Tensile modeling of titanium-aluminum composite with a wave profile of a welded joint and local melts

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Abstract. Finite element simulation of tensile deformation of titanium-aluminum composite D20 – AD1 – VT6 was carried out. The joint boundary had a wave profile and local melts. 3D modeling of deformation of the composite D20 – AD1 – VT6 with a wave profile of the welded joint was carried out using the SIMULIA / Abaqus software. The relative thickness of the AD1 interlayer and the area of the melt were varied during the simulation. To determine for metal hardening during plastic deformation and the failure deformations for aluminum and aluminum alloy both Johnson-Cook deformation and fracture models was used. The influence of the size of the local melting zone and thickness of the soft interlayer on the distribution of stresses and strains in the composite is shown. The wave profile of the boundaries junction leads initially to localization of plastic deformation in the aluminum interlayer in the zone of free surfaces of the sample near the interface with the titanium alloy. A change in the length of vortices with areas of local melting near the tops of the wave profile from 0.3 to 0.8 mm had little effect on the profile of the curves "equivalent stress - absolute elongation of the sample”.

1. Introduction
Explosion-welded bi-metal connecting elements are widely used for joining parts made of titanium and aluminum alloys, which are difficult to weld by fusion welding [1, 2]. The reliability of new technology structures made of titanium-aluminum composites operating in difficult conditions is determined by the structural strength of such adapters. Explosion-welded adapters contain intermediate soft interlayers that act as a “plasticity buffer” and extend the range of process parameters between the lower and upper limits of weldability.

In addition, soft interlayers increase the temperature-time operating conditions, under which brittle intermetallic compounds are not formed. The boundary profile between titanium alloy and aluminum can be rectilinear [3-5] or wavy [6-10]. Local melted zones (LMZs) are formed near depressions and protrusions of the wave-shaped Ti / Al joint boundary at overestimated technological parameters of explosion welding [11-16]. The degree of fusion in compounds welded by the explosion is determined by the level of plastic deformation of the surface layers, and, consequently, by the specific energy \( W_2 > 0.7 \text{MJ/m}^2 \), zones of intense mixing of materials appear in the form of «vortices» in the direction of the shock front [17]. Local melts are often observed within vortices. Studies by a number of authors of the joint zone of explosion-welded Ti / Al composites have shown that they consist of intermetallic compounds such as TiAl_3, TiAl and metastable TiAl_2 [17 -19].

The mechanical strength of the composition depends on the relative thickness of the soft layer \( \chi=\delta/d \), \( \delta \) – thickness of the soft layer, \( d \) – transverse dimension of the tested [20]. With the advent of high-performance computer technology, computer methods for modeling the behavior of dissimilar joints under various loading options, based on the finite element method, began to actively develop [20, 21]. In a number of works performed at the Volgograd State Technical University, the results of
modeling the deformation of layered composites were verified on the basis of accumulated experimental data [20, 21]. The purpose of this work was to determine by the finite element method the change in the strength of an explosion-welded titanium-aluminum composite material with a wavy soft interlayer and local zones of melting under tension.

2. Materials and finite element model

Prismatic samples of the simulated three-layer titanium-aluminum composite VT6-AD1-D20 had a thickness and width of the working part, respectively, 6 and 10 mm. The joint boundary profile was symmetric sinusoidal waves with a wavelength $\lambda = 2$ mm and a swing value of $2a = 0.5$ mm. The von Mises criterion determined the change in the nature of material deformation from elastic to plastic. The materials of the layers of the deformable solid were set isotropic.

To determine for metal hardening during plastic deformation and the failure deformations for aluminum and aluminum alloy both Johnson-Cook deformation [22] and fracture [23] models was used. Strengthening of materials under plastic deformation was described by the Johnson-Cook plasticity model

$$
\sigma_y = (A + B\varepsilon_p^n)(1 + C\ln\dot{\varepsilon})[1 - T^{*m}]
$$

where $\varepsilon_p$ – is an effective plastic strain; $T_m$ – is a melting point; $T_r$ – is a room temperature; $A$ – is a yield strength of non-hardened material; $B$ – is the hardening modulus; $C$ – is the strain rate sensitivity coefficient, $n, m, \varepsilon_0$ – are model parameters; $\dot{\varepsilon}_0$ and $\dot{\varepsilon}_p$ – are the first time derivatives of $\varepsilon_0$ and $\varepsilon_p$.

The Johnson-Cook fracture model can be written as follows [23]

$$
\varepsilon_f = D_1 + D_2\exp\left(D_3\frac{\sigma_m}{\sigma_{eq}}(1 + D_4\ln\dot{\varepsilon}_0^*)\right)(1 + D_5T^*)
$$

where $D_1$ to $D_5$ are the damage model constants, $\sigma_m$ is the mean stress, and $\sigma_{eq}$ is the equivalent stress. The fracture model describes the history of damage to each element using the damage parameter

$$
D = \sum \frac{\Delta\varepsilon}{\varepsilon_f}
$$

where $\Delta\varepsilon$ is the equivalent plastic strain increment, and $\varepsilon_f$ is the equivalent strain to fracture under the present conditions of stress, strain rate and temperature. Element destroyed when $D > 1$. The parameters for the deformation and fracture models of layered composite components are shown in Tables 1 and 2 [20]. The effect of low strain rate (less than 0.0025 sec$^{-1}$) was not taken into account.

| Material             | Thickness [mm] | A [MPa] | B [MPa] | $m$ | $n$ | $\dot{\varepsilon}_0$ [sec$^{-1}$] | $T_m$ [K] | $T_r$ [K] |
|----------------------|----------------|---------|---------|-----|----|-----------------------------------|-----------|----------|
| Aluminium alloy      | D20            | 218,3   | 704,6   | 0,93| 0,62| 1                                 | 873       | 293      |
| Алюминий АД1         | 0,25 -2        | 60,0    | 6,4     | 0,859| 0,62| 1                                 | 933       | 293      |
| Titanium alloy VT6   | 5              | 420,0   | 52      | 1,00| 0,48| 1                                 | 1940      | 293      |
| Local melting zone   |                | 290     | 1770    | 0,55| 2,787| 1                                 | 1720      | 293      |

Table 1. The coefficients for Johnson-Cook plasticity model
Table 2. The coefficients for Johnson-Cook fracture model

| Material                        | D_1   | D_2   | D_3    | D_4 | D_5 | \(\dot{\varepsilon}_0\) [sec^{-1}] | T_m [K] | T_r [K] |
|---------------------------------|-------|-------|--------|-----|-----|-----------------------------------|---------|---------|
| Aluminium alloy D20            | 0.178 | 0.389 | -2.246 | 0   | 0   | 1                                 | 873     | 293     |
| Local melting zone             | -0.09 | 0.25  | -0.5   | 0.014 | 3.87 | 1                                 | 1720    | 293     |
| Aluminium AD1                  | 0.071 | 1.428 | -1.142 | 0.0097 | 0   | 1                                 | 933     | 293     |

The C3D10M-type cells (three-dimensional ten-node tetrahedrons) with a side size of 0.1 mm were used for all elements of the composite. The thickness of the AD1 interlayer varied from 2 (\(\chi_{AD1} = 0.334\)) to 0.25 mm (\(\chi_{AD1} = 0.042\)). Discrete rigid plates were attached to the free ends of D20 and VT6S alloys layers. The plate attached to the D20 aluminum alloy layer is stationary, and the plate attached to the titanium alloy moved along the sample axis at a speed of 2 mm / s.

3. Results and Discussion

The curves “equivalent stress - absolute elongation of the sample” obtained during the simulation under tension of the specimens of the D20 – AD1 – VT6S composite with different relative thicknesses \(\chi_{AD1}\) of the aluminum interlayer without local melting zones are shown in figure 1.

![Figure 1. Curves "equivalent stress - absolute elongation of the sample" under tension of composite samples D20-AD1-VT6 without local melting zones with different relative thicknesses of the interliner \(\chi_{AD1}\): 1 – \(\chi_{AD1}=0.041\); 2 – \(\chi_{AD1}=0.083\); 3 – \(\chi_{AD1}=0.167\); 4 – \(\chi_{AD1}=0.333\) ](image)

The shapes of the curves "equivalent stress - absolute elongation of the sample" are close for all simulated thicknesses of the soft interlayer. A decrease in the thickness of the soft layer led to an increase in the maximum values of the equivalent stress which is associated with the effect of contact hardening [19, 20]. Plastic deformations in AD1 are restrained by stronger adjacent layers D20 and VT6S. Shear stresses arise and increase on the contact surfaces, the stress state in the interlayer
becomes triaxial. This causes an increase in strength characteristics.

The maximum values of plastic deformation in the aluminum interlayer with elongation of the sample with $\chi_{AD1} = 0.083$ are localized near the interface with the titanium alloy on the free surfaces of the prismatic sample. They are typical for the places of contact with the protrusions of the wavy surface of the titanium plate (figure 2, a).

During the elongation of the sample, the zone with high equivalent plastic deformation gradually covers almost the entire aluminum soft layer near the free surface. In this case, the maximum plastic deformation is concentrated in the aluminum interlayer near the free surfaces at the border of the protrusions of the wavy connection with the titanium alloy. In the axial part of the sample, plastic deformation develops in a stronger aluminum alloy.

An increase in the thickness of the soft interlayer practically does not affect the deformation of the VT6 layer, but it leads to a decrease in the deformation of the D20 alloy layer (figure 3); practically all deformation develops in the AD1 interlayer.

![Figure 2](image_url)

**Figure 2.** Development of plastic deformation in the aluminum interlayer as the sample is stretched with $\chi_{AD1}=0.083$: 1 – sample elongation 0.2 mm; 2 - 0.6 mm; 3 - 0.8 mm (D20 the layer is at the bottom, a quarter of the sample is conventionally cut out)

![Figure 3](image_url)

**Figure 3.** Changes in the nature of plastic deformation in samples D20 – AD1 – VT6S with an absolute elongation of 2 mm of a sample with different relative thicknesses of the aluminum interlayer: 1 – $\chi_{AD1}=0.042$; 2 – $\chi_{AD1}=0.083$; 3 – $\chi_{AD1}=0.167$ (D20 the layer is at the bottom, a quarter of the sample is conventionally cut out)
Modeling the tensile behavior of D20 – AD1 – VT6 composite samples with local melted zones showed that even with a zone length of about 0.8 mm, no plastic deformation is observed in titanium (figure 4) at thicknesses of the AD1 interlayer from 0.25 mm to 1.0 mm.

However, the appearance of zones of local melting led to the formation of von Mises stresses in the VT6 titanium alloy up to 1000 MPa near these zones (figure 5) and nonuniform stress distribution on free surfaces. The used strain values did not lead to the achievement of the fracture criteria according to the Johnson-Cook fracture model.

The bands of equivalent stress concentration in titanium up to 1000 MPa are clearly visible both at the tops of the wavy profile and near the "vortices" with areas of local melting after conditional removal of AD1 aluminum and D20 aluminum alloy layers at the interface in a stretched sample (figure 6). This appeared for all simulated thicknesses of the AD1 interlayer.

Figure 4. Plastic deformation in samples D20 – AD1 – VT6 with a local fusion zone length of 0.8 mm at an absolute specimen elongation of 2 mm: 1 – \( \chi_{AD1}=0.042 \); 2 – \( \chi_{AD1}=0.167 \) (D20 the layer is at the bottom, a quarter of the sample is conventionally cut out)

Figure 5. Bands of equivalent stresses concentration up to 1000 MPa in titanium at the tops of the wave profile and near the "vortices" with areas of local melting: 1 – \( \chi_{AD1}=0.042 \); 2 – \( \chi_{AD1}=0.167 \) (layers AD1 and D20 are conditionally removed)

A change in the length of the vortices with areas of local melting near the tops of the wave profile from 0.3 to 0.8 mm had little effect on the nature of the curves "equivalent stress - absolute elongation"
of the sample”, similar to the curves in figure 1. Varying in the specified range of vortex lengths with a constant thickness of the aluminum interlayer changed the force value by no more than 1% with comparable deformations. This is true in the absence of crystallization defects (cracks, large pores) in the zones of local melts. Earlier studies [17 -19] indicated the absence of such defects in a wide range of technological parameters of explosion welding.

4. Conclusions

3D modeling of deformation of the composite D20 – AD1 – VT6 with a wave profile of the welded joint was carried out using the SIMULIA / Abaqus software. The relative thickness of the AD1 interlayer varied in the range 0.042 ≤ \( z_{AD1} \) ≤ 0.167. A decrease in the thickness of the aluminum interlayer leads to an increase in the maximum values of the equivalent stress, after which the formation of a neck begins. The wave profile of the boundaries of the VT6S – AD1 and AD1 – D20 junction leads initially to localization of plastic deformation in the aluminum interlayer in the zone of free surfaces of the sample near the interface with the titanium alloy. The maximum deformation values are typical for the places of contact with the protrusions of the titanium plate.

5. References

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