SPH simulation of plastic deformation in high velocity impact welding process of 6061-T6 alloy plates

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Abstract. In this study, the plastic deformation process of two plates of aluminum alloy 6061-T6 was simulated at different collision point velocities using the method of smoothed-particle hydrodynamics (SPH). The results of numerical simulation were compared with the results obtained in experimental and theoretical studies of other authors. The data obtained indicate that the SPH method reproduces the wavy interface between the plates, which was previously observed in numerous experiments. In addition, SPH simulation allows one to study in better detail the features of plastic deformation occurring near the interlayer boundaries, in particular at the vortex zones.

1. Introduction
The formation of a joint during high velocity impact welding occurs due to a number of interrelated phenomena, including the cleaning of the impact surfaces by a jet in front of the contact point and the mutual plastic material flow in the contact area of the colliding plates. During the solid state welding process, the value and distribution of plastic deformation play a key role, which determine the formation of physical contact and bonding of metals. A large number of studies were aimed at creating and improving methods that provide qualitative and quantitative information about the patterns of plastic flow of material in the immediate vicinity of the weld line, since all processes responsible for the activation of surface layers occur in relatively small volumes of metal adjacent to the zone of physical contact.

All experimental methods for the analysis of plastic deformation can be divided into microstructural, in which the residual plastic strain is evaluated based on the change in the shape of natural markers such like individual grains or twins, as well as based on the use of artificially prepared layered inserts or monolithic inserts with special grids. The method of layered model inserts is based on fabrication of composite packages of thin foil material, which is close in mechanical properties to the studied one [1]. These packages are installed in preliminary prepared grooves in welded plates. After the welding process, the photographs of the packages are combined and the resulting image is mathematically processed. This method has several limitations and inaccuracies, it also requires complex and time consuming sample preparation. The method of mechanically prepared grid is as follows: the insert sample is cut from the center of the flyer or the base plate, the grid of the grooves is applied on its side faces, after that it is placed on its previous position. After the welding the insert is removed from the plate again and the materials strain is measured by the distortions of the grid [2]. However, this method is not suitable for the analysis of deformation with high collision point velocity since the grid is erased due to intensive flow of material in the vortex zones.
Currently, various methods of numerical simulation are used to analyze the processes of plastic deformation, heating and cooling of the material during explosion welding. By other authors, Euler, Lagrange, Euler–Lagrange grid numerical methods and their modified versions [3, 4] as well as gridless methods like smoothed particle hydrodynamics (SPH) [5 - 9] were used to simulate the high velocity impact welding process. The use of grid methods doesn’t allow one to completely reproduce such phenomena as wave and jet formation. Moreover, the computational process can be interrupted for large values of deformation. Therefore, in this paper, the gridless SPH method was chosen for the study, which is widely used for problems with fast moving boundaries and intensive plastic material flow.

2. Selected methodology
The Ansys Autodyn environment, the smoothed-particle hydrodynamics method, the Johnson-Cook strength model, and the modified Mie-Gruneisen equation of state were chosen to simulate the process of plastic deformation under conditions of high velocity collision. Aluminum alloy 6061T6 was chosen as studied material. It should be noted that several experimental investigations [10–12], including the classic work of Wittman [10], were devoted to the study of explosion welding of this material. The data obtained in the experiments of other authors were used for comparison with the results of simulation performed in this work.

| Table 1. Parameters of 6061-T6 alloy used in numerical simulation. |
|---------------------------------------------------------------|
| **Johnson-Cook strength model**                                |
| Parameter                  | Value | Dimension |
|---------------------------|-------|-----------|
| Shear Modulus             | 26    | GPa       |
| Yield Stress              | 0.324 | GPa       |
| Hardening Constant        | 0.114 | GPa       |
| Hardening Exponent        | 0.42  | -         |
| Strain Rate Constant      | 0.002 | -         |
| Thermal Softening Exponent| 1.34  | -         |
| Melting Temperature       | 925   | K         |
| Ref. Strain Rate (/s)     | 1     | -         |

| modified Mie-Gruneisen equation of state                       |
|---------------------------------------------------------------|
| Parameter                  | Value | Dimension |
|---------------------------|-------|-----------|
| Reference density         | 2.7   | g/cm³     |
| Grüneisen coefficient     | 1.97  | -         |
| Parameter C1              | 5.35  | m/ms      |
| Parameter S1              | 1.34  | -         |
| Reference Temperature     | 293   | K         |
| Specific Heat             | 8.85·10⁻⁴ | kJ/gK    |
At the initial moment of time, two plates with a thickness of 6 mm were located at an angle to each other; the upper plate had an initial impact velocity $V_p$, which defines a collision point velocity as:

$$V_C = \frac{V_p}{2 \sin \frac{\alpha}{2}}$$  \hspace{1cm} (1)

where $\alpha$ is collision angle.

Several collision regimes were simulated in this study. For all of the simulation the collision angle $\alpha$ was 25°. The following impact velocities were simulated (the corresponding values of $V_C$ are given in brackets): 216 m/s, 563 m/s, 909 m/s, 1255 m/s and 1602 m/s (500 m/s, 1300 m/s, 2100 m/s, 2900 m/s and 3700 m/s).

The materials constants used for the simulation are shown in Table 1.

3. Results of numerical simulation

An effective (equivalent) plastic strain was chosen as one of the main parameters used in this work for the assessment of plastic deformation in the contact zone, which value is expressed as an integral of plastic deformation increment over a period of time $t$:

$$\varepsilon_{ef} = \int_0^t \sqrt{\frac{2}{3}} \epsilon_{ij} d\epsilon_{ij}$$  \hspace{1cm} (2)

There is an exponential increase in the effective plastic strain as it approaches the interface, which is well observed at low collision point velocities (Figure 1).

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**Figure 1.** Effective plastic strain distribution for different values of $V_C$ (dotted line corresponds to the position of the interface).

**Figure 2.** Equal strain zones ($V_C = 2900$ m/s, $\alpha = 25^\circ$).
Analysis of the resulting plots of effective plastic strain in the heat-affected zone allowed conditionally dividing the deformed metal layer into three characteristic zones: (i) the zone adjacent to the weld line, in which the largest strain values are achieved, or the zone of maximum material flow; (ii) the transition zone in which the deformations are distributed more uniformly; and (iii) the peripheral zone, the strain of which was close to zero. A schematic arrangement of equal strain zones for one of the studied regimes is presented in Figure 2. The obtained data are consistent with theoretical data and observations of the previous studies [1, 2].

The selected method of numerical simulation made it possible to study the nature of plastic deformation in the near contact region for both plates – the flyer one and the base one. It may be noticed that when two plates having similar composition are welded the distribution of strain near the interface is rather symmetric for most of the simulated regimes.

The solid-phase mechanism for the formation of a strong connection of metal layers during collision interaction involves the generation in the heat-affected zone of a certain level of shear deformations responsible for the activation of the contact surfaces and the development of processes of mutual plastic flow of the flyer and base plates. The biaxial stress-strain state is realized during the explosive welding of metals [2], a necessary condition for the formation of the joint is to achieve the maximum value of the critical strain. In the case of collision at relatively low velocities (collision point velocity \( V_C = 500 \) m/s, impact velocity \( V_P = 216 \) m/s and collision angle \( \alpha = 25^\circ \)), the strain in the contact zone didn’t reach the threshold value to form a region of maximum material flow. This in good agreement with classical models [10], according to which such collision regime doesn’t lead to the formation of a bond. It seems that a necessary condition for a successful explosive welding process is the presence of all three regions of plastic flow.
According to the obtained data, the process of jetting begins when the effective plastic strain near the interface reaches value \( \varepsilon = 3 \) (Figure 3-a), which corresponds to the welding regime with \( V_P = 563 \) m/s, \( V_C = 1300 \) m/s and \( \alpha = 25^\circ \). For this collision regime, the strain is predominantly localized in a narrow contact zone within a distance of 2 mm from the interface, while the largest values of strain are observed in a layer of 0.33 mm from the interface. The interface has a straight shape, thus the residual strain field along the interface is rather uniform.

The process of wave formation starts when the effective plastic strain reaches value \( \varepsilon \approx 6 \), which corresponds to the welding regime \( V_P = 909 \) m/s \( V_C = 2100 \) m/s and \( \alpha = 25^\circ \). The wave amplitude in this welding mode is about 1 mm (Figure 3-b), the effective plastic strain in near the wave area is in the range from \( \varepsilon = 1 \) to \( \varepsilon = 6 \). The dependence of strain on the distance from the interface has an exponential form, which is in a good agreement with the experimental results obtained by Chugunov et al. [1].

Chugunov et. al. [1] also reported that experimental estimation of shear strain using inserts with preliminary prepared grids was difficult in cases of intense waving with formation of vortices, because the grid was erased, or it was difficult to analyze the samples using standard metallographic methods. The smoothed-particle hydrodynamics method made it possible to calculate the effective plastic strain even for cases with fast-moving collision point and a complex interface morphology. The obtained strain values for one of the sections are presented in Figure 1 (green line) at \( V_C = 2900 \) m/s, \( V_P = 1255 \) m/s, \( \alpha = 25^\circ \). The dependence of the plastic strain on the distance from the interface also has an exponential form, however, the zone of plastically deformed material in the base plate is significantly larger than in

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**Figure 3.** Distribution of the effective plastic strain in the plates interface: a - \( V_C = 1300 \) m/s; b - \( V_C = 2100 \) m/s; c - \( V_C = 2900 \) m/s; d - \( V_C = 3700 \) m/s.
the flyer plate. This fact requires special attention in the production of composite bimetals, for which residual strain has a key role in the exploitation.

The welding mode at the collision point velocity \( V_C = 3700 \text{ m/s} \) with the collision angle \( \alpha = 25^\circ \) is in the region of optimal collision regimes according to the Deriba hydrodynamic model [13] and is close to the upper welding limit according to the Wittman model [10]. The corresponding curve (Figure 1) shows a significant plastic flow of material at a depth of more than 3 mm. The curve also differs from those for the previously described regimes. The maximum value of plastic strain is lower compared to the previous regimes having lower collision point velocity, however, the thickness of the deformed area increases, which is associated with an increase in wave amplitude, as well as with a change in their morphology (Figure 3-d).

4. Conclusions
Summarizing the obtained results, we can conclude that the plastic flow of the metal in the heat-affected zone has a decisive role in the formation of a solid-phase bonding in high velocity collisions. It is subjected to strict regularity depending on the welding parameters, providing an opportunity to manage purposefully the activation processes of the contacting surfaces and control the properties of the obtained bond.

The smoothed-particle hydrodynamics method reproduces the process of jetting and wave formation. The data obtained using numerical simulation with different welding regimes are in good agreement with the experimental data presented in the experimental studies of other authors. It is possible to use this approach for further study of welded plates of dissimilar materials with various physical and mechanical properties.

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