

# Variable Order/Step Integration by 3-stage Diagonally Implicit Runge-Kutta Method for Electromagnetic Transient Simulations

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## ABSTRACT

Explosive welding is a useful method for joining similar or dissimilar metal alloys that are not easily joined by any other means of welding. Insertion of an interlayer between two-parent plates is beneficial to control the welding parameters and improve the welding quality. In order to investigate the importance of interlayer during the explosive welding process, this paper presents the numerical simulation of explosive welding of Ti6Al4V-SS304 in the presence of different interlayer materials, i.e. SS304, Ti6Al4V, CP-Ti, Cu, Al. To understand the whole welding process with efficient computational time, coupled smoothed particle hydrodynamics -Euler -Arbitrary Lagrangian-Eulerian formulation was opted. Results were analyzed on the basis of different material interlayers. Welding parameters, i.e. pressure, temperature, plastic strain and interface morphology revealed that interlayer improved the welding quality. Furthermore, as an interlayer, the materials with high strength showed high welding strength.

## 1. INTRODUCTION

Welding technology is applied in many fields, i.e. aerospace, power plants, chemical industries and transportation etc. Explosive welding is one of the most productive techniques which is used to weld various kind or similar metal alloys. More than 260 combinations of different kinds of alloys can be joined by explosive welding technique [1], [2]. In the explosive welding technique, explosively accelerated plate (flyer) is collided with another metal plate (base) to form a composite welded plate. One of the main advantages of this method is that it provides a large welding area as compared to other conventional welding techniques[3]. Many complex processes are involved in explosive welding method [4], which relates the explosive chemical reaction to mechanical and metallurgical processes, e.g. flyer acceleration, welding joints etc.

Since explosive welding is short interval process in which pressure and temperature are abruptly increased therefore, physically it is not easy to observe and measure these parameters. To understand the explosive welding conditions, i.e. interface morphology, pressure, plastic strain, temperature, etc., simulation is one of the best tools to predict these values. Earlier, different researchers used several methods to simulate explosive welding process. Mousavi et al. [5] simulated the plates collision process to understand the interface morphology, i.e. jetting, humps, wavy and flat shapes etc. For this purpose, they used ANSYS Autodyne software package. Nassiri et al. [6] used a smoothed particle hydrodynamics (SPH) method to understand the jetting process during explosive welding. Furthermore, they used the Arbitrary

Lagrangian Eulerian (ALE) method to obtain the impact parameters such as temperature, flyer velocity, pressure, shear stress etc. Similarly, X. Wang et al. [7] used SPH approach to replicate the shear stress and effective plastic strain. Y. Wang et al. [8] applied the material point method (MPM) to simulate the explosive welding process.

Two-layered explosive welding is although useful and extensively applied technique. However, welding joint strength is being compromised due to the formation of intermetallics in the interface. These brittle intermetallics are weakened the joint strength of the composite welded plate. Formation of these intermetallics can be decreased by controlling the energy loss during impact [9]. Insertion of the third layer (interlayer) can be helpful for energy loss control. Previously, the importance of the interlayer effect were explained in the literatures. Saravanan et al.[10] used Al, Cu and SS304 as an interlayer to examine the mechanical and microstructural characteristics of Al-Cu composite plate. Izuma et al. [11] employed Cu interlayer between Al-Cu to increase the bonding strength, and compared the results to Al-Cu composite plate welding. Manikanden et al. [9] investigated the importance of interlayer for interface morphology. They concluded that the kinetic energy loss is directly proportional to interface wavelength and amplitude. Sarawanan et al. [12] observed that the welding area is enhanced with the help of interlayer.

In the current paper, the effect of interlayer during explosive welding process was studied with the help of simulation. For this purpose, coupled Euler-ALE-SPH approach was used with ANSYS-AUTODYNE software package. Ti6Al4V, SS304 was used as a flyer and base plate, respectively, while CP-Ti, SS304, Ti6Al4V, Cu and aluminium were used as an interlayer. Results were analyzed on the basis of interface morphology, pressure, temperature and plastic strain.

## 2. NUMERICAL SIMULATION

The explosive welding simulations were performed with the help of ANSYS-AUTODYNE (ANSYS v15). For the current study, the SPH method was taken with the Euler-ALE coupling. Explosive detonation process was simulated in Euler formulation because this method has no grid deformations in high strain rate problems. However, it requires some additional calculation to simulate the problem of solid content. Flyer, Interlayer and base plates were simulated in ALE formulation (mesh size 0.5 mm). ALE method is useful for high deformation problems of metals alloys. In ALE simulation, element shapes within the mesh are automatically modified while the boundary movement is used to track mesh borderlines. The top portion of the flyer and base plate (thickness 0.5 mm) and interlayer were simulated with SPH morphology (particle size 20  $\mu\text{m}$ ). SPH is a gridless lagrangian scheme which is very useful at high impact problems. Especially it helps us to observe the transient interface appearance during the explosive welding process. Previously, Aizawa et al. [13] applied SPH-Lagrange coupling method to simulate the interface of bimetallic plate welding. Similarly, Feng et al. [14] simulated the whole explosive welding process with the help of SPH scheme. The schematic diagram and the parameters for the current simulation are shown in Figure 1. and Table 1.

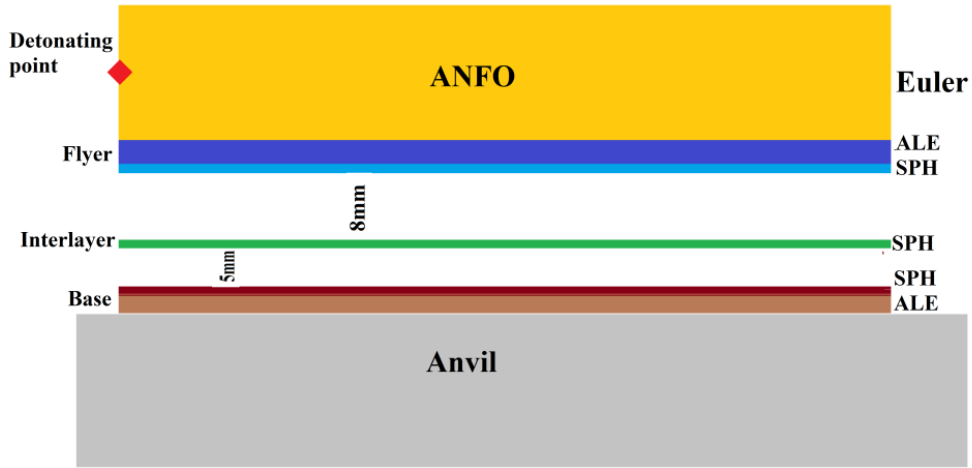


Figure 1. Schematic setup for simulation

Table 1. Materials and parameters used for explosive welding simulation

| Case study         | Flyer                     | SOD1* | Interlayer material                               | SOD2** | Base                    |
|--------------------|---------------------------|-------|---|--------|-------------------------|
| with interlayer    | Ti6Al4V<br>Thickness(3mm) | 8mm   | Al/Cu/CP-Ti/<br>SS304/Ti6Al4V<br>Thickness(0.3mm) | 5mm    | SS304<br>Thickness(3mm) |
| without interlayer | Ti6Al4V<br>Thickness(3mm) | 13mm  | No interlayer                                     | —      | SS304<br>Thickness(3mm) |

\*Flyer-interlayer standoff distance

\*\* Interlayer-base standoff distance

### 2.1. JWL equation of state

The explosives detonation and shock initiation can be explained with the help of using Jones-Wilkins-Lee (JWL) equation of state. JWL equation describes the relation of isentropic pressure-volume relation. Generalised JWL equation of state is written as follows,

$$P = A \left(1 - \frac{\omega}{R_1 V}\right) e^{-R_1 V} + B \left(1 - \frac{\omega}{R_2 V}\right) e^{-R_2 V} + \frac{\omega e}{V} \quad (1)$$

where A, B, C, R1, R2 and  $\omega$  all are constants and found experimentally. A, B, C have pressure dimensions, and remaining constants are dimensionless values. For the current study, the modified density-based JWL equation of state was being used [15]. Moreover, this equation is extracted from the experimentally calculated JWL equation of state [16]. Detail JWL parameters are shown in Table 2.

Table 2. JWL parameters for ANFO

| JWL parameter for ANFO      | Experimental data [16] | Modified JWL equation |
|-----------------------------|------------------------|-----------------------|
| $\rho$ (kg/m <sup>3</sup> ) | 830                    | 700                   |
| Det. velocity (m/s)         | 3233                   | 2740                  |
| $P_{cj}$ (GPa)              | 2.20                   | 1.49                  |
| $E_o$ (MJ/m <sup>2</sup> )  | 1.56                   | 1.33                  |
| R1                          | 7.162                  | 7.162                 |
| R2                          | 0.865                  | 0.865                 |
| $\omega$                    | 0.34                   | 0.34                  |
| A (GPa)                     | 216.044                | 89.39                 |
| B(GPa)                      | 1.838                  | 1.07                  |
| C(GPa)                      | 0.153                  | 0.23                  |

## 2.2. Material Model and Equation of state

Mei-Gruneisen equation of state was used for shock wave propagation in the materials. Mei-Gruneisen Equation is a solution of Rankin-Hugoniot equation and empirical relation of particle-shock velocity equation and it is expressed as

$$p = p_H + \Gamma\rho(e - e_H) \quad (2)$$

If it is assumed that  $\Gamma\rho = \Gamma_o\rho_o = \text{Constant}$ , then  $p_H$  and  $e_H$  are given as

$$p_H = \frac{\rho_o c_o u(1+u)}{(1-(s-1)u)^2} \quad (3)$$

$$e_H = \frac{1}{2} \frac{p_H}{\rho_o} \left( \frac{u}{1+u} \right) \quad (4)$$

where  $p_H$  is pressure,  $e_H$  is energy,  $\rho_o$  is initial density,  $\rho$  is current density,  $\Gamma$  is Gruneisen constant,  $u$  is particle velocity,  $c_o$  is bulk sound speed in material,  $s$  is slope of shock-particle velocity relation.

For the simulation of explosive welding, Johnson-Cook material model was used. This model is useful for high strain rate simulation problems. Johnson-Cook model can be written as

$$Y = (A + B\varepsilon^n)(1 + C \ln\dot{\varepsilon}_p)(1 - T^{*m}) \quad (5)$$

where  $Y$  is Yield stress,  $A$  is yield strength of material,  $m$  is softening exponent,  $B$  is Strain hardening coefficient and  $T^* = \frac{(T - T_{room})}{(T_{melt} - T_{room})}$  is homologous temperature,  $\varepsilon$  is plastic strain,  $C$  is strain rate constant,  $\dot{\varepsilon}_p$  is plastic strain rate,  $n$  is hardening exponent. Moreover, the above equation has three parts: 1st part shows stress as function of strain at  $\dot{\varepsilon}_p = 1, T^{*m} = 0$ , 2nd and 3rd parts exhibit the effect of strain rate and temperature. Material models used for simulation are shown in Table 3.

Table 3. Johnson-cook model parameters of simulated materials

| Material                          | Ti-6Al-4V[17] | CP-Ti[18] | Cu[19] | SS304[18] | Al-1060[20] |
|-----------------------------------|---------------|-----------|--------|-----------|-------------|
| <b>A (MPa)</b>                    | 1098          | 1500      | 90     | 350       | 66.56       |
| <b>B (MPa)</b>                    | 1092          | 380       | 292    | 275       | 108.8       |
| <b>N</b>                          | 0.93          | 0.32      | 0.31   | 0.36      | 0.23        |
| <b>C</b>                          | 0.014         | 0.22      | 0.025  | 0.022     | 0.029       |
| <b>m</b>                          | 1.1           | 0.7       | 1.09   | 1.0       | 1.0         |
| <b>Density (kg/m<sup>3</sup>)</b> | 4430          | 4520      | 8960   | 7896      | 2707        |
| <b>C<sub>0</sub> (m/s)</b>        | 5130          | 5020      | 3940   | 4569      | 5386        |
| <b>G</b>                          | 1.23          | 1.23      | 1.99   | 2.17      | 1.97        |
| <b>S</b>                          | 1.028         | 0.767     | 1.489  | 1.49      | 1.339       |

### 3. RESULTS AND DISCUSSION

Figure 2. exhibits the simulation process of explosive welding at different time intervals. Explosive accelerated the flyer (Ti6Al4V) plate, and then it struck the interlayer. During the collision process, the certain kinetic energy of the flyer was reduced. While the remaining energy furtherly accelerated both plates together and were collided with a base plate (SS304). During the collision process, a jet was formed which moved with collision point. Two interfaces were formed: (i) flyer-interlayer (F-I); (ii) Interlayer-base (I-B).

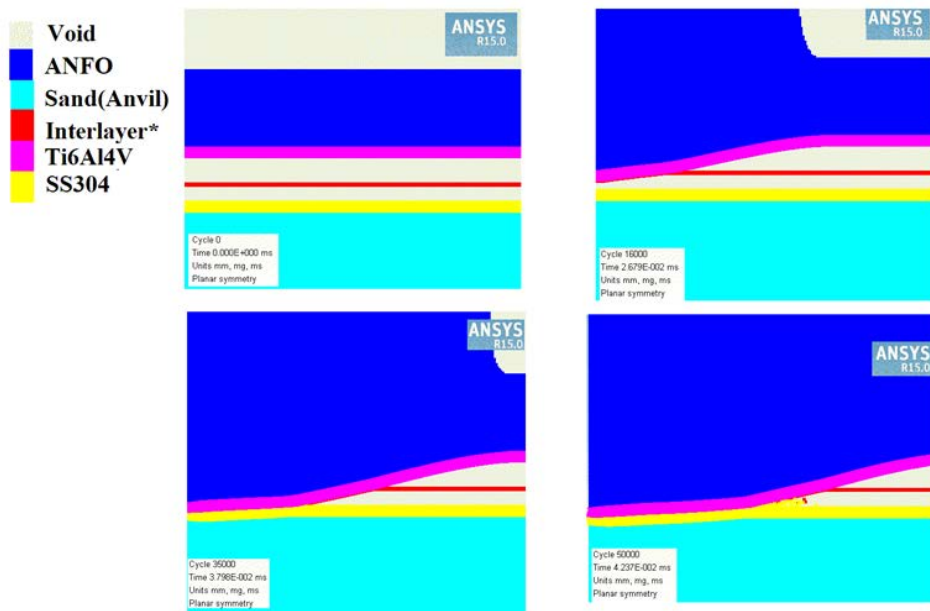


Figure 2. Explosive welding simulation at different time intervals

Figures 3. (a-f) revealed the detailed micrograph of simulated interface morphology. Simulation results showed that at given welding conditions, Ti6Al4V and SS304 were welded in the presence of interlayers that are either belongs to parent materials (Ti6Al4V, SS304) or

different kind (Cu, Al, CP-Ti) of materials. However, interface morphology and joint quality may vary. F-I interlayer for all cases has smooth or straight shape while I-B has a wavy pattern.

Moreover, the wavy pattern of the I-B interface had some vortices. These vortices were formed along the detonations direction in the interlayer side of I-B interface except Cu interlayer. In Cu, the interlayer vortices had the opposite direction of the detonation wave and were more prominent as compared to other interlayers. Figure 3. (c) shows that the flyer suppresses soft Al interlayer at I-B interface. Due to this suppression, partially smooth I-B interface were created with peninsula or island morphology of intermetallics. These peninsula or island type shapes were to be suitable for good quality welding joints. Previously many researchers [21]–[23] observed these types of shapes and analysed them.

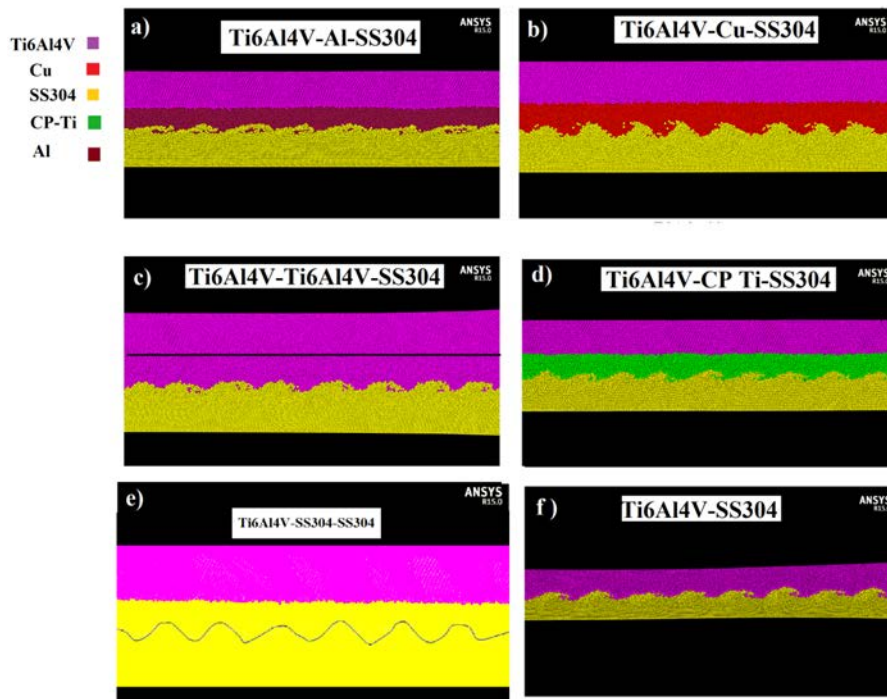


Figure 3. Simulated interface morphology of Ti6Al4V-SS304 composite plate with interlayer materials, (a) Al, (b) Cu, (c) Ti6Al4V, (d) CP-Ti, (e) SS304, (f) No interlayer

### 3.1. Interface morphology

Figure 4. shows that the wavelength of I-B interface was significantly decreased with the insertion of an interlayer. In the presence of an interlayer, I-B interface wavelength was from 600 to 700  $\mu\text{m}$ . However, there was a small variation observed in wave amplitude. The comparative study showed that Cu and CP-Ti interlayer has a smaller wavelength as compared to other materials. For good quality joints, a smaller wavelength and amplitude at the interface were preferable because they decrease the probability of intermetallics formation. Earlier, manikandan et al. [9], [24] and Izuma et al. [11] investigated the importance of interlayer in interface morphology.

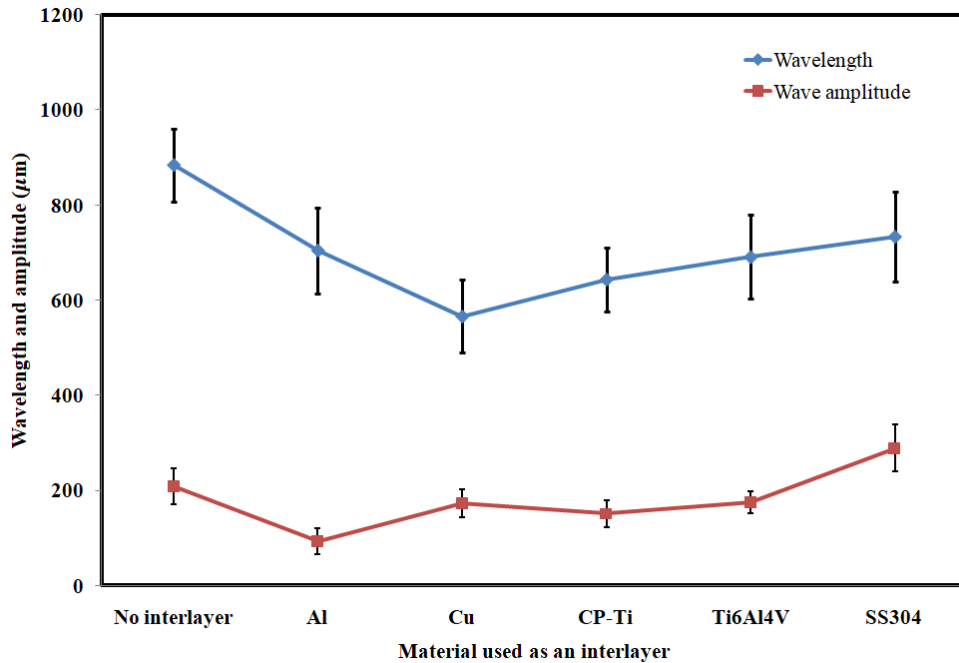


Figure 4. Wavelength and amplitude variation at I-B interface with respect to interlayer materials

### 3.2. Plastic strain

The high impact can create shear deformation at the interface that raised the temperature locally. This rise in temperature stimulates the joining capability of different kind of materials. Plastic deformation is a short interval process and is not possible to observe it experimentally. Therefore, simulation is a better choice to understand the process.

Counter plots at the interface with different interlayers are shown in Figure 5. (a-d). Results revealed that at I-B interface plastic strain reaches up to value 5. However, its intensity was not the same at all joining points except in Figure 5. (a), where the plastic strain was almost very high at all joining point. It indicated that a composite plate with Al interlayer has more brittle intermetallics which weaken the joint strength. Moreover, composite plates with SS304 and Cu showed high deformation at crest and trough of the I-B interface wave. It means vortices are formed at these both points. These vortices consist of intermetallics which affects the joining strength. Furthermore, Ti6Al4V interlayer shows minimum deformation among all simulated cases because it holds high tensile strength and hardness.

Figure 6. indicates that the flyer plate faced very high deformation during the direct welding process and reach up to value. Flyer (Ti6Al4V) was a sturdy material, that's why it has low ductility. At high plasticity, there is a possibility of cracks or shear band formation, which affects the reliability of the composite plate. Insertion of interlayer can reduce the plastic deformation more than half value (Figure 6.).

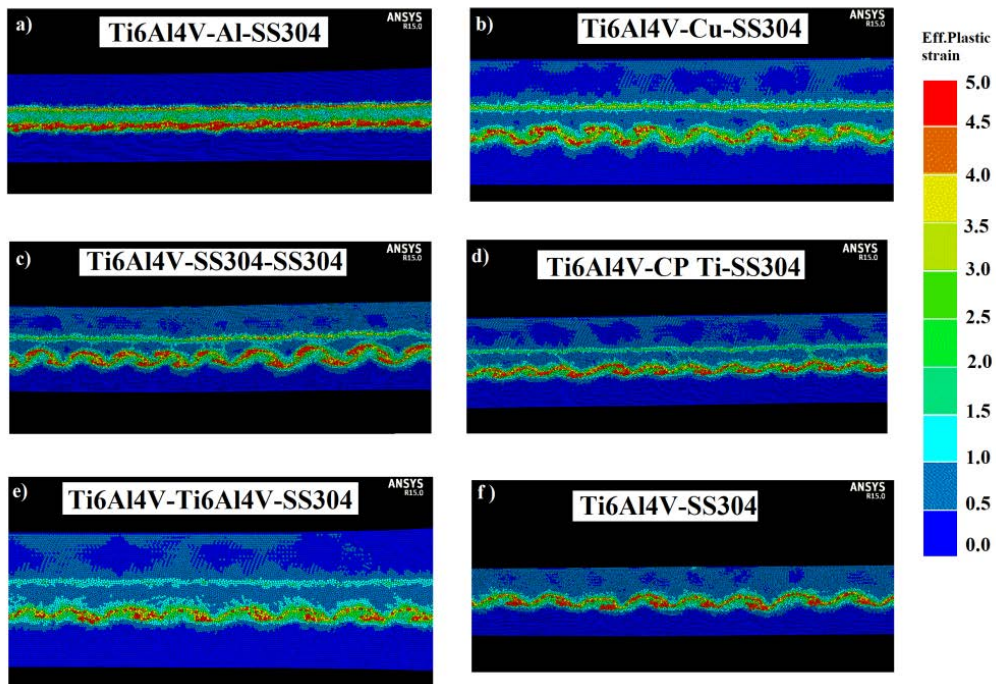


Figure 5. Simulated Effective plastic strain contour plots of Ti6Al4V-SS304 composite plate with interlayer materials, (a) Al,(b) Cu, (c) SS304, (d)CP-Ti, (e)Ti6Al4V, (f)No interlayer

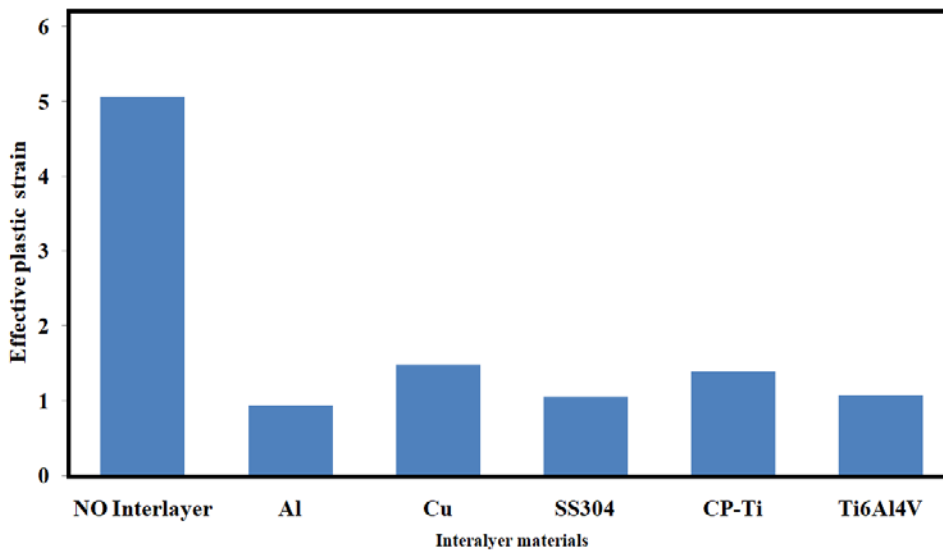


Figure 6. Flyer peak plastic strain with different interlayer materials and without interlayer

### 3.3. Pressure

Figure 7. (a-d) shows the pressure contour plot of all welding simulations. Blazynski [1] described that for good quality joints, impact pressure should be higher than the constituent material yield strength. The contour plots showed that for current simulation condition, impact pressure was more than 10GPa, which was significantly higher than the yield strength of the flyer, base plate and all interlayer materials. Moreover, Figure 7. (b) exhibited that simulation with Cu interlayer contained maximum peak pressure contour area. It was due to the higher conductivity of Cu.

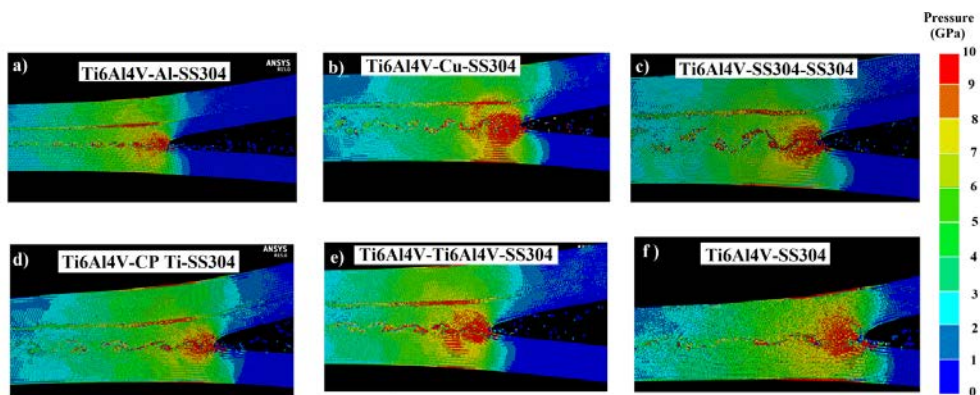


Figure 7. Simulated pressure contour plots of Ti6Al4V-SS304 composite plate with interlayer materials, (a) Al, (b) Cu, (c) SS304 (d) CP-Ti, (e) Ti6Al4V, (f) No interlayer

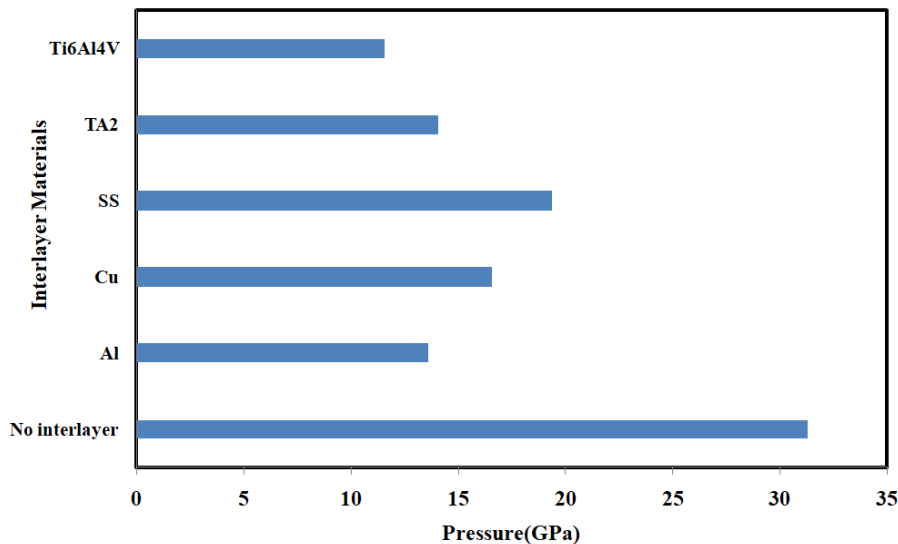


Figure 8. Flyer peak pressure with different interlayer materials and without interlayer

Figure 8. shows the maximum pressure of flyer during the impact with the base plate. The insertion of an interlayer considerably decreased impact pressure. From Figure 8., the flyer impact pressure was found to be decreased from 32 GPa to 13-18 GPa. This reduction in pressure was due to energy loss during the collision with an interlayer. Under very high pressure, welded materials can have adiabatic shear bands and cracks that is harmful for quality welding.

### 3.4. Temperature

During the explosive welding process, high deformation and impact pressure can produce sudden increment in local temperature. This increment is for short interval because during explosive welding cooling rate is very high, it is about  $10^5$ - $10^7$  K/s [25]. Temperature contour plots in Figure 9. (a-f) confirmed that temperature increment was purely a local phenomenon, and during this process, the temperature raised to the melting point for all conditions. However, Along with the interfaces temperature profile was not smooth. Figure 9. (a-f) revealed that temperature rised during the welding process was like small packets at crest and trough of the I-B interfaces. These temperature packets maked easy mixing of melted interlayer and base metals. These intermetallics were cooled down suddenly due to high cooling rate. This phenomenon annealed the interface and made it harder.

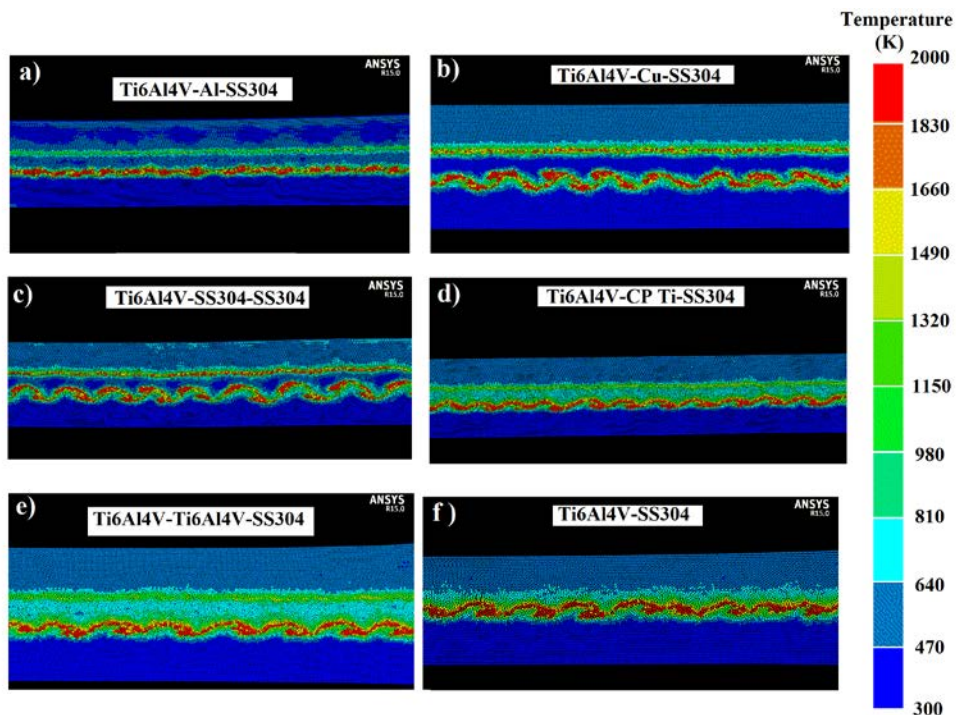


Figure 9. Simulated temperature contour plots of Ti6Al4V-SS304 composite plate with interlayer materials: (a) Al, (b) Cu, (c) SS304, (d) CP-Ti, (e) Ti6Al4V, (f) No interlayer

#### 4. CONCLUSIONS

The current paper provided a possible option to simulate the whole explosive welding process, especially in the presence of an interlayer with less computational time. Numerical simulation results revealed that interlayer performed a significant role to control the energy loss. By controlling the energy loss, the formation of intermetallics can be decreased. Good quality welded joints depended on threshold values of impact pressure and plastic deformation; interlayer might be used to control these parameters. Numerical simulation results showed that impact pressure had enough value to cross the yield strength of all constituent materials. Furthermore, the interlayer-base interface had maximum deformation as compared to the flyer-interlayer interface. Due to high distortion, I-B interface was melted, and the wavy pattern was created. The interlayer could decrease the wave parameters. The comparative study showed that high strength material is more suitable to use an interlayer.

For the current study, the materials used as an interlayer were found suitable for good quality joints. However, Al and Cu contain high thermal diffusivity and are relatively softer materials as compared to Ti and SS304. Especially, Al having a low melting point, that's why it can be easily deformed. Simulation results indicated that Al interlayer wave was suppressed and formed like continuous packets of the melted region. Due to these melted regions, the probability of the formation of brittle intermetallics was increased. Although Cu satisfied all welding conditions, however, its yield strength was much lower than constituent parent materials (Ti6Al4V, SS304) which could decrease the joint strength of the welded composite plate.

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