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Simulation of mechanical and thermal behavior in explosive welding of aluminum 1050 to copper

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Abstract

Explosive welding is a solid-state joining method used for bonding dissimilar metals. In this study, the effect of stand-off distance on the mechanical and thermal behavior of aluminum 1050 to copper joints was investigated using Abaqus 6.12. The Johnson-Cook model was used to simulate the mechanical response, and the Williams-Bourg equation of state modeled the explosive material. The results showed that increasing the stand-off distance from 1.5 mm to 5 mm increased the impact velocity of the flyer plate from 900 m/s to 1073 m/s, and raised the dynamic impact angle from 20.70° to 24.75°. Plastic strain in the collision area and peak pressure (exceeding several GPa) also increased with stand-off distance. Optical microscopy confirmed that higher stand-off distances led to vortex-like wave formations and localized melting at the interface. These findings provide valuable insights for optimizing explosive welding parameters to achieve stronger and more uniform joints.

Keywords: Explosive welding, Simulation, Stand-off distance, Aluminum-copper joint.

1- Introduction

Explosive welding is a method that uses the controlled energy of an explosive material to bring together the welded surfaces, which are positioned at a specific stand-off distance. This process occurs at high speed, resulting in the collision of two surfaces that creates a local plastic deformation field at the joint interface. The pressure from the impact increases the temperature, leading to the formation of a high-speed jet from the two joining surfaces, which creates clean joint surfaces and removes surface contaminants. The formation of this jet is a key factor in achieving a proper bond in explosive welding [1].

Explosive welding has garnered significant attention in recent years as a novel and efficient technology for joining dissimilar materials, especially aluminum and copper. This method is utilized in various industries, including aerospace, automotive, and electronics, due to its ability to produce high-quality and strong joints. Aluminum, with its lightweight, corrosion resistance, and high formability, is one of the most commonly used materials in modern industries. In contrast, copper is crucial in electrical and electronic applications due to its unparalleled electrical and thermal conductivity. However, joining these two metals presents challenges due to significant differences in their physical and chemical properties [2].

Explosive welding serves as an effective solution for creating strong connections between aluminum and copper, helping to mitigate these challenges. In this method, controlled energy from the explosion of an explosive material is used to bring the welded surfaces close together, resulting in the creation of a local plastic deformation field at the joint interface upon impact. This process not only leads to strong connections but can also eliminate surface contaminants, providing clean and high-quality joining surfaces [3].

Numerous studies have been conducted on the simulation of explosive welding of aluminum to copper. For instance, the use of simulation software like Abaqus has allowed researchers to investigate the mechanical and thermal behavior of joints under various explosive loading conditions. A study by Hang et al. [4] examined the effects of various process parameters on the mechanical properties of explosive joints between aluminum and copper, demonstrating that precise adjustment of these parameters can achieve high-strength connections.

Additionally, Zhang et al. [5] analyzed the impact of stand-off distance and explosive thickness on the quality and properties of the joint interfaces in another study. The results of these studies indicate that optimizing welding conditions can yield positive and satisfactory outcomes. Numerical simulations in this field have assisted in analyzing thermal and mechanical behavior during explosive welding and have provided a better understanding of the physical and chemical processes occurring at the joint interface. For example, Li et al. [6] investigated the effects of explosive parameters on the quality of aluminum and copper joints, revealing that pressure and temperature during the welding process significantly affect the final properties of the connections.

Overall, the simulation of explosive welding of aluminum to copper not only aids in a better understanding of this process but can also lead to the development of new technologies and improvements in joint quality across various industries. Given the increasing demand for lightweight and high-strength connections in diverse fields, this research is particularly important. These advancements can contribute to achieving industrial and scientific goals in optimizing welding processes and enhancing joint efficiency.

In this study, the effect of stand-off distance on the joint interface properties in explosive welding between aluminum 1050 and copper sheets was investigated using Abaqus version 6.12. The relationship between microstructure, mechanical behavior, and process parameters was examined through both numerical simulation and experimental analysis. This approach enables a detailed understanding of how dynamic impact conditions influence joint formation. The novelty of the research lies in combining advanced finite element modeling with microstructural validation to explore the role of stand-off distance in wave morphology and localized melting phenomena. These insights not only enhance the scientific understanding of explosive welding mechanisms but also contribute to optimizing dissimilar metal bonding for high-performance industrial applications.

2- Experimental materials and methods

2-1 Materials

In this study, aluminum 1050 sheets and copper were selected as the base sheets (mm 230×230×3) and flyer sheets (mm 260×260×5), and their chemical analysis was performed using emission spectrometry (Table 1). The explosive welding process was carried out using Amatol 95/5 explosive and M8 detonator. Samples numbered 1 to 3 were welded with stand-off distances of 2.5, 5, and 1.5 mm, respectively, and an explosive charge of 2.

To simulate this process, Abaqus version 6.12 was used, which performs the dynamic analysis of explosive welding using the Williams-Bourg equation of state. By using a load application program in Abaqus, the load or pressure written by the compiler can be applied as a distributed load on the surfaces. For this purpose, an auxiliary program was designed in Fortran that inputs the results of the Williams-Bourg equation into equations 1 and 2. This pressure is transmitted as a time- and space-dependent equation to the upper surface of the flyer plate as shown in Figs. 3-5. The exponential equation relating pressure to time is as follows [7]:

$$P=P_0 \exp(-t/\theta) \tag{1}$$

$$P_0 = \rho_e V_d / (1+k) \tag{2}$$

In these relations, (t) is the time of the explosion front advance, (ρ_e) is the density of the explosive, (Vd) is the velocity of the explosive, and (θ) and (k) are constants related to the explosive. The constant (k) for the explosive was considered to be 1.376. The total analysis time was set to 90 microseconds, and the parameters of explosive loading and the velocity of the explosive were taken into account in the simulation design. Finally, the effects of stand-off distance and other design variables on pressure and welding dynamics were examined. This research was conducted to optimize the explosive welding process and reduce errors arising from ineffective parameters.

Table 1: Chemical Composition of Base and Flyer Plates (%wt)

Element	Sn	Pb	P	Zn	Si	Mg	Mn	Cr	Ti
Cu	0.92	0.0123	0.0892	0.119	-	-	-	-	-
Al	0.02	-	-	0.25	0.4	4.75	0.7	0.25	0.15

Table 2: Constants for Simulation and Johnson-Cook Equation for Used Alloys [7]

Material	Poisson's Ratio	Elasticity (MPa)	n	m	C	B (MPa)	A (MPa)	Density Kg/m^3
Al	0.3	69	0.73	1.7	0.011	684	369	2700
Cu	0.3	117	0.35	0	0.02	280	95	8940

In this study, the Johnson-Cook model was used to simulate the plastic deformation of the sheets, expressing the yield stress as a function of plastic strain, strain rate, and temperature. The necessary constants for simulating the alloys are presented in Table 3. The flyer and base plates were modeled in three dimensions with deformable behavior, and meshing was performed using C3D8R elements with a hexagonal structure, with a mesh size of 0.003 meters in the impact region. Energy and momentum transfer occurs through the contact surfaces between the explosive charge and the sheets. The boundary conditions were simulated, and the contact behavior was considered as frictional with a coefficient of friction of 0.1.

The Johnson-Cook constitutive model is defined as:

$$\sigma = (A + B * \varepsilon^{n}) * (1 + C * \ln(\dot{\varepsilon} / \dot{\varepsilon}_{0})) * (1 - T^{*m})$$

The Johnson–Cook constitutive model describes the flow stress of a material under combined effects of plastic strain, strain rate, and temperature. In this model, σ is the flow stress, ε is the equivalent plastic strain, and $\varepsilon^{\cdot}$ is the strain rate. The term T∗T^*T∗ represents the normalized temperature relative to melting. Constants A,B,nA, B, nA,B,n describe strain hardening; CCC represents strain rate sensitivity; and mmm accounts for thermal softening. This model was implemented in Abaqus to simulate the dynamic plastic behavior of aluminum and copper during explosive welding, providing realistic predictions of deformation under high strain rate conditions.

3- Results and discussion

3-1 Welding progress and flyer plate

The Johnson–Cook model was applied to define the plastic behavior of the materials during high strain rate conditions. This allowed accurate simulation of localized deformation and energy dissipation at the collision interface under explosive loading. Simulation results of the explosive welding process indicate the influence of physical parameters such as impact velocity, plastic strain, pressure, and shear stress on the process analysis. These parameters depend on variables like charge type and amount, as well as stand-off distance.

Fig. 1 illustrates the stages of welding progress during the simulation, showing that the plates are fully bonded together. Changes in the impact velocity of the flyer plate at 50 microseconds after impact, depicted in Fig. 2, reveal that as the stand-off distance increases, the impact velocity also increases, affecting the kinetic energy consumed during the collision. Furthermore, results indicate that the flyer plate's velocity does not reach its maximum and varies with the stand-off distance. The variations in the dynamic impact angle also increase with the stand-off distance, as presented in Table 2. These plots highlight how the stand-off distance directly affects the flyer plate's velocity profile across the interface. The increase in flyer velocity results in a greater kinetic energy transfer at the moment of impact, intensifying localized deformation. This, in turn, contributes to higher jet formation probability and influences the interface wave morphology in subsequent bonding stages.

The pressure generated at the explosion front is transmitted as an impact stress wave to the flyer plate. This pressure must be applied sufficiently and in an appropriate time frame at the point of impact, surpassing the dynamic strength of the alloys. This leads to the formation of suitable atomic bonds between the colliding surfaces and appropriate deformation in these areas, ultimately creating an effective jet that results in a desirable connection.

Table 3: Calculated Impact Velocities and Angles in samples

Test Number	Impact Angle	Impact Velocity m/s	Impact Point Velocity m/s
1	24.75	1073	2274
2	24.57	1066	2277
3	20.70	900	2342

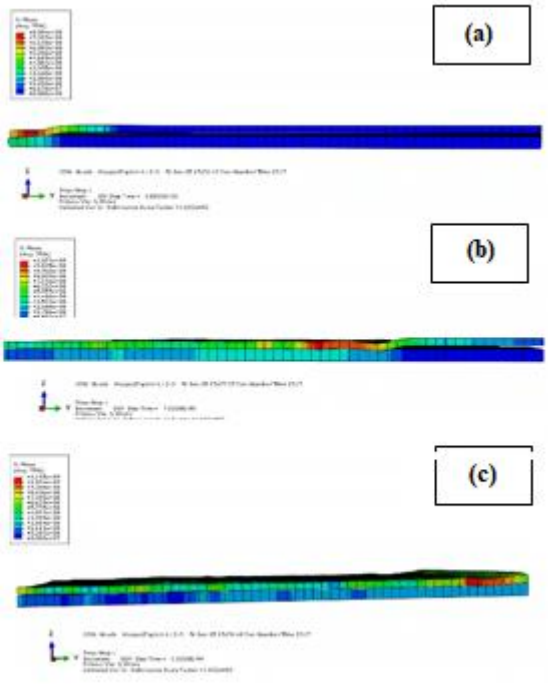

Fig. 1 Progress of Plate Bonding: (a) Before Impact, (b) After Impact

Figs. 3 and 4 illustrate the variations in impact pressure at 50 microseconds after collision for the flyer plates and base at the point of impact. The highest pressure at the impact point, on the order of gigapascals, is more than ten times the yield strength of the welded metals. This threshold aligns with the conditions stated by Blazinski for achieving optimal bonding between the welded components. This high pressure creates a region of severe plastic deformation at the point of contact.

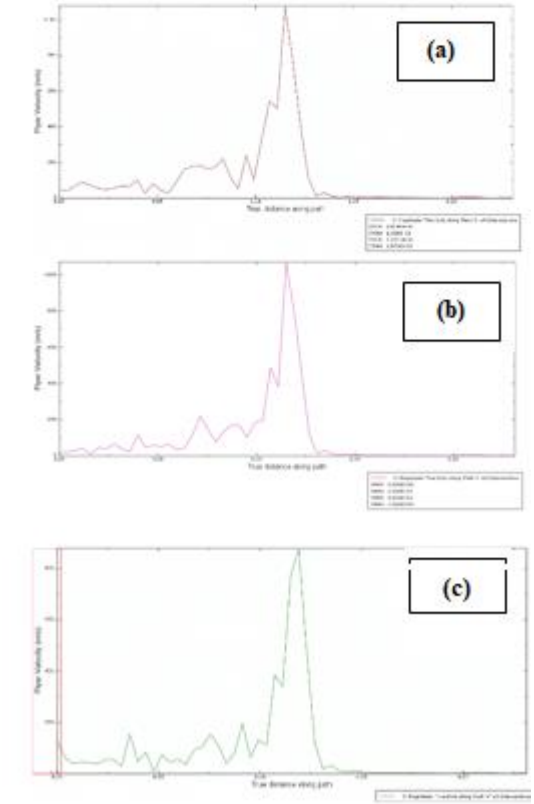

Fig. 2 Changes in Impact Velocity with Progression of Impact Point at 50 Microseconds After Impact, (a) Test 1, (b) Test 2, (c) Test 3

Surface atoms bond by sharing electrons, forming an appropriate metallurgical bond. Khanzadeh et al. [8] also achieved similar results in the simulation of a three-layer connection of Aluminum 1050 - Aluminum 5083 and carbon steel. Due to the fluid-like behavior of the materials, waves can form at the interface of the created connection and stabilize shortly after the application of pressure at the interface. The results in Figs. 3 and 4 indicate that as the stand-off distance increases, the pressure at the interface rises due to the increasing impact velocity (as shown in Fig. 2). Additionally, pressure variations are not uniform throughout the collision of the plates; these changes are influenced by the dynamic impact angle during the collision, affecting the impact velocity components at the interface and resulting in pressure fluctuations there [9].

As seen in Fig. 4, the pressure peak shifts and intensifies with increasing stand-off distance, indicating a more concentrated energy transfer. This localized pressure amplification is critical in initiating the plastic deformation and metal jetting required for metallurgical bonding. The variation in pressure also implies non-uniform strain distribution, which directly influences microstructural characteristics at the joint interface.

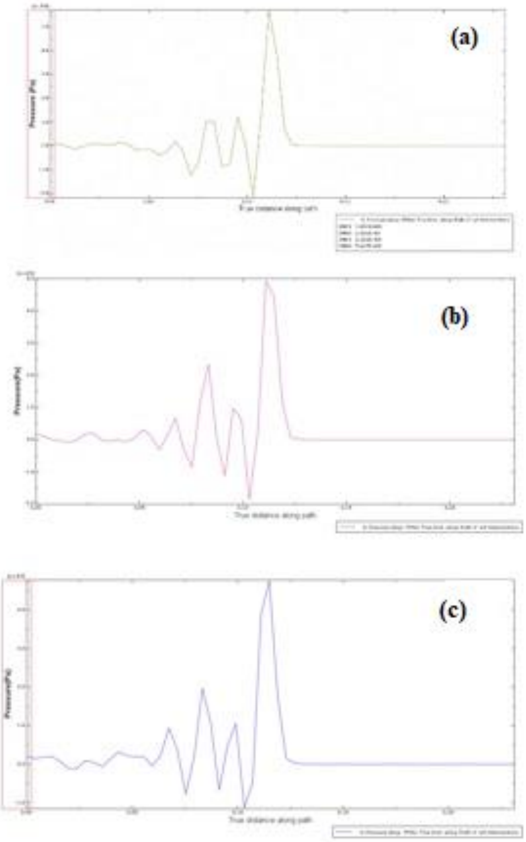

Fig. 3 Changes in impact pressure at 50 microseconds after impact for base plates at the point of impact, (a) test 1, (b) test 2, (c) test 3

3-2 Investigation of jet formation possibility

In the simulation using Abaqus software with Lagrangian formulation, the possibility of simulating a jet is limited due to the inability of materials to exit the mesh boundaries. However, the analyses conducted, as shown in Fig. 5, indicate high particle velocities at the point of impact on both sides of the joint and around the plastic bulging region.

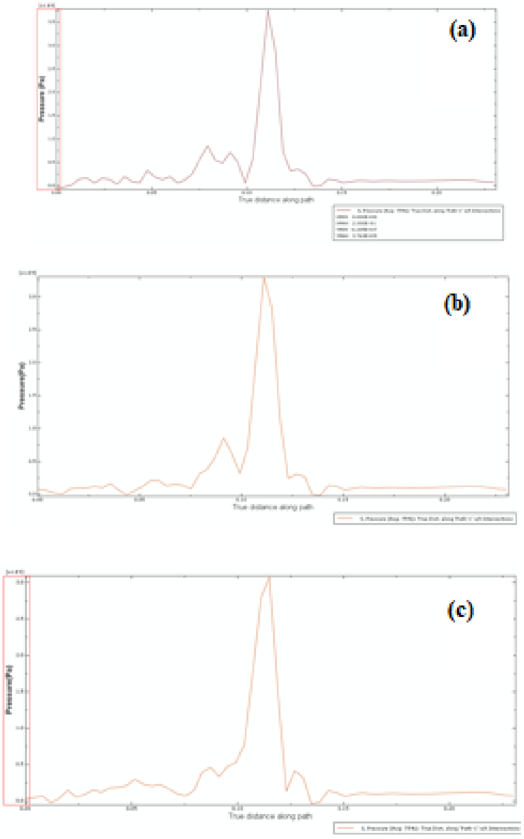

Fig. 4 Changes in impact pressure at 50 microseconds after impact for flyer plates at the point of impact, (a) test 1, (b) test 2, (c) test 3

3-3 Plastic strain induced during impact

Fig. 6 illustrates the variations in equivalent plastic strain in the colliding plates at 50 microseconds after impact for the tests. Due to the high impact velocity and significant pressure in the impact area, a region of severe plastic deformation is created, leading to high values of plastic strain in this region. The results indicate that the plastic strain at the point of impact has reached its maximum value, reflecting the maximum deformation during the collision.

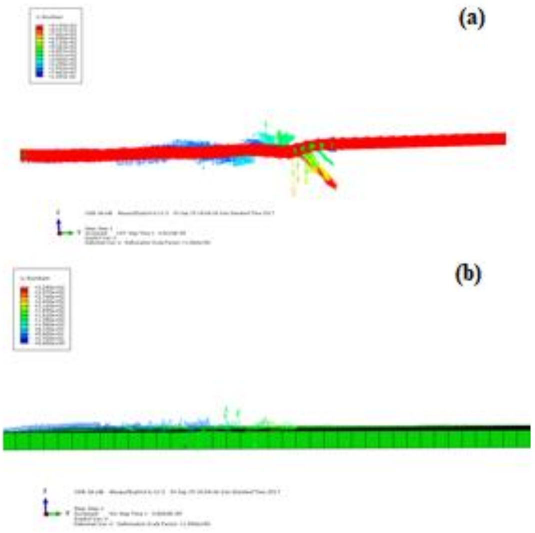

Fig. 5 Changes in Surface Particle Velocities in the Impact Region for Test 1, (a) Flyer Plate, (b) Base Plate

Additionally, with a constant explosive load, as the stand-off distance increases and due to the rising impact velocity, the plastic strain at the point of impact also increases. Fig. 6 demonstrates that the highest plastic strain occurs in the immediate vicinity of the impact point, forming a concentrated deformation zone. The increased strain with higher stand-off distance suggests enhanced energy absorption and metal flow at the interface, which are key factors for forming strong interfacial bonds. These high-strain regions are potential sites for wave initiation and possible vortex formation due to severe shear forces.

3-4 Speed of the impact point movement

In the parallel arrangement for explosive welding, the speed of the impact point is equal to the explosive velocity. However, the simulation results indicate the formation of a plastic bulge during the collision of the plates with each other, as shown in Fig. 7 Therefore, the effect of the dynamic impact angle and its cosine component on the explosive speed must be considered. Taking into account the influence of the dynamic impact angle, the speed of the impact point for each test has been calculated, and the results are shown in Table 4-1.

3-5 Examination of microstructure of samples by optical microscope

Fig. 8 displays images of the waves generated along the longitudinal direction of the joint. As seen, the joint interface (Al 1050/Cu) in this case exhibits a vortex-like wave pattern. During the joining process, a wide area of localized melting occurs at the joint interface due to the high stopping distance and the greater density difference between the two alloys.

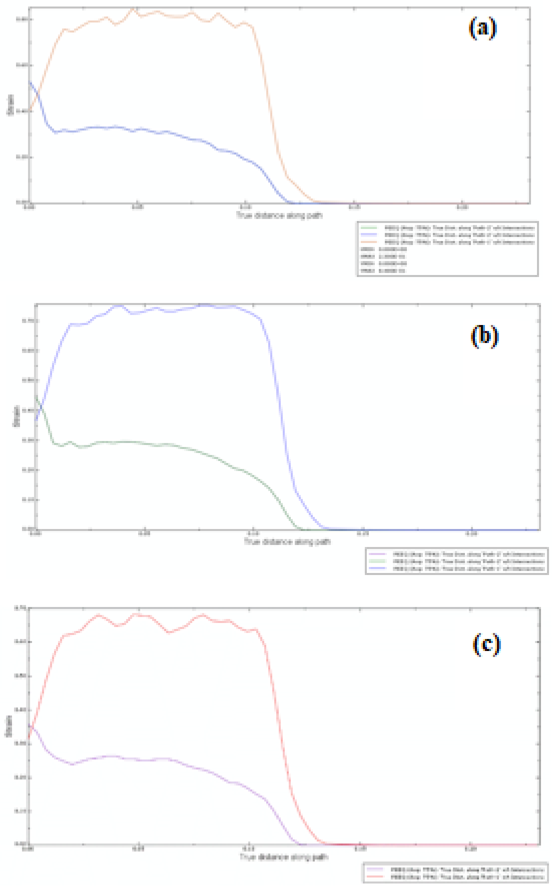

Fig. 6 Variations in Plastic Strain in the Colliding Plates at 50 Microseconds After Impact, (The upper curve represents the base plate, while the lower curve represents the flyer plate) (a) Test 1, (b) Test 2, (c) Test 3

Additionally, according to the simulation results shown in Figures 2 to 6, this sample has the highest impact velocity and impact pressure, resulting in a significant amount of kinetic energy being transferred to the joint interface, thus creating a higher temperature in the impact region. The vortex-like wave patterns observed in Fig. 8 are indicative of a strong bonding mechanism characterized by intense localized plastic deformation and potential partial melting.

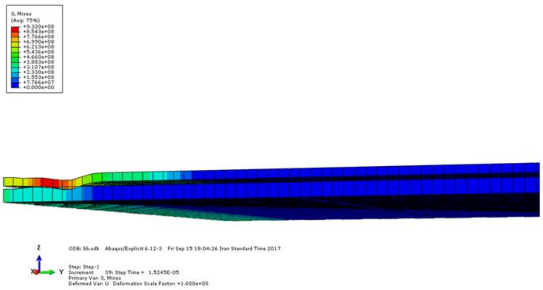

Fig. 7 Plastic bulge during explosive welding

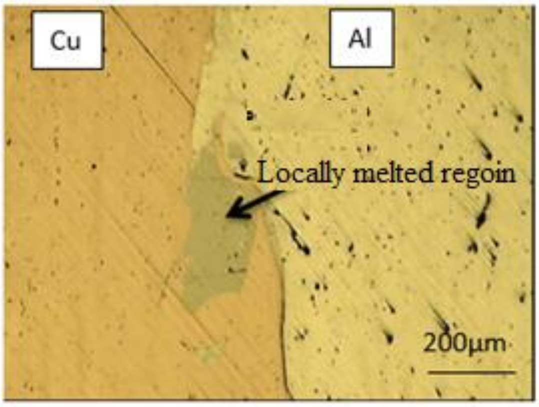

Fig. 8 Optical microscope images of different regions of the joint interface for the first series sample

These structures are typical of high-energy explosive welding conditions and confirm the simulation data regarding the high impact pressure and velocity in the first test. Their formation also supports the presence of metallurgical bonding aided by jetting and mechanical interlocking.

Furthermore, as indicated in Fig. 6, this sample experienced a higher strain compared to other tests. For these reasons, the resulting joint appears as a vortex-like wave with localized melting areas. In explosive welding, the joint can consist of two types: metal-to-metal and metal-to-solidified melt joints.

Alongside a minimum velocity for the flyer plate, there exists a minimum amount of kinetic energy for effective joining. Due to the impact of the flyer plate, the consumed kinetic energy transforms into potential energy, leading to deformation of the impact surface. If the amount of plastic deformation is insufficient, short waves are generated, and localized melting does not appear [10]. With an increase in the kinetic energy of the impact, severe deformation occurs beneath and at the crest of the wave, resulting in high impact pressures. Vortices can then form at the joint interface, and these vortices may create localized melting areas in certain regions of the joint. These areas are produced by internal heat generated due to the high pressure caused by shock waves from the explosion and severe plastic deformation, along with the adiabatic heat from the trapped gases between the plates. These regions are surrounded by cold metal and are subject to high cooling rates, in the range of 10^5-10^7 K/S° [11, 12]. As shown in Fig. 9, the joint interface exhibits a short-wave vortex structure. This morphology differs from that of the first series due to a reduced stopping distance and lower kinetic energy during impact. Simulation results indicate that this sample has lower impact pressure and velocity compared to the first sample, leading to less plastic strain and lower temperatures at the joint. Similar to the first series, localized melting areas are also observed in this series.

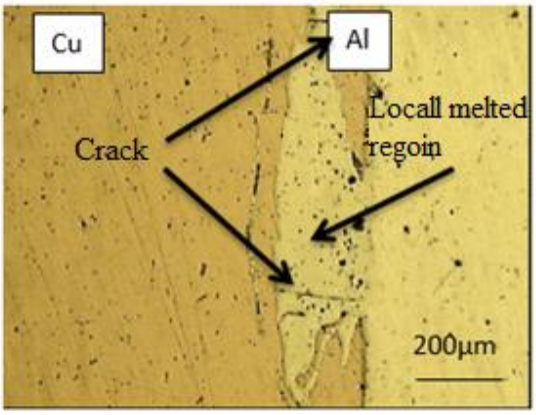

Fig. 9 Optical microscope images of different regions of the joint interface for the second series sample

With an increase in impact velocity, the impact pressure rises, and the dynamic impact angle and consumed kinetic energy at the impact point also increase. Part of the consumed kinetic energy at the joint interface converts into potential energy, causing the plates to deform along the contact surface. As the consumed kinetic energy increases, greater plastic deformation occurs at the joint, and the material behavior tends to become more fluid-like. The speed of the flyer plate increases with a greater stopping distance. Moreover, due to density differences and wave propagation speeds in metals, the compressive momentum on both sides of the joint changes with the increased speed of the flyer plate, resulting in fluctuations at the impact point during joining. These fluctuations increase with higher impact speeds, leading to a larger volume of material adjacent to the impact point losing strength and exhibiting quasi-fluid plastic behavior [13]. Additionally, in the localized melting area, a mixture is observed, which is attributed to the formation of brittle intermetallic phases in these regions.

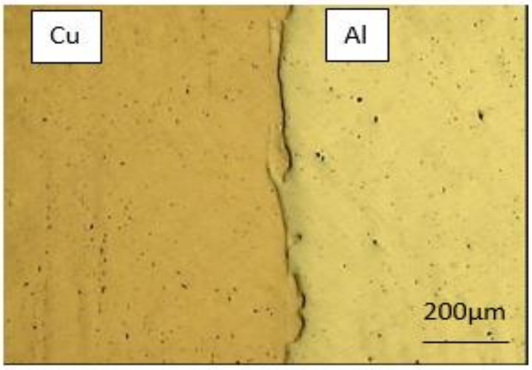

Fig. 10 Optical microscope images of different regions of the joint interface for the third series sample

By comparing Tests One and Two along with the simulation results shown in Figures 2 to 6, the variations in shear stress and plastic strain at the joint interface lead to changes in the morphology of the joint waves. These two factors can be considered primary and significant contributors to altering the joint morphology.

The images of the joint interface created along the axis perpendicular to the explosion are shown in Fig. 10. The resulting joint interface appears as a short wave pattern without any localized melting areas. Simulation results indicate that the third sample experiences the lowest impact pressure and velocity, leading to reduced temperature and kinetic energy transferred to the joint interface. Furthermore, the simulations show a lower amount of plastic strain in this sample.

Fig. 10 illustrates the interface morphology under low kinetic energy impact conditions. The short-wave structure without any signs of localized melting confirms the limited plastic deformation and absence of jetting behavior. This morphology is often associated with insufficient energy transfer, leading to mechanical interlocking without substantial metallurgical bonding. The uniform and shallow waves indicate that the collision dynamics were not intense enough to disrupt surface oxide layers or initiate mixing, which is critical in forming high-strength joints. The reduction of these parameters results in a joint interface characterized by shorter wave amplitudes and heights, along with the absence of localized melting areas [14 , 15]. By comparing the test results with the simulation data from Figs. 2 to 6, the variations in shear stress and plastic strain at the joint interface lead to changes in the morphology of the joint waves. These two factors can be considered primary and significant contributors to the alteration of the joint morphology.

4. Conclusions

In this study, the effect of stopping distance on the properties of the explosive joint interface between Aluminum 1050 and Copper was investigated using ABAQUS version 6.12 The key findings are summarized as follows:
factors influencing the morphology of the joint interface.

1. This study demonstrated that modeling the pressure generated by the explosion, considering variables such as explosive load and stopping distance, can effectively analyze the variations in the joint interface.
2. Simulation results indicate that the maximum pressure, strain, and shear stress occur at the point of impact, emphasizing the importance of this point in the explosive welding process.
3. As stopping distance increases, the shape of the joint interface transforms towards a vortex-like structure, which can lead to the formation of localized melting areas.
4. Variations in impact pressure and velocity have a significant effect on the formation of localized melting compounds, impacting the final quality of the joints.
5. Changes in shear stress and plastic strain are identified as key factors influencing the morphology of the joint interface, which can aid in optimizing explosive welding processes.

These findings can contribute to better design and optimization of explosive welding processes in various industries.

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