International Journal of Engineering Trends and Technology
ISSN: 2231–5381 / https://doi.org/10.14445/22315381/IJETT-V72I2P108

Volume 72 Issue 2, 69-76, February 2024

Original Article

Advances in Explosive Welding of Dissimilar Metals: A Mini Literature Survey

Sunil Bhat[1], Yashpal Khedkar[2], Priyank Prasad[3]

[1]*Department of Mechanical Engineering, RVITM, Bangalore, Karnataka, India.*
[2]*SVERI's College of Engineering, Pandharpur, Maharashtra, India.*
[3]*Centre for Airborne Systems, DRDO, Bangalore, Karnataka, India.*

[2]*Corresponding Author: ymkhedkar@coe.sveri.ac.in*

Received: 28 September 2023 Revised: 20 December 2023 Accepted: 06 January 2024 Published: 03 February 2024

Abstract **-** *Explosive welding, which has emerged as a promising field of research in the recent past, is a solid-state welding process that uses controlled explosive detonation to join two pieces of metal. A flyer plate collides with the base plate at high velocity, leading to significant local plastic deformation at the interface of the metals, resulting in a metallurgical bond between the metals. A high-velocity jet is formed in the process that eliminates the contaminants on the metal surfaces. Explosive welding can join materials that are similar or different. Some of the recent and important research work pertaining to explosive welding of dissimilar metals is briefly reviewed in this paper. Various aspects of the explosive welding process have been touched upon. A study of several parameters involved in the welding process is undertaken.*

Keywords **-** *Detonator, Dissimilar metals, Explosive welding simulations, Weldability.*

1. Introduction

Dissimilar metals, which are difficult to be joined or welded by conventional welding techniques due to their different thermal expansion and melting point coefficients, can be joined by the explosive welding process. Explosive welding is a solid-state welding process that offers one of the most reliable solutions for joining dissimilar metals. Metallurgical bonding between the metals occurs below their melting points in explosive welding. As a result, some common defects associated with fusion welding during solidification, such as porosity, distortion cracking, etc., are also avoided.

Refer to Fig.1. The explosive welding process involves controlled detonation on the surface of the metal, leading to very high pressure at the interface of the metals that cause considerable plastic deformation at the interface, leading to a metallurgical bond that is even stronger than the parent metals. This paper examines various aspects of explosive welding for joining unidentical metals. The overview will help concerned researchers apply experimental approaches and simulation techniques to further develop explosive welding technology.

2. Recent Advances

An innovative method of explosive welding (EWMP) [1] that is advantageous for fabricating multiple plates was demonstrated experimentally and numerically. The method involved the placement of 6 metal plates in parallel and getting 3 composite plates as the result of the process. Compared with Traditional Explosive Welding, the explosive consumption for the explosive welding method for fabricating plates with a three-layer arrangement was half timeless.

An excellent bonding interface was also observed in this welding due to EWMP. It confirmed the viability of this approach. In short, this method increased the energy efficiency of the process. Numerical simulations are very helpful in exploring explosive welding because conducting experiments is time-consuming and complex.

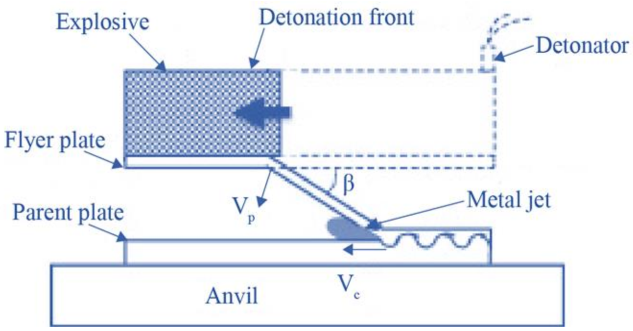

Fig. 1 Explosive welding operation

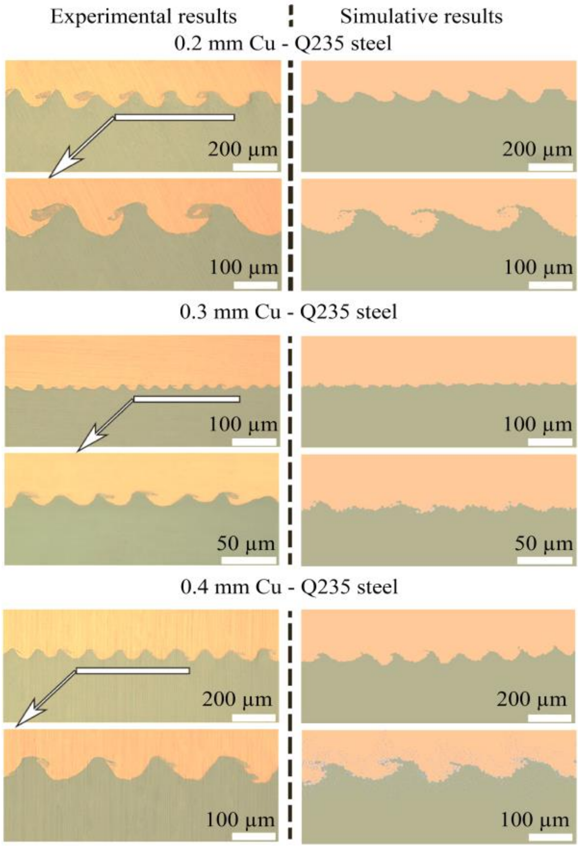

Fig. 2 Comparisons of Cu/Fe contact simulation and experimental results for various Cu foil thicknesses

A new approach for numerical simulations, dual step Lagrangian-Eulerian, was proposed by Davide Campanella et al. [2] and was validated by the experimental studies. Yank et al. [3] performed a comprehensive study using the simulation method. The Comparisons of Cu/Fe contact simulation and experimental results for various Cu foil thicknesses are shown in Fig. 2. Smoothed Particle Hydrodynamics (SPH) and advanced characterization of the simulation resulting in an understanding of nanomechanical properties, interfacial evolutions, and governing mechanisms in welding of copper foil and iron were taken up. They also proposed a new explanation for the formation of vortex based on simulation results.

They observed that SPH simulations can quantitatively predict the microstructure evolution during the high-speed impact explosive welding process. Aluminium and titanium are both regarded as premium lightweight metals. Strong corrosion resistance and high specific strength are advantages of industrially pure titanium. Xiaoming Wu et al. [4] first calculated the welding parameters of TA2/1060/5083 using a weldability window and numerical simulations and then used these parameters to conduct the experiments. They found that the TA2/1060 combination resulted in a straight bond while the 1060/5083 interface presented a sine wavelike structure with vortex and splashing of molten block structure.

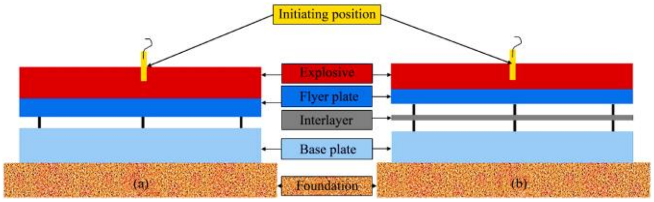

Fig. 3 Schematic diagram of (a) explosive welding with interlayers and (b) traditional explosive welding

Wu et al. [5] performed a comparative study on welding energy and interface characteristics of titanium alloy-magnesium alloy composites with and without interlayers. They found that the use of interlayers redistributes the energy. As a result, energy utilization efficiency also increases. Their study revealed that aluminium alloy could be effectively used as an interlayer to prepare a titanium alloy-aluminum alloy-magnesium alloy composite metallic body. A schematic diagram of (a) explosive welding with interlayers and (b) traditional explosive welding is shown in Fig. 3.

Explosive cladding is renowned for being able to bond a range of metals together that other welding techniques are unable to. Praveen Raj et al. [6] evaluated the tensile and shear strength of explosive cladding mild steel with aluminium alloy in their study. The study included the effect of the angle of inclination, loading ratio, and standoff distance of the detonative on the weld strength. Single replication experimental tests were used to determine the results. The bonding strength has been evaluated using a ram tensile test. With higher standoff distance, tensile and shear strength increased, while higher inclination and loading ratios also resulted in the same. A wavy profile that produced high weld strength was obtained at the interface.

Various studies pertaining to weldability, parameter selection, and quality of explosive welded joints were performed by Carvaalho et al. [7-9]. In their research, the explosive welding of aluminium to stainless steel by Carvaalho et al. mentioned that the reason for poor weldability is the low thermal conductivity of the flyer, viz., stainless steel plate. According to them, The optimum material for the flyer should be less dense than the baseplate and have a greater melting temperature, specific heat, and thermal conductivity [7]. Explosive welds between carbon steel and 6082 aluminium alloy were examined for the development of intermetallic structures and their effect on the weldability of the two materials. According to this study, The interface between the flyer and the baseplate should be reduced, and there should not be too many molten layers to prevent the development of these intermetallic compounds [8]. A study was done on the effects of an interlayer on the microstructure and mechanical behaviour of explosively welded aluminum-carbon steel and aluminum-stainless steel clads. Various series of welds were created with and without an aluminium interlayer to test different welding parameters.

Fig. 4 Experimental setup for fatigue tests

Aluminium and carbon steel together offered greater weldability. Low-velocity welds had the best microstructure and mechanical strength for both pairs. Mechanical evaluations demonstrated that the application of the interlayer did not improve the connection of aluminium to carbon steel. Low-velocity direct welding produced a joint with outstanding tensile-shear qualities and acceptable interfacial morphology, with the fracture taking place elsewhere. The interlayer's application improved the weldability of the coupling made of stainless steel and aluminium. However, the joint's mechanical strength is constrained due to the interlayer's weakening. Even when intermetallic compounds are present at the weld contact, this does not automatically lead to a subpar explosive weld. The weld's quality is determined by how the interface handles and distributes these intermetallics[9].

Explosive welding of aluminium to steel was studied by Corigliano et al. This research explored AL/FE explosive weld joints applied in shipbuilding applications. On rectangular specimens manufactured of ASTM A516 low carbon steel, encased by explosion welding with A5086 aluminium alloy and furnished with an intermediary layer of pure aluminium, static and fatigue bending tests were performed. During the bending tests, two full-field methods were used: digital image correlation and infrared thermography. The fatigue test setup is shown in the Fig. 4.

The aluminium side has a higher strain than the steel side, according to the displacement and strain fields determined by the digital image correlation technique, which was also used to detect the specimen's surface temperature and determine the fatigue limit. The Thermographic Method's anticipated values of the fatigue limit for static and fatigue testing are in good agreement with the actual values of the fatigue limit [10]. In their research, Sherpa et al. [11] and Miao et al. [12] studied the application of interlayers in explosive welding was examined. The interlayer was found to improve the weld quality. They noticed that interlayer in explosive welding reduces excessive melting and enlarges the weldability window. It reduces the vortex region and, therefore, the excessive plastic deformation. They carried out SPH simulations to understand interface morphology, temperature, pressure, and melting of the joints.

Feng et al. [13] studied the bonding between iron and copper using explosive welding through molecular dynamics simulations. Using these simulations, the bonding between copper and iron to create a bi-layer composite is examined. When modeling the creation of the bonding interface, three stages of the joining process—loading, unloading, and cooling are progressively taken into account. Based on whether melting occurs, the results show three different types of bonding interfaces can be created. Analysis is done on the atomic structures and morphologies of three different types of bonding contacts at each stage. From atomic simulations of tensile testing, it can be seen that melting is not required for the bonding contact to develop. Furthermore, the joining technique can be classified as pressure welding or fusion-diffusion welding based on whether melting takes place.

The melting and subsequent cooling process is primarily responsible for the creation of nanograins in the vicinity of the bonding interface. Liang et al. [14] used an explosive underwater welding technique to weld Zr-based BMG/Al composites without visible defects successfully. The weld interlayer was formed between the Zr-based BMG and Al plates, and the Zr-based BMG retained an amorphous structure after underwater explosive welding. The results of the numerical simulation demonstrated the validity of the JH-2 constitutive model for the selection of BMG materials, and they also demonstrated the weldability of Zr-based BMG and Al, which are in good accord with experimental findings.

Ming et al. [15] conducted explosive welding of Ti2 titanium with Q235 steel using colloid water as a covering for explosives. Using colloid water improved energy efficiency and reduced dust and noise pollution. Covering thickness was used as a parameter to understand its effect on the microstructure of the bonding interface, impact velocity of the flyer plate, and pollution. Their study showed that pollution caused by explosion reduced significantly, the impact velocity of flyer plate increased, and the wavelength and amplitude of microstructure first increased and then decreased with covering thickness. The honeycomb structure explosive and colloidal water used for experimental work are shown in Figs. 5 and 6, respectively.

Fig. 5 Honeycomb structure explosive

Fig. 6 Colloidal water used in the tests

Mahmood et al. [16] performed experimental and numerical investigations of microstructural and mechanical properties of Ti6Al4V/CP-Ti/Cu welded composite plate. Welded composite plate microstructure features were examined using optical and scanning electron microscopes. The morphology of the contact between the interlayer and the base plate revealed a wavelike structure with solid melted patches inside the vortices. Additionally, the interlayer-base interface investigation using energy dispersive spectroscopy reveals that there are some areas with various Cu-Ti chemical equilibrium phases that have been found. Mechanical tests, such as the tensile test, bending test, shear test, and Vickers hardness test, were performed in order to evaluate the mechanical characteristics of composite plates. An explosive welding simulation was also done. Simulated outcomes demonstrate that the interlayer base plate interface was produced as a result of the parent plates' localised melting and significant plastic deformation. Both alloys act like fluids when they collide.

Sun et al. [17] explored double-vertical explosive welding to understand energy distribution and interface morphology. In this method, two composite plates were formed simultaneously. The energy distribution and interface morphology in the parallel and double approaches were examined through numerical simulation and experimentation. In this study, energy balances at the start and end of welding were determined using the hypothesis of "energy flow in stages during explosive welding" that was initially put forth. The method produced higher internal energy and lower kinetic energy. Energy efficiency was increased, and as a result, half of the explosives were saved.

Yang et al. [18] studied the welding of tantalum foil and Q235 steel plates using explosive welding. Due to potential technical issues such as large melting point variations and the creation of intermetallic compounds, creating high-quality tantalum coatings on common metals is still a difficult operation. In their work, tantalum coatings on a steel substrate were effectively prepared using an upgraded explosive welding approach.

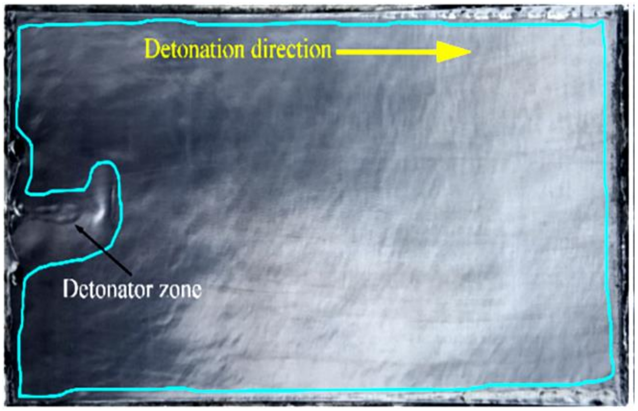

Fig. 7 Photograph of the recovered Ta/Fe sample after explosive welding

A novel charge structure and a double-layer buffer structure were used to achieve the best welding conditions. A Photograph of the recovered Ta/Fe sample after explosive welding is shown in Fig. 7. A successful coating with excellent bonding with improved corrosion resistance was achieved.

To understand the explosive welding process, Bataev et al. [19] studied various dissimilar metallic combinations with computational and experimental methods. Various tools, such as high-speed shooting, were used to estimate the morphology of the interface. Simulations and experimental studies have been conducted on the high-velocity oblique collision of plates. By using experimental techniques, it was possible to capture the emergence of jets, waves, and vortices and pressure-induced phase changes close to the interface. The SPH collision process simulation and the FDM cooling process simulation both successfully captured the key aspects of the explosive welding process. The findings are in good agreement with theories that are currently held about welding during high-velocity collisions.

Arab et al. [20] performed research on joining AlCoCrFeNi high entropy alloy and Al-6061 by explosive welding. Plates made of Al-6061 and High Entropy Alloys are joined together using the explosive welding method. A scanning electron microscope was used to describe the shape and chemistry of the chemical. Three distinct circumstances were chosen to conduct the trials, and the weldability window was estimated to confirm the weldability of the AlCoCrFeNi to Al-6061. AlCoCrFeNi and Al-6061 were properly welded together in all of the experiments. However, the welded samples obtained in high-velocity collision show minor cracks. The findings indicate that explosive welding could be a useful approach for attaching high entropy alloys to other metals. S. Jiang et al. [21] in their study, performed interfacial characterization of bonding between vanadium alloy and Hastelloy X alloy joined by explosive welding. Connecting the Flibe blanket's coolant pipes to exterior parts like the heat exchanger and tritium extractor is crucial for fusion reactors.

Evaluation is done on the corresponding microstructure and nano-indentation hardness at the interface. The study of normal wavy interface showed good weldability following explosive welding. At the contact, discontinuous vortex areas show clear stiffening up to 806 HV. Despite the phase diagrams of the constituent elements showing the production of intermetallics, the entropy and enthalpy of the multi-component alloy system indicated the formation of a solid solution based on the compositions. Research on the hardening mechanism at the interlayer showed that dislocation and solid-solution hardening are mostly responsible for visible hardening.

R. Mendas et al. [22] studied the effect of explosive characteristics on the explosive welding of stainless steel to carbon steel in a cylindrical configuration. According to research, the primary welding parameters—particularly collision point velocity—are influenced by the type of explosive and the type and quantity of explosive sensitizers.

The impact velocity, the type, and particle size of the explosive sensitizers (which rises with particle size) have an impact on the morphology of the wavy weld surfaces, most notably the amplitude and length of the waves. With the exception of ANFO welds, every weld interface showed localised melted and solidified patches, which were chemically made up of both flyer and base metal. Lysak and Kuzmin determined the energy balance during explosive welding [23]. Determining the energy balance in explosive welding is a crucial scientific task because it enables effective management of energy-release items and, as a result, allows for effective control of the structure and properties of the composite materials produced. This information is on the itemised energy expenditure released during an explosion.

A technique is suggested to calculate energy losses in the colliding plate system. By converting the specific energy of an explosion to the energy required for the plastic deformation of metal in the weld joint zone, the findings produced allow for the evaluation of the explosive welding efficiency needed for explosive welding. It is demonstrated that the efficiency varies depending on the welding regime from 0.5 to 3%. Bogumił Wronka [24] tested explosive welding and welded joints to determine the joint mechanism and properties of explosive welded joints. The problem was explained using plastic strain, viscosity, and acoustic waves. In our own model of the oxidation mechanism removal of the direct joint and confirmation of test results, the bonding mechanism was demonstrated. Chen et. Al [25] proposed investigating the atomic diffusion behavior in the Cu-Al explosive welding process. The method blends the simulation of molecular dynamics with classical diffusion theory. Cu-Al explosive welding and scanning electron microscopy experiments are performed to validate the approach. Using the method, we discovered that atomic diffusion occurs primarily during the unloading step of the welding process.

When no transverse velocity exists, the diffusion coefficient is proportional to the longitudinal velocity. The diffusion coefficient is proportional to the square of the transverse velocity when the longitudinal velocity is fixed. For modelling explosive welding, a density-adaptive SPH approach with kernel gradient correction was used by Liu et al. [26]. To simulate explosive welding, a unique Smoothed Particle Hydrodynamics (SPH) model is created in this work. It is shown that the current SPH technique can capture common physics in explosive weldings, such as explosion waves, welding surface shapes, jet flow, and flyer plate acceleration. A diagram of the detonation process of the 1D TNT slab is shown in Fig. 8.

Gladkovsky et al. [27] investigated the microstructure and mechanical characteristics of sandwich copper/steel composites fabricated by explosive welding. Research indicated that introducing dynamic polygonization and recrystallization techniques led to grain refinement in copper and steel layers. Fig. 9 depicts the experimental setup used in their study.

A new concept of Universal Substitutive Explosive Welding was introduced by Choi et al. [28]. It was recently developed by the Australian Defence Science and Technology Group to improve military vehicle survivability and mobility. The novel technology outperforms existing industrial explosive welding techniques regarding integrity, quality, and stability. It can greatly increase the target material’s hardness upper limit and ensure a perfect welding bond between the flyer (soft) and target (hard) panels without regard to target panel size.

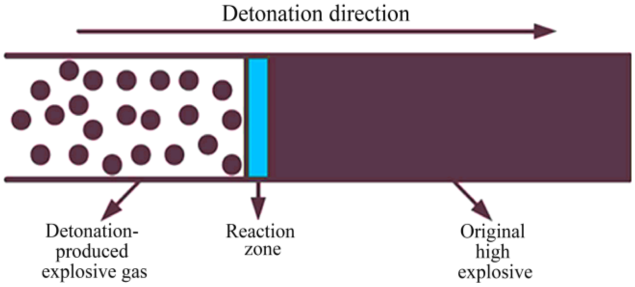

Fig. 8 Schematic diagram of the detonation process of 1D TNT slab

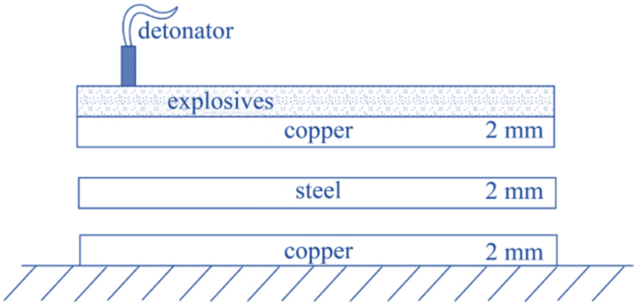

Fig. 9 Experimental setup for the explosive welding by Gladkovsky et. al [27]

The innovative technique increased the ballistic velocity limit (V50) of the explosively welded panel by up to 20% while decreasing the bulging depth (associated with dynamic flexibility) significantly without causing rupture or fragmentation. The Charpy impact test on the novel technique-fabricated sample revealed strong recovery effects with time and no transition temperature. Significantly, there were no rupture or fragmentation difficulties. Yang et al. [29] used prefabricated dovetail grooves in base plates were used to provide meshing bonding interfaces to improve the mechanical properties of the Al-Fe transition joints by explosive welding. Direct bonding and melting zone bonding at the interface were used to generate metallurgical bonding without pores. Near the interfaces, fractography on tensile specimens revealed cleavage fractures on the steel side and ductile fractures on the aluminium side. Tensile shear test findings showed that the shear strength of the meshing interfaces at 0° and 90° was raised by 11% and 14%, respectively, when compared to regular AlFe transition joints. The microhardness values dropped as the distance from the interface grew.

Wang et al. [30] fabricated a thick copper-stainless steel-clad plate by explosive welding for nuclear fusion equipment. Explosive welding tests alone are insufficient for producing high-quality clad plates. The technical parameters of the explosive welding process were collected and optimised by theoretical analysis and numerical calculations to make high-quality TU1/316 L clad plates. Through a combination of numerical calculations and experimentation, the technique for creating explosive bonded TU1/316 L clad plates was successfully developed, and the bimetallic plates were used to build International Thermonuclear Experimental Reactor (ITER) components.

Durgutlu et al. [31] studied the bonding ability of copper and steel with explosion welding using different ratios of explosive and standoff distances. Experimental studies showed that copper and stainless steel could be joined with a good-quality bond by explosion welding. At the bonding interface, intermetallics were not formed. It was observed that when the explosive ratio and standoff distance were increased, the smooth bonding interface was transformed into a wavy bonding interface. As the ratio of explosive and standoff distance increased, the amplitude and wavelength of the wave increased. It was also found that the hardness of the bonding interface and the outer face of plates increased because of deformation originating from impact. The total interface area increased as a result of the wavy interface, which was caused by increased explosive ratio and standoff distance. The interfacial characteristics of the welded joint are shown in Fig. 10. Zhang et al. [32] presented a systematic study of the microstructure and mechanical properties of the Cu-Fe explosive-bonded interface. The periodic wavy bonding structure with both the vortex region and solid-solid bonding region was embedded in the interface.

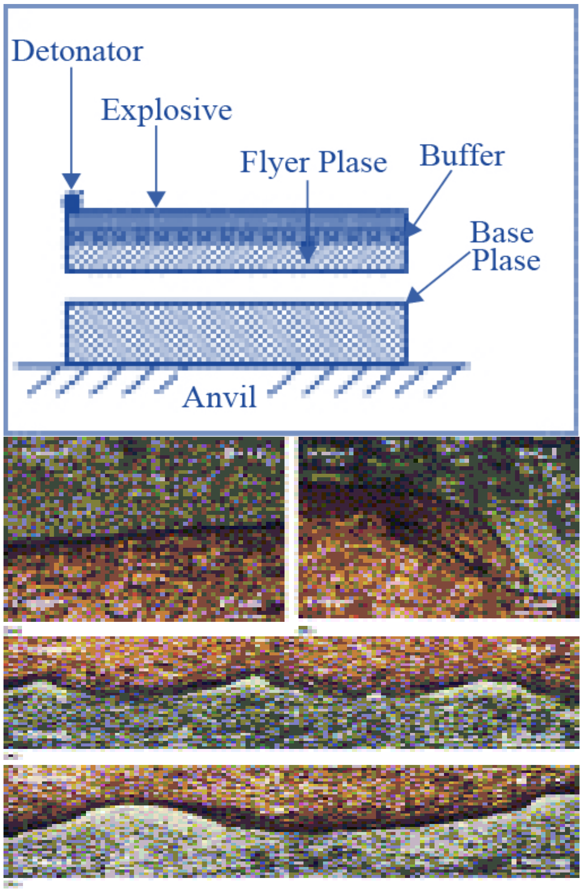

Fig. 10 Cu-steel interface [31]

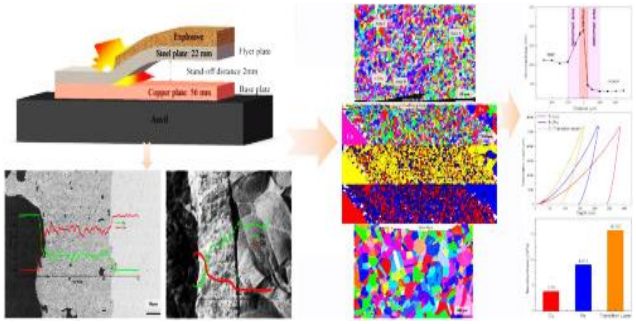

Fig. 11 Microstructural images of Cu-Fe interface [32]

Typical annealing twin structures were observed in the texture and orientation analysis of the Cu matrix. The Adiabatic Shear Bands (ASB) filled with a few much smaller size equiaxed grains and orientation variations in different areas were found in the Fe matrix. The transition layer consisting of nano-sized grains of 60 nm was formed. The micro-indentation results showed that the strength measure of the hardness of the interface (330.9 MPa) and deformation area (Cu 100 HV and Fe 286.8 HV) was higher than the matrix regions. The higher hardness of the transition layer (15.707 GPa) determined by nano-indentation analysis was explained by the existence of nano-crystallines in the zone. The induced tensile tests showed that the cracks didn't exist along the interface wave structure but inside the copper matrix, reflecting the high quality of the bonding. Ref Fig. 11 for microstructure images at the interface of the welded joint.

3. Discussion

The following dissimilar material combinations are reported to be successfully joined by explosive welding: -
a) Copper-Iron; b) Titanium-Aluminium; c) Titanium-Magnesium; d) Aluminium-Mild steel; e) Steel-Aluminium alloy; f) Zirconuim based composite-Aluminium; g) Titanium-Q235 steel; h) Titanium alloy-copper; i) Tentalum-Q235 steel; j) Copper-aluminium; k) Copper-Low carbon steel; l) Aluminum-Iron; m) Copper-Stainless steel. Some innovative methods in explosive welding that are useful for manufacturing many plates at a time are tried out. In one approach, colloid water is used as a cover for explosives. Using colloid water increases energy efficiency while decreasing dust and noise pollution. From the comparison of the welding energy and interface parameters of welded composites with and without the application of interlayer, it is found that the usage of interlayers redistributes energy that, in turn, boosts energy utilisation efficiency. Weldability, parameter selection, and the quality of explosive welded junctions are important parameters associated with explosive welding. Findings from the numerical simulation methods reveal that numerical techniques are mature and can predict the actual welding results with minimum errors.

4. Conclusion

A mini literature survey on explosive welding of dissimilar metals is presented in the paper. Due to metallurgical bonding, explosive welding appears to be a promising field for joining dissimilar metals that are otherwise difficult to join by conventional welding techniques.

References

[1] Zijun Chen et al., “Experimental and Numerical Investigation on Fabricating Multiple Plates by an Energy Effective Explosive Welding Technique,” *Journal of Materials Research and Technology*, vol. 14, pp. 3111-3122, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[2] Davide Campanella, Gianluca Buffa, and Livan Fratini, “A Two Steps Lagrangian–Eulerian Numerical Model for the Simulation of Explosive Welding of Three Dissimilar Materials Joints,” *CIRP Journal of Manufacturing Science and Technology*, vol. 35, pp. 541-549, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[3] Ming Yang et al., “Microstructure Development during Explosive Welding of Metal Foil：Morphologies, Mechanical Behaviors And Mechanisms,” *Composites Part B: Engineering*, vol. 212, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[4] Xiaoming Wu et al., “Experimental and Numerical Approach to Titanium-Aluminum Explosive Welding,” *Materials Research Express*, vol. 8, no. 9, pp. 1-14, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[5] Xiaoming Wu et al., “Comparative Study on Welding Energy and Interface Characteristics of Titanium-Aluminum Explosive Composites with and Without Interlayer,” *Materials and Design*, vol. 197, pp. 1-16, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[6] Praveen Raj et al., “Tensile and Shear Strength Evaluation in Joining Dissimilar Plates of Mild Steel with Aluminum Alloy through Explosive Cladding Approach,” *Materials Today: Proceedings*, vol. 80, no. 3, pp. 2753-2759, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[7] G.H.S.F.L. Carvalho et al., “Explosive Welding of Aluminium to Stainless Steel,” *Journal of Materials Processing Technology*, vol. 262, pp. 340-349, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[8] G.H.S.F.L. Carvalho et al., “Formation of Intermetallic Structures at the Interface of Steel-to-Aluminium Explosive Welds,” *Materials Characterization*, vol. 142, pp. 432-442, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[9] G.H.S.F.L. Carvalho et al., “Microstructure and Mechanical Behaviour of Aluminium-Carbon Steel and Aluminium-Stainless Steel Clads Produced with an Aluminium Interlayer,” *Materials Characterization*, vol. 155, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[10] Pasqualino Corigliano et al., “Full-Field Analysis of AL/FE Explosive Welded Joints for Shipbuilding Applications,” *Marine Structures*, vol. 57, pp. 207-218, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[11] Bir Bahadur Sherpa et al., “Examination of Joint Integrity in Parallel Plate Configuration of Explosive Welded SS-Al Combination,” *Materials Today: Proceedings*, vol. 4, no. 2, pp. 1260-1267, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[12] Yusong Miao, Xiang Chen, and Hailiang Wang, “Some Applications of Interlayer Explosive Welding,” *Composite Interfaces*, vol. 29, no. 4, pp. 345-360, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[13] Jianrui Feng et al., “Formation of Bonding Interface in Explosive Welding - A Molecular Dynamics Approach,” *Journal of Physics: Condensed Matter*, vol. 31, no. 41, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[14] Hanliang Liang et al., “Experimental and Numerical Simulation Study of Zr-Based BMG/Al Composites Manufactured by Underwater Explosive Welding,” *Journal of Materials Research and Technology*, vol. 9, no. 2, pp. 1539-1548, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[15] Yang Ming, Ma Hong-hao, and Shen Zhao-wu, "Study on Explosive Welding of Ta2 Titanium to Q235 Steel Using Colloid Water as a Covering for Explosives," *Journal of Materials Research and Technology*, vol. 8, no. 6, pp. 5572-5580, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[16] Yasir Mahmood et al., "Experimental and Numerical Investigations of Interface Properties of Ti6Al4V/CP-Ti/Copper Composite Plate Prepared by Explosive Welding," *Defence Technology*, vol. 17, no. 5, pp. 1592-1601, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[17] Zerui Sun et al., "Comparative Study of Energy Distribution and Interface Morphology in Parallel and Double Vertical Explosive Welding by Numerical Simulations and Experiments," *Materials and Design*, vol. 195, pp. 1-26, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[18] Ming Yang et al., "Dissimilar Material Welding of Tantalum Foil and Q235 Steel Plate Using Improved Explosive Welding Technique," *Materials and Design*, vol. 186, pp. 1-12, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[19] Ivan Bataev et al., "Towards Better Understanding of Explosive Welding by Combination of Numerical Simulation and Experimental Study," *Materials and Design*, vol. 169, pp. 1-16, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[20] Ali Arab et al., "Joining AlCoCrFeNi High Entropy Alloys and Al-6061 by Explosive Welding Method," *Vacuum*, vol. 174, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[21] Shaoning Jiang et al., "Interfacial Characterization of Dissimilar-Metals Bonding between Vanadium Alloy and Hastelloy X Alloy by Explosive Welding," *Journal of Nuclear Materials*, vol. 539, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[22] R. Mendes, J.B. Ribeiro, and A. Loureiro, "Effect of Explosive Characteristics on the Explosive Welding of Stainless Steel to Carbon Steel in Cylindrical Configuration," *Materials and Design*, vol. 51, pp. 182-192, 2013. [CrossRef] [Google Scholar] [Publisher Link]

[23] V.I. Lysak, and S.V. Kuzmin, "Energy Balance During Explosive Welding," *Journal of Materials Processing Technology*, vol. 222, pp. 356-364, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[24] Bogumił Wronka, "Testing of Explosive Welding and Welded Joints: Joint Mechanism and Properties of Explosive Welded Joints," *Journal of Materials Science*, vol. 45, pp. 4078-4083, 2010. [CrossRef] [Google Scholar] [Publisher Link]

[25] S.Y. Chen et al. "Atomic Diffusion Behavior in Cu-Al Explosive Welding Process," *Journal of Applied physics*, vol. 113, no. 4, 2013. [CrossRef] [Google Scholar] [Publisher Link]

[26] Moubin Liu, Zhilang Zhang, and Dianlei Feng, "A Density-Adaptive SPH Method with Kernel Gradient Correction for Modeling Explosive Welding," *Computational Mechanics*, vol. 60, pp. 513-529, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[27] S.V. Gladkovsky, S.V. Kuteneva, and S.N. Sergeev, "Microstructure and Mechanical Properties of Sandwich Copper/Steel Composites Produced by Explosive Welding," *Materials Characterization*, vol. 154, pp. 294-303, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[28] C. Choi et al., "A New Concept of Universal Substitutive Explosive Welding," *Materials and Design*, vol. 115, pp. 393-403, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[29] Ming Yang et al., "Microstructure and Mechanical Properties of Al-Fe Meshing Bonding Interfaces Manufactured by Explosive Welding," *Transactions of Nonferrous Metals Society of China*, vol. 29, no. 4, pp. 680-691, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[30] Yuxin Wang et al. "Fabrication of a Thick Copper-Stainless Steel-Clad Plate for Nuclear Fusion Equipment by Explosive Welding," *Fusion Engineering and Design*, vol. 137, pp. 91-96, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[31] Ahmet Durgutlu, Behçet Gülenç, and Fehim Findik, "Examination of Copper/Stainless Steel Joints Formed by Explosive Welding," *Materials and Design*, vol. 26, no. 6, pp. 497-507, 2005. [CrossRef] [Google Scholar] [Publisher Link]

[32] Heng Zhang et al, "Microstructure and Mechanical Properties Investigations of Copper-Steel Composite Fabricated by Explosive Welding," *Materials Science and Engineering: A*, vol. 731, pp. 278-287, 2018. [CrossRef] [Google Scholar] [Publisher Link]