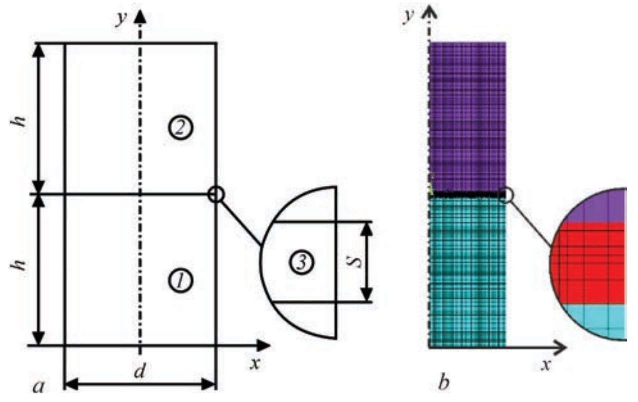

Figure 1. Physical (*a*) and FE (*b*) models of components of C–C type with an interlayer (*1*, *2* are materials *1*, *2*, respectively; *3* — interlayer)

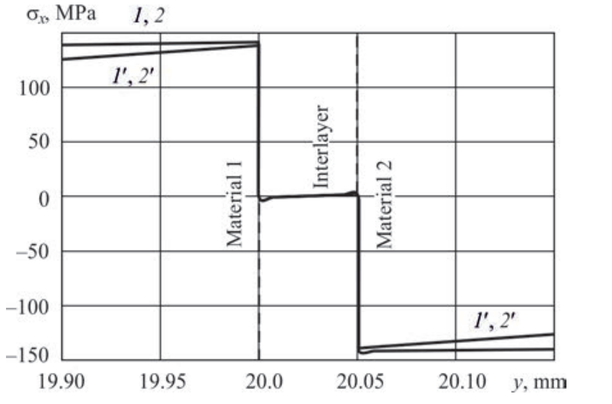

Figure 2. Curves of radial stresses along the cylinder axis near the butt (variants *1*, 2, *1′* and *2′*)

fect of exactly the plastic component of deformation on the assembly SSS.

Loading was performed by lowering the assembly temperature by 100 deg after formation of the joint, in which SSS is created due to different TCLE of the materials being joined. When cooling is replaced by heating by 100 deg, the level of stresses and strains does not change, and the signs are reversed.

Results were compared with similar assemblies (interlayers of small and medium rigidity) at elastic deformation (variants *1*, *2*) considered in work [6].

Analysis of the fields and curves of all the components of stresses in the assemblies, and their comparison with the results of modeling the SSS of similar assemblies with an interlayer when working at the elastic stage (variants *1* and *2*) showed that SSS in the materials being joined near the butt and in the interlayer is of a complex bulk nature, with nonuniform distribution across the assembly cross-section, both in the elastic and plastic variants, but the level of stresses decreases on the greater part of the butt due to plastic deformations.

Nature of distribution of radial σ_x and circumferential σ_z stresses in the assembly in the presence of plastic deformations is preserved, on the whole, but their value changes. They reach maximum values in the materials being joined in the vicinity of the butt plane (on the interfaces with the interlayer) in its middle part, but decrease more abruptly than at purely elastic deformation, when moving away from the butt (Figure 2). Along the butt in the base metal (Figure 3, *a*, *b*) the radial stresses are more nonuniformly distributed in the interlayer in the presence of plastic deformations, decreasing quickly from the maximum on the assembly axis to a minimum near the edge and abruptly increasing again on the very edge.

Along the butts the nature of radial stress distribution inside the interlayer is more uniform, they being small on the greater part of the butt (not exceeding 5 MPa), and increasing markedly (up to 90 MPa) near the outer cylindrical surface of the assembly (Figure 3, *c*, *d*). Here, the nature and level of stresses in materials *1*, *2* and interlayer on the boundaries with them differ only by their sign.

Maximum axial stresses σ_y, similar to the elastic stage of the work, are concentrated near the butt in immediate vicinity of the cylinder outer surface and decrease, when moving away from them (Figures 4, 5). Here, the nature and level of stresses in materials *1* and *2* also differ only by their sign. On the greater part of the butt and the side surface axial stresses are markedly lower than at the elastic stage of the work.

Tangential stresses are concentrated near the interlayer, having the largest value on the interfaces of the interlayer and base materials. They increase only slightly on the greater part of butt length, to a smaller degree than at the elastic stage of deformation, reaching a maximum at the very edge of the butt (Figure 6). Maximum tangential stresses in the presence of a soft interlayer (with a low yield limit) decrease similarly in both the materials and assemblies, irrespective of the interlayer rigidity. On the interfaces of both materials and the interlayer the dependence differs only by the stress sign.

Maximum equivalent stresses, similar to all the other components, are concentrated near the butts, i.e. the interfaces of materials *1*, *2* and the interlayer. Here, unlike the elastic stage, in the materials being joined they decrease up to two times with greater distance from the assembly axis, and only at the very

Variants of combinations of material properties (moduli of elasticity *E*, yield limits σ_y and TCLE α in the assemblies)

Variant number	Material 1			Material 2			Interlayer		
	E, 10^5 MPa	σ_y, MPa	α, 10^{-6}·1/deg	E, 10^5 MPa	σ_y, MPa	α, 10^{-6}·1/deg	E, 10^5 MPa	σ_y, MPa	α, 10^{-6}·1/deg
1	2	–	20	2	–	10	1	–	15
2	2	–	20	2	–	10	2	–	15
1′	2	200	20	2	200	10	1	38	15
2′	2	200	20	2	200	10	2	38	15

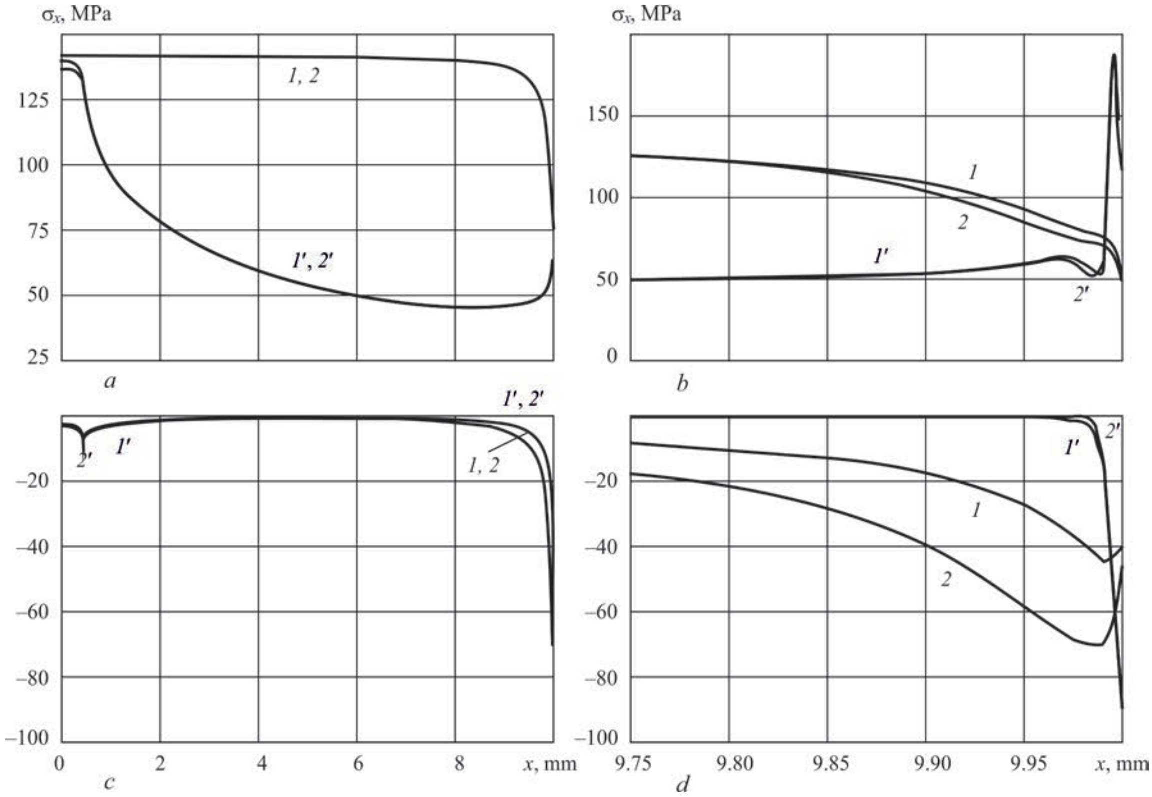

Fig re 3 Curves of radial stresses σ_x in metal *1* (*a*, *b*) and interlayer (*c*, *d*) over the entire butt (*a*, *c*) and near the outer edge (*b*, *d*) of the assemblies (variants *1*, *2*, *1′* and *2′*)

edge of the butt they increase abruptly up to 200 MPa (Figure 7, *a*, *b*).

In the interlayer, equivalent stresses are much lower, than at the elastic stage of the work, somewhat exceeding the yield limit of the interlayer material due to strengthening at plastic deformation and are practically uniformly distributed along the entire butt (Figure 7, *c*, *d*).

Plastic deformations in the interlayer along the butt are nonuniformly distributed, practically the same in variants *1′* and *2′* with an interlayer of different rigidity (Figure 8). They are absent in the «stagnation zone» [7] on the axis of the cylindrical assembly and increase gradually, when moving closer to the cylinder surface generatrix, reaching maximum values (6.5 %). The high level of plastic deformations is indicative of the rationality of application of thermal loading in diffusion welding with soft interlayers.

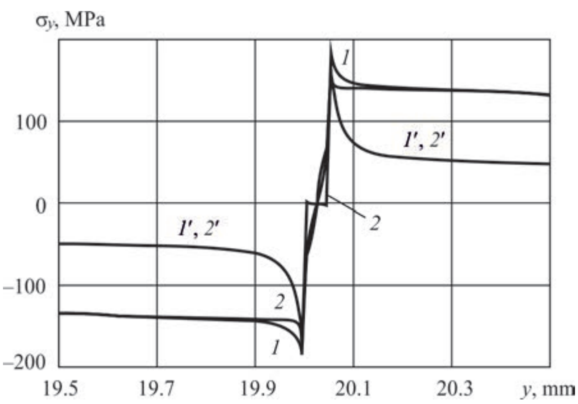

Fig re 5 Curves of axial stresses along the cylinder generatrix near the interlayer (variants *1*, *2*, *1′* and *2′*)

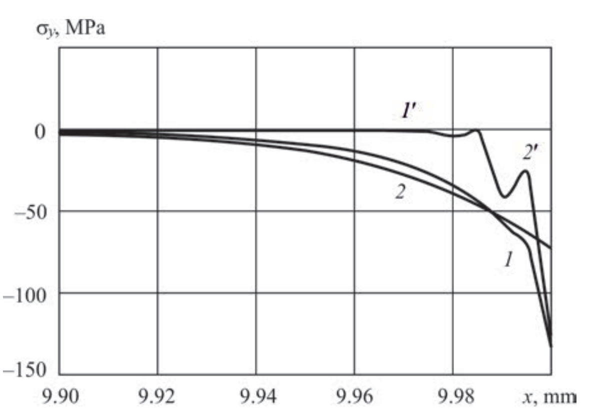

Fig re 4 Curves of axial stresses σ_y over the butt of base metal *1* and interlayer near the outer edge (variants *1*, *2*, *1′* and *2′*)

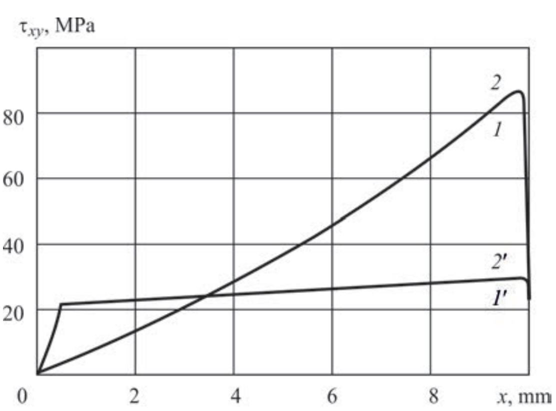

Fig re 6 Curves of tangential stresses τ_{xy} over the butt of base metal and interlayer (variants *1*, *2*, *1′* and *2′*)

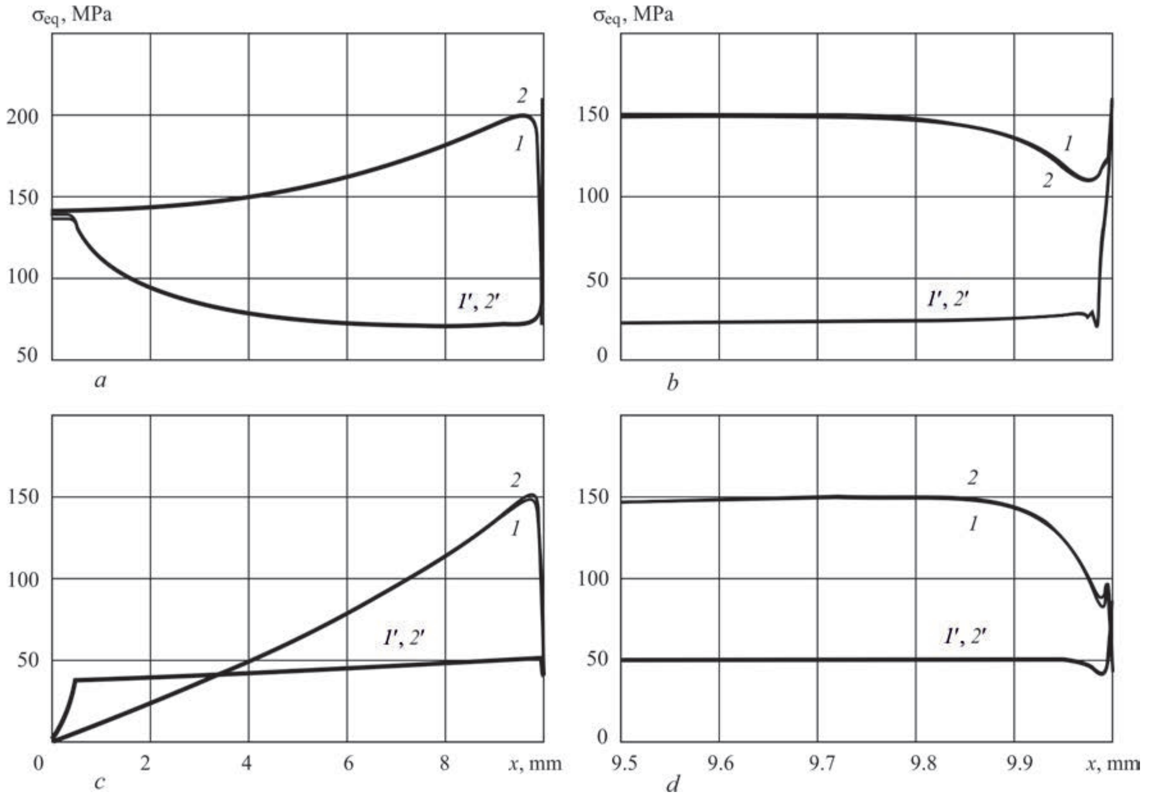

Figure 7 Curves of equivalent stresses σ_{eq} in the base metal (*a*, *b*) and in the interlayer (*c*, *d*) all over the butt (*a*, *c*) and near its outer edges (*b*, *d*)

Diagrams in Figures 9 and 10 give the most complete and visual presentation of the change of maximum values of all the stress components in assembly materials in the presence of a soft interlayer, allowing for plastic deformations in it (var. *1′* and *2′*), and comparison with the elastic stage of the work (var. *1* and *2*) of assemblies with an interlayer of low (var. *1* and *1′*) and normal (var. *2* and *2′*) rigidity.

Maximum radial stresses in the presence of a soft interlayer (var. *1′* and *2′*) increase in both the materials being joined, somewhat more in variant *2′*, i.e. in the assemblies with an interlayer, where the «softness» is determined only by a lower yield limit at the same modulus of elasticity as that of the base metal (Figure 9).

Maximum axial stresses in the presence of a «soft» interlayer (var. *1′* and *2′*), unlike the assemblies with an interlayer of a low rigidity at the elastic stage (var. *2*), remain practically the same, as in the assemblies with an interlayer of normal rigidity at the elastic loading stage (var. *1′*), i.e. in this case the effects of lowering of the rigidity and strength of interlayer material are different [8].

Maximum circumferential stresses in both the variants of the soft interlayer remain practically the same, as at the elastic loading stage, i.e. plastic deformations, developing in the interlayer, only slightly influence their magnitude.

Maximum tangential stresses in the presence of a soft interlayer (var. *1′* and *2′*) decrease the most markedly (more than 2 times), to the same degree in both the assembly variants.

Despite the change of maximum values of individual stress components, maximum equivalent stresses

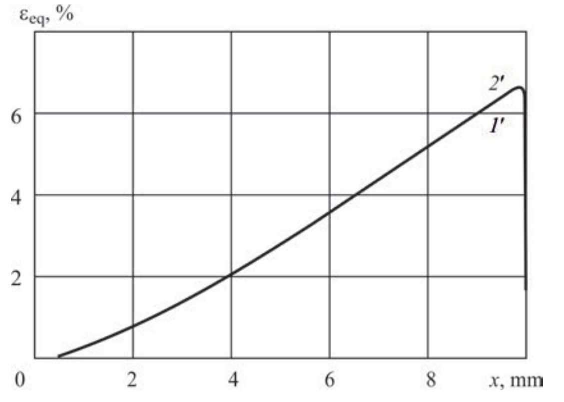

Figure 8 Curves of plastic deformations in the interlayer on the butts with materials being joined (variants *1′* and *2′*)

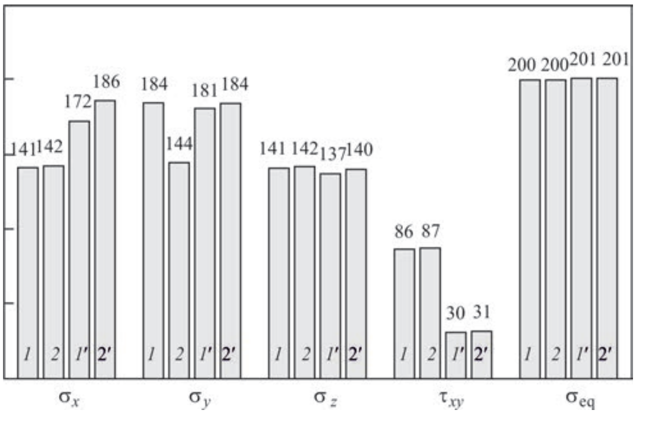

Figure 9 Maximum (by modulus) stresses (MPa) in materials *1* and *2* of C–C assemblies (variants *1*, *2*, *1′* and *2′*)

in the base metal remain practically on the same level, as under assembly loading at the elastic stage.

In the interlayer the pattern is different (Figure 10). Plastic deformations noticeably change both the individual components, and the equivalent stresses, but the change of the modulus of elasticity (rigidity) of the interlayer practically does not influence the level of maximum stresses.

Radial stresses in the presence of plastic deformations increase up to two times, compared to elastic deformation of assemblies with an interlayer of low rigidity (var. *1*) and by 30 %, compared to an interlayer of normal rigidity (var. *2*).

Axial stresses, contrarily, increase markedly at plastic deformation of the interlayer, only compared to the variant of elastic deformation of the interlayer of normal rigidity (var. *2*), and only slightly, compared to the interlayer of low rigidity (var. *1*). Here, the level of these stresses at plastic deformation, is practically independent on interlayer rigidity (var. *1′* and *2′*).

Circumferential stresses in the soft (low-strength) interlayer increase markedly, compared to the elastic loading stage (more than 2 times), practically the same, irrespective of the rigidity (modulus of elasticity) of the interlayer.

Tangential stresses in plastically deformed soft interlayer (var. *1′* and *2′*), contrarily, are much (by more than 2 times) lower, than at the elastic stage of the work, both at its normal (var. *2′*), and low (var. *1′*) rigidity.

Plastic deformation of the interlayer material significantly (up to three times) lowers also the equivalent stresses in it. Here their level is also independent on the interlayer modulus of elasticity.

Conclusions

1. At thermal loading under the conditions of instantaneous plasticity in the assemblies with a «soft» interlayer, having a lower yield limit, than the base metal, the SSS in the assemblies near the butts is of a complex bulk nature, with non-uniform distribution across the assembly cross-section both in the elastic and plastic variants, similar to assemblies with an interlayer with a smaller modulus of elasticity in the elastic problem.

2. In the considered variants, when cooling is replaced by heating, all the components of stresses in the materials being joined change only their sign, and equivalent stresses are completely the same. Here, their level on the greater part of the assembly, both in the materials being joined and in the interlayer, decreases due to plastic deformations, and is practically independent on the modulus of elasticity.

3. Computer modeling of SSS showed that the main regularities, established for the elastic stage of deformation, are preserved.

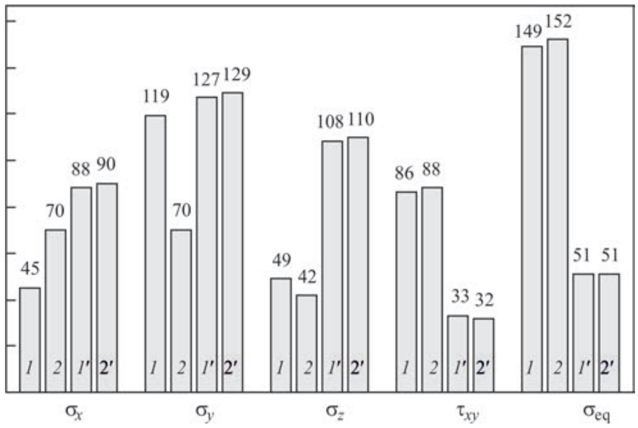

Figure 11. Maximum (by modulus) stresses (MPa) in interlayer *1* and *2* of C–C assemblies (variants *1*, *2*, *1′* and *2′*)

4. Plastic deformations in the interlayer along the butt are distributed nonuniformly, and are independent on the modulus of elasticity. They form a stagnation zone on the assembly axis, and increase with greater distance from it, reaching maximum values (about 6.5 %) at the outer cylindrical surface of the assembly that is indicative of the rationality of application of thermal loading in diffusion welding with soft interlayers, i.e. diffusion welding with thermal cycling.

5. Degree of interlayer «softness» and its influence on assembly SSS at plastic deformation is determined chiefly by its yield limit and is practically independent on its modulus of elasticity that should be taken into account at selection of interlayer or braze alloy material.

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