Contact hardening of Al interlayer in laminated Mg/Al composites during compressive and tensile loading

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Abstract. The study presents result of the FEM simulation of Mg alloy/Al/Ti alloy composite under tensile and compression loads. The simulation revealed the strength of Al interlayer at its various thickness values.

1. Introduction
Fusion welding of Al alloys with Mg alloys results in the formation of brittle intermetallic compound at the interface between metals [1]. Therefore explosion welded Al/Mg bimetals are usually applied to join Al with Mg. Mg alloy is fusion welded to Mg layer of the bimetal, while Al alloys are joined with Al layer. Laminated Al alloy–Al–Mg alloy joints can be utilized in the −196°C−+100°C temperature range, if the Al–Mg alloy interface is not overheated during the fusion welding. Strength of the joint is determined by Al interlayer which prevents diffusion and intermetallic formation at high temperatures and performs the plasticity buffer function during explosion welding.

The contact hardening effect is observed when the relative thickness ratio of the interlayer decreases. The relative thickness ratio is given by \( \chi = \frac{h}{d} \), where \( h \) denotes the interlayer thickness in mm, \( d \) – specimen diameter. Stress state FEM simulation under tensile loads of such composites results converged with experimentally obtained data [2]. Currently there is little knowledge on the behaviour of the composites during compression testing; however utilization of the materials under compression conditions is also possible.

The aim of the present study was to investigate the behaviour of laminated Al alloy-Al-Mg alloy joints under compression and tensile loads.

2. Materials and methods
Abaqus FEM simulation software was applied to carry out investigations. 6 mm diameter Al alloy–Al–Mg alloy specimens were loaded transversally to the bond. The hardening of the materials was considered using Johnson-Cook model [3], which gives the hardening function of the material:

\[
\sigma_f = \left( A + B \cdot \dot{\varepsilon}_p^n \right) \left( 1 + \ln \frac{\dot{\varepsilon}_p}{\dot{\varepsilon}_0} \right)^m \left[ 1 - \left( \frac{T - T_r}{T_m - T_r} \right)^n \right].
\] (1)
where \( \varepsilon_p \) – accumulated plastic strain, \( \dot{\varepsilon}_p \) – plastic strain rate, \( \dot{\varepsilon}_0 \) - reference strain rate, \( T \) – current temperature, \( T_r \) – room temperature, \( T_m \) – melting point, \( A, B, C, n \) and \( m \) – model constants.

Material rupture was also considered using Jonson-Cook model [4], which establishes the rupture when \( D=1 \), where:

\[
D = \frac{1}{\varepsilon_f} \sum_i \varepsilon_{f,i}^p, \tag{2}
\]

where \( \varepsilon_f \) – the equivalent strain to fracture, given by:

\[
\varepsilon_f = \left[ D_1 + D_2 \exp \left( D_3 \cdot \frac{p}{\sigma_{ef}} \right) \right] \times \left( 1 + D_4 \ln \frac{\varepsilon_p}{\varepsilon_0} \right) \times \left[ 1 + D_4 \left( \frac{T-T_r}{T_m-T_r} \right) \right], \tag{3}
\]

where \( D_{1,2,3,4,5} \) – material constants, \( \sigma_{ef} \) – effective stress, \( p \) – pressure in the considered element.

The Jonson-Cook model parameters for researched materials are given in the tables 1 and 2. The deformation rate impact was not considered in this study.

Table 1. Johnson Cook constitutive model parameters for materials used in this study [5].

| Material     | \( A, \text{MPa} \) | \( B, \text{MPa} \) | \( m \) | \( n \) | \( \varepsilon_0, \text{sec}^{-1} \) | \( T_m, \text{K} \) | \( T_r, \text{K} \) |
|--------------|---------------------|---------------------|--------|--------|-------------------------------|------------------|------------------|
| Mg alloy     | 218.3               | 704.6               | 0.93   | 0.62   | 1                             | 773              | 293              |
| Al           | 60.0                | 6.4                 | 0.859  | 0.62   | 1                             | 933              | 293              |
| Al alloy     | 100.0               | 380                 | 1.04   | 0.28   | 1                             | 773              | 293              |

Table 2. Fracture constants for materials used in this study [5].

| Material     | \( D_1 \) | \( D_2 \) | \( D_3 \) | \( D_4 \) | \( D_5 \) |
|--------------|----------|----------|----------|----------|----------|
| Mg alloy     | 0.178    | 0.389    | -2.246   | 0        | 0        |
| Al           | 0.071    | 1.428    | -1.142   | 0.0097   | 0        |
| Al alloy     | -0.35    | 0.6025   | -0.4537  | 0.206    | 7.2      |

The simulation was carried out in the relative Al interlayer thickness ratio range from \( \chi_{Al}=0.67 \) (4 mm) to 0.041 (0.25 mm). The thickness of Mg alloy and Al alloy layers was 10 mm. Mesh size in the loading direction was 1/20 of the thickness of the each considered layer. Mesh size in the parallel to the bond direction was 1/125 of the cylinder’s perimeter.

The extension/compression rate was 2 mm/s.
3. Results and Discussion
The simulation revealed significant difference in the deformation and rupture behaviour of the composite base layers both for various interlayer thickness values and for loading conditions.

Figure 2. von Mises stress distribution in Mg alloy–Al–Al alloy composite during tensile loading at the moment of the first rupture: a – $\chi_{Al}=0.67$; b – $\chi_{Al}=0.33$; c – $\chi_{Al}=0.17$; d – $\chi_{Al}=0.08$

Al interlayer ruptured in the whole range of investigated $\chi_{Al}$ values and both under tensile and compressive loads. The initial Al rupture was observed in the adjacent to base metals area. The reduction in Al interlayer thickness contributed to von Mises stress growth in Al and Mg alloy layers. The maximum Mises stress was observed in adjacent to the bond interface central parts of base materials during compression loading (figure 1) and in the peripheral parts of base materials during tensile loading (figure 2).

Figure 3. Plastic deformation distribution in 4 mm thick Al interlayer of Mg alloy-Al-Al alloy composite during compressive loading when the total deformation is equal to: a – 0.21 mm; b – 0.28 mm; c – 0.35 mm

The simulation revealed the non-uniform strain distribution in the Al interlayer. When the interlayer thickness was 4 mm, peak deformation was observed in the peripheral zones of the cylinder in the adjacent to base materials areas, as well as in the central part of the interlayer along its axis (figure 3). The increase in the specimen strain rate results in the strain value and size growth of the particular regions.
The decrease of the interlayer thickness down to 2 mm changes the deformation localization: peak interlayer deformation is observed along the bond in adjacent to Mg and Al alloy base layers (figure 4). The deformation of the central part of the interlayer perpendicular to the bond starts only when the total deformation of the specimen exceeds 9% of the Al interlayer thickness.

![Figure 4. Plastic deformation distribution in 2 mm thick Al interlayer of Mg alloy-Al-Al alloy composite during compressive loading when the total deformation is equal to: a – 0.135 mm; b – 0.18 mm; c – 0.225 mm](image)

The obtained during the simulation stress-strain curves for both loading methods are presented in figure 5. The peak stress values both for compression and tensile loading remain on the same level,
however the strain values are significantly higher for tensile loading (figure 5). Compression leads to the 20-25% Al interlayer deformation. Thus the compression of composite materials with soft interlayers can lead to the rupture at relatively small deformation values.

4. Conclusion
1. FEM simulation of the tensile and compressive loading revealed significant differences in the deformation and rupture behavior of the composite both due to various interlayer thickness values and loading conditions.
2. For the whole range of investigated interlayer thickness values and for all loading conditions rupture was only observed in the Al interlayer.
3. The variation in loading direction does not significantly influence the critical stress values, but the acceptable strain rate is approximately 10 times lower for compression loading.

Acknowledgements
The study was supported by Russian Science Foundation grant No 14-29-00158.

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