Chapter

Explosive Welding Process to Clad Materials with Dissimilar Metallurgical Properties

Bir Bahadur Sherpa and Reetu Rani

Abstract

Explosive welding is a solid-state process, which is an advanced form of joining two metal plates with dissimilar metallurgical properties, irrespective of the differences in physical and chemical properties. In this process, high pressure of explosive is used to accelerate one metal plate over another to form the bimetallic product. The pressure needs to be sufficiently high and for enough length of time to achieve inter-atomic bonds. During the explosive welding process, a jetting phenomenon occurs at the collision point which cleans the top oxide layer over metals and leaves the virgin surfaces that help in the joining process. The metals are joined without losing their pre-bonded properties with higher bond strengths than the strength of the weaker parent material. There are various critical factors such as explosive type, mass of explosive, stand-off distance, type of plate material, velocity of detonation etc. which affect the bond quality. Researchers mainly play with all these parameters to bring out the best characteristics of the bimetallic product that can be used for the desired applications such as heat exchanger, pressure vessels etc.

Keywords: bond strength, dissimilar materials, detonation velocity, explosive welding, metallurgical properties

1. Introduction

Welding is a process of joining two materials together through pressure, heat and sometimes with the addition of filler materials. The important condition for any welding technique is that the two surfaces that need to be joined should be cleaned and uncontaminated. Moreover, if the two surfaces are brought together in such a way that the surfaces exchange the outer orbit of the valence electrons and form interatomic bonds, the weld formed will be very strong in terms of mechanical properties. But this kind of bond formation is not possible through conventional means. In most of the welding techniques melting is involved in joining the two components. There are also some welding processes such as solid-state welding processes where heat required is below the melting point of the base material being welded and therefore, no melting is observed during joining for example ultrasonic welding [1, 2], friction welding [3–5], cold welding [6], explosive welding [7–10] and diffusion welding [11, 12]. All of the welding methods have some advantages and disadvantages in their particular field and are applied as per the need of the applications. In the current world, there is an increasing trend of using dissimilar material combinations for various applications such as automobile, shipbuilding, military, aerospace and oil industries etc. The bi-metallic product takes the mechanical advantage of both the materials such as wear resistance, corrosion resistance, high tensile strength and lightweight. To meet such requirements many researchers are extensively working in this field to produce such combinations. In which explosive welding is considered as one of the potential welding technique and is gaining more attention due to its vast features as mentioned [13, 14]. Explosive welding is one of the solid-state welding processes in which explosive energy is used to create a high-velocity impact collision between the two plates to be joined. The process can join a wide area of non-compatible material combination irrespective of the difference in mechanical and chemical properties and which cannot be joined by any other conventional means. It is a surface bond welding, which provides a strong metallurgical bond at the molecular level and provides strength higher than the base materials [15]. There are various applications of explosive welding products such as in cryogenic pressure vessels [16], scram jet engine components [17], shipbuilding application [18].

2. Working principle of explosive welding

In the explosive welding process, the explosive is used as a source of energy to accelerate one of the metal plates into another. **Figure 1a** shows the initial set-up of the explosive welding process showing the two plates i.e. base plate which is kept stationary and the movable flyer plate is kept at a particular calculated distance called stand-off distance. The explosive box is placed with a buffer sheet over the plates. This buffer sheet protects the flyer plate from damage due to explosion. To initiate the main explosive detonator is used, which is placed above explosive. **Figure 1b** shows the schematic diagram after the detonation of explosive has initiated in the explosive welding process. Here we can observe the collision point, where the two plates collide and the bond formation occurs. Along with this jetting phenomenon is witnessed which is one of the most important criteria and also an essential condition for bond formation. Jetting occurs during an oblique collision at the collision point, in which it cleans the mating surfaces and Leaves behind a virgin surface free from oxide layers and contaminants. This helps to interact two mating materials at the atomic level when subjected to high impact pressure waves arising from the explosion effects. This process is capable of joining large surface area due to its ability to distribute high energy density. Explosive welding can be basically

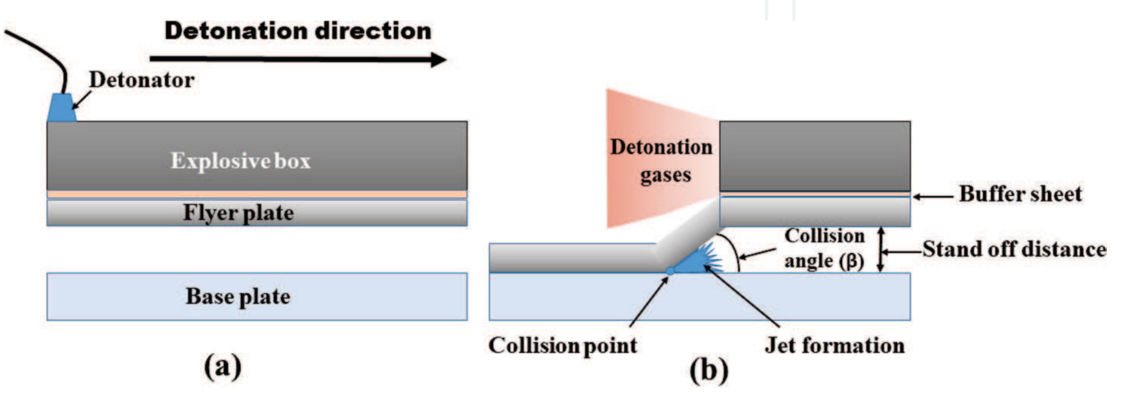

Figure 1.
Schematic diagram of explosive welding process in parallel set-up, a) initial set-up, b) after the explosion has initiated.

defined in two steps; first jet phenomenon occurs and cleans up the oxide layers and second, the high impact pressure forces the mating surfaces into such intimate contact that they meet at the interatomic level and results in strong metallurgical bond.

2.1 Plastic deformation in explosive welding process

In explosive welding process due to detonation effect of explosive many critical phenomena occur such as release of large gas product i.e. explosion, high impact collision between mating surfaces, high temperature, generation of heat, plastic deformation in the metal plates, pressure generation, jetting and bonding occurs for a very short period of time i.e. microseconds [19–21]. Out of these, plastic deformation that occurs at the weld interface due to high impact pressure is considered as one of the important factor responsible for good bond formation. Pastic deformation in explosive welding process occurs when pressure at the collision front overcomes the yield strength of the materials. Through plastic deformation an intimate contact is formed where the two mating surfaces are brought too close together that atomic reaction occurs between the mating surfaces [22–24]. Plastic deformation can be examined using visioplastic methods without disturbing the original properties of materials. The most distinctive form of plastic deformation is the wave formation in explosive welding [25]. Occurrence of high plastic deformation of the mating surfaces lead to grain refinement [26]. Difference in grain size adjacent to weld interface is observed due to severe plastic deformation [27]. Various researchers have witnessed high hardness value at the weld interface of explosively welded specimens in microhardness examination study. It was mainly attributed to intense plastic deformation developed across the weld interface. The level of plastic deformation in explosively welded specimens decrease gradually with increase in distance from the weld interface [28–30].

2.2 Types of experimental set-up

There are two types of explosive welding set-up i.e. parallel and the inclined set-up [31]. **Figure 1** shows the parallel set-up where the two plates are placed parallel to each other. This kind of configuration is used for joining large and thick plates. While the inclined set-up is shown in **Figure 2** in which flyer plates are inclined at a particular angle (α). This kind of configuration is generally applied for joining small and thin plates.

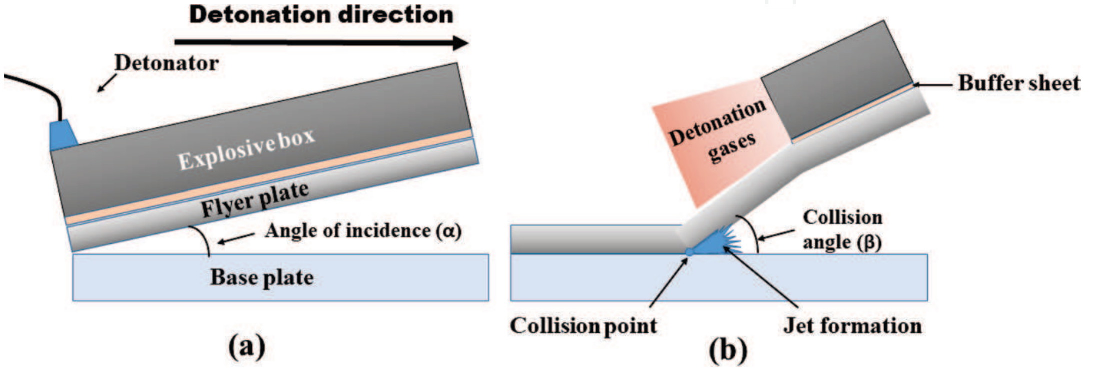

Figure 2.
Schematic diagram of explosive welding process in inclined set-up a) initial set-up, b) after the explosion has initiated.

2.3 Terminology used in explosive welding

Base plate: It is the one which is placed at the open ground or at the anvil. This is kept stationary and is the one on which the cladding is performed. Both the base plate and the flyer plate are cleaned thoroughly and polished gently before welding.

Flyer plate: It is the one which is placed above the base plate and during collision this plate hits onto the base plate. The selection of flyer plate and base plate is done on the basis of mass per unit area, whoever is less is placed as flyer plate. As compared to base plate it has the lowest density as well as tensile strength.

Stand-off distance: It is the one which maintains the distance between the flyer plate and the base plate. Stand-off distance helps the flyer plate to accelerate and acquire the required impact velocity to generate jetting. Apart from this, it also provides the exit path to the jet and the air formed between the flyer and base plate during the collision. In general stand-off distance is kept half or equal to the thickness of flyer plate.

Buffer sheet: This sheet is placed over the flyer plate. It is made up of rubber or PVC. The main role of this sheet is to protect the flyer plate from damage which can occur during collision due to explosion effects.

Explosive box: It is placed over the metal plates to be welded. This acts as a source of energy which provides the required forces to weld the materials. Explosive can be used as powder, slurry or sheet form which is spread over the buffer sheet uniformly.

Detonator: This is placed at the top of the explosive box. The main function of the detonator is to help in initiating the main explosive. The detonator is detonated with the help of dynamo placed at some distance from the trial site.

3. Different parameters affecting the explosive welded products

There are various parameters which influence the final product of the explosive welding process. Therefore, careful control of welding parameters is very critical. The criteria for selection of the welding parameters depends upon the mechanical properties of the matting surfaces [32, 33]. Many researchers change the magnitude of these parameters by playing with the different parameters such as detonation velocity, stand-off distance, explosive type etc. The various process parameters are discussed below.

Explosive: In explosive welding, controlled energy of explosive is used to accelerate the flyer plate and help to impact on to the base plate, to produce a strong metallurgical bond. Explosive is generally characterized by their velocity of detonation (VoD) and density. In most of the engineering materials, the velocity of sound is between 4.5–6 km/s and most of the common explosives have VoD ranging between 6 and 7 km/s. Therefore, high VoD in explosive welding is not preferable as in case of joining the weld will get dismantle or in some cases it will destroy the material. In explosive welding, VoD is mostly applied in the range of 2–3 km/s to obtain a uniform detonation across the joining metal plates [32–34]. Many researchers have worked with different explosives to obtain a sound weld. A. Loureiro et al. have studied the effect of explosive mixture i.e. emulsion explosive with two different sensitizers i.e. hollow glass microspheres (HGMS) and expanded polystyrene spheres (EPS) on the weld interface of copper-aluminum. They observed improved surface using HGMS and higher wave amplitude was witnessed by employing EPS [35]. Similarly, many works related to explosive optimization have been done in the past in explosive welding [36, 37]. Recently Sherpa et al. have developed a low velocity of detonation (VoD) explosive welding process (LVEW) in which VoD was less than 2 km/s and obtained a sound joint [38]. Some of the explosives used for explosive welding process are shown in **Table 1**.

Stand-off distance: Stand-off distance is normally selected based on the thickness of the flyer plate and the explosive parameters. It is one of the critical parameters which influence the bond quality. Stand-off distance is selected basically to provide necessary dynamic bend angle and the impact velocity for proper bond to form. Durgutlu et al. studied the effect of stand-off distance on copper and stainless steel bond. They observed an increase in wavelength and amplitude of the wave with an increase in stand-off distance. As well as hardness value across the weld interface also increased with increasing stand-off distance [48]. M.R. Jandaghi et al. studied the effect of stand-off distance on the copper and aluminum interface. They observed that with an increase in stand-off distance, plastic deformation, kinetic energy at the collision point and as well as the melting increases at the weld interface which lead to the increase in corrosion rate [49].

Flyer plate velocity: It is the velocity at which the flyer plate strike into the base plate after the detonation has started. To obtain good bonding, the flyer plate velocity should be in the described limits i.e. between the minimum and maximum flyer velocity. Experimenting with flyer plate velocity above defined range can lead to certain defects such as melting zone, cracks, brittle phases, bend and damage of flyer plate [50, 51].

Collision angle (β): It is the angle formed between the flyer plate and the base plate during the collision process. Collision angle should be selected very carefully to meet the requirement of the bonding parameters. If the angle is selected below the critical collision angle, a jet-less phenomenon will occur and if β is chosen above defined limit it will cause entrapment of jet [33, 52].

Collision velocity (Vc): It is the velocity with which collision point moves along the area being welded. For proper welding to occur there should be some plastic flow ahead of the collision point. Hence, the collision point velocity should be less than the sonic velocity in the metals. The smooth interface is observed at lower collision velocity while the wavy interface is observed at higher collision velocity at the weld interface. Increasing the collision velocity may also increase the chances of melt pockets across the weld interface [20].

3.1 Weldability window

The condition that should satisfy for proper bonding to take place is defined by weldability window. Detailed view with the description of weldability window is shown in **Figure 3**. It is plotted between collision angle (β) and collision velocity (Vp), where it is well defined by four different lines [50, 51]. The first limit is placed at the rightmost side in which formation of the jet at the collision point

Explosive	Velocity of detonation (m/s)	Density (kg/m^3)	Ref.
ANFO (ammonium nitrate with fuel oil)	2300–2800	650–700	[39, 40]
SEP	7000	1300	[41, 42]
Emulsion explosive	2200	1150	[43]
Elbar-5	3000–3800	700–800	[44–46]
PAVEX	2000–3000	530	[37, 47]

Table 1.
Different explosives used in the explosive welding process.

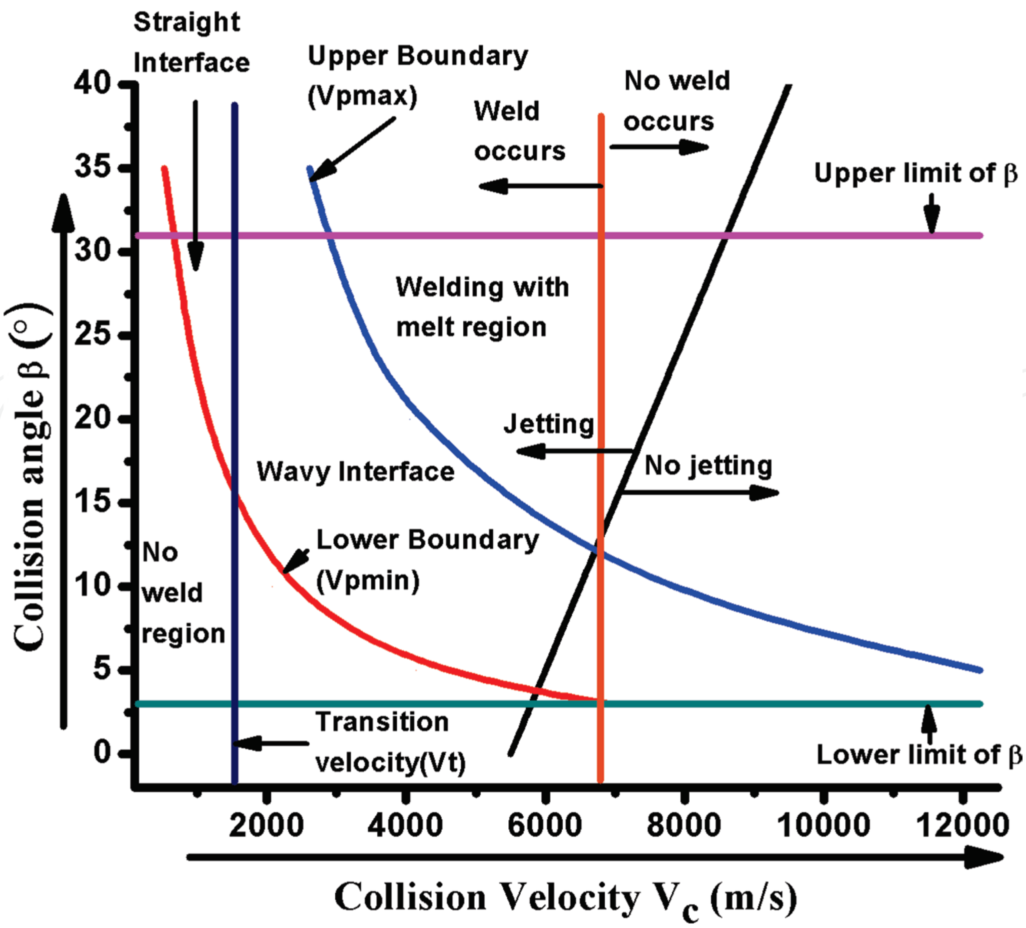

Figure 3.
Weldability window concepts for explosive welding process.

is considered. As jetting is one of the important criteria in explosive welding. Abrahamson [53] linked welding velocity with the collision angle β as shown in Eq. 1 for the first limit. The second limit is placed at the left side of the weldability window which is related to the formation of wavy morphology at the weld interface. Cowan et al. introduced Reynolds number for describing the laminar and turbulent flow [20] as shown in Eq. 2. The third limit is related to the minimum flyer plate velocity (Vpmin) which ensure that the impact pressure developed at the collision point exceeds the yield strength of the materials. Lower boundary equation was developed for third limit as shown in Eq. 3. While the fourth limit corresponds to the maximum flyer plate velocity (Vpmax) which maintains the required impact pressure below the value so that the melting does not occur at the weld interface. To avoid melting Eq. 4 was developed by Wittman [50]. Therefore, in order to obtain good bond, selection of welding parameters should be with in the described limits of weldability window [20, 34, 50, 54].

$$V_c = \frac{\beta}{10} + 5.5 \tag{1}$$

$$R_t = \frac{(\rho_a + \rho_b) V_c^2}{2(H_a + H_b)} \tag{2}$$

Where ρ_a & ρ_b : ρ Density of flyer plate and base plate

H_a & H_b : Hardness value of flyer plate and base plate

R_t : Reynolds number

$$\sin\beta = k\sqrt{\frac{H_V}{\rho V_C^2}} \tag{3}$$

Where H_V : Vickers hardness no.

P: Density of the material

K: Constant value

Take value 0.6: Plate surface is very clean

1.2: Imperfectly cleaned plate surface

$$\sin\left(\frac{\beta}{2}\right) = \frac{1}{2N}\frac{\left(T_m C_o\right)^{1/2}}{V_c^2}\left(\frac{KC_pC_b}{\rho h}\right)^{1/4} \tag{4}$$

Where Tm: Melting temperature,

Cp: Specific heat capacity,

K: Thermal conductivity,

h: Thickness of flyer plate,

Cb: Bulk sound speed

3.2 Different materials combination joined by explosive welding

Explosive welding process is capable of joining similar and dissimilar material combinations irrespective of the difference in physical and chemical properties.

Similar materials combinations			
Material combination	**Welding configuration**	**Explosive used**	**Ref.**
Al alloy -Al alloy	Tube	PETN	[55]
Steel-steel plates	Parallel set-up	Elbar-5	[56–58]
Steel-steel	Cylindrical	Emulsion explosive/ ANFO	[36]
Copper-copper	—	—	[59]
Copper-copper alloy	Parallel set-up	Powder emulsion explosive	[43]
Dissimilar materials combinations			
Material combination	**Welding configuration**	**Interlayer used**	**Ref.**
Titanium and magnesium alloy AZ31	Inclined set-up (Under water)	Thin AZ31	[60]
Aluminum to stainless steel	Parallel set-up	Cu, Ti & Ta	[16]
C103 niobium alloy and C263 nimonic alloy	Parallel set-up	Not used	[17]
Titanium and aluminum	Parallel set-up	Not used	[61, 62]
Aluminum and copper	Parallel set-up	Al5052, Cu & SS304	[63]
Sn and Cu	Inclined set-up (Under water)	Not used	[41]
Al and Mg alloy	Parallel set-up	Not used	[64, 65]
Aluminum and carbon steel and Aluminum-stainless steel	Parallel set-up	Aluminum AA1050	[66]
Aluminum and copper	Parallel set-up	Not used	[67–69]
Aluminum and steel	Parallel set-up	Not used	[70–73]

Table 2.
Material combinations joined using explosive welding process.

The various material combinations joined using explosive welding process i.e. similar and dissimiliar combinations are given in **Table 2.** In this process, different authors have also used the concept of the interlayer to minimize the kinetic energy loss as well as the formation of meting zone at the weld interface.

3.3 Important points in explosive welding process

Following points should be considered for explosive welding process to produce a strong metallurgical bond.

- The pressure generated at the collision point should be enough in magnitude so as to exceed the dynamic elastic limits of the mating materials in order to ensure that deformation has occurred at the weld interface [74].
- Stand-off distance should be calculated properly to ensure that the flyer plate can accelerate to the required impact velocity needed for good bonding. Use of high stand-off distance will result in edge instability and can also affect the bonding quality [74, 75].
- The explosive used should provide sufficient energy in order to accelerate the flyer plate to the preferred velocity. The high detonation velocity of explosive should also be avoided as it can lead to spalling and damage of the joining materials. Therefore, the velocity of detonation must be less than 120% of the sonic velocity of the materials being welded [76, 77].
- Flyer plate velocity (Vp) and collision velocity (Vc) should be less than the velocity of sound in either of the participant material. In order that the reflected stress waves do not interfere with the incident wave at the collision point [19, 78, 79].

4. Conclusions

a. Explosive welding is a solid-state welding process capable of joining any material combination which cannot be joined by any other conventional means. It can join materials irrespective of the difference in chemical and physical properties.

b. Jetting is one of the important criteria in explosive welding process which removes the oxide layers present at the mating surfaces. This jetting freely exit at the corners of the joint if the welding parameters are selected properly else if it gets trapped will result in the defects.

c. Plastic deformation is caused due to high impact pressure and is considered as one of the important condition for joint formation in explosive welding process. Plastic deformation leads to the intimate contact of the two mating surfaces and results in strong metallurgical bond formation. It is responsible for grain refinement as well as increase in hardness value across the weld interface of explosively welded samples.

d. To obtain a good bond, various welding parameters such as type of explosive, stand-off distance, flyer plate velocity, and collision velocity need to be selected very carefully. As these parameters will directly or indirectly affect the product of the weld.

e. During explosive welding, there are various defects which are uncounted especially intermetallic formation at the weld interface. To minimize these defects researchers are using different approaches such as interlayer concept and low velocity of detonation explosives which will reduce the kinetic energy loss at the collision point.

f. In the explosive welding process, we can join two materials and take the mechanical advantage of both the materials in the final product. Due to its enormous advantages, it has great application in the field of aerospace, automobiles, oil industries, defense and ship industries.

Acknowledgements

I would like to deeply acknowledge Dr. Pal Dinesh Kumar, Scientist-F, Joint director (MEMWD), Terminal Ballistics Research Laboratory (TBRL-DRDO) and Dr. Sachin Tyagi, Sr. Scientist, Central Scientific Instruments Organization (CSIO-CSIR), Chandigarh, India for their motivation and guidance during the whole journey.

Conflict of interest

The authors declare no conflict of interest.

Author details

Bir Bahadur Sherpa[1,2*] and Reetu Rani[1,2]

1 Academy of Scientific and Innovative Research (AcSIR), Ghaziabad-201002, India

2 CSIR-Central Scientific Instruments Organisation (CSIO), Sector-30, Chandigarh-160030, India

*Address all correspondence to: sherpa7419@gmail.com

References

[1] Benatar, A. and T.G. Gutowski, *Ultrasonic welding of peek graphite APC-2 composites.* Polymer Engineering & Science, 1989. **29**(23): p. 1705-1721.

[2] Watanabe, T., H. Sakuyama, and A. Yanagisawa, *Ultrasonic welding between mild steel sheet and Al–Mg alloy sheet.* Journal of Materials Processing Technology, 2009. **209**(15-16): p. 5475-5480.

[3] Meshram, S., T. Mohandas, and G.M. Reddy, *Friction welding of dissimilar pure metals.* Journal of Materials Processing Technology, 2007. **184**(1-3): p. 330-337.

[4] Uday, M., et al., *Advances in friction welding process: a review.* Science and technology of Welding and Joining, 2010. **15**(7): p. 534-558.

[5] Dey, H., et al., *Joining of titanium to 304L stainless steel by friction welding.* Journal of Materials Processing Technology, 2009. **209**(18-19): p. 5862-5870.

[6] Lu, Y., et al., *Cold welding of ultrathin gold nanowires.* Nature nanotechnology, 2010. **5**(3): p. 218-224.

[7] Akbari-Mousavi, S., L. Barrett, and S. Al-Hassani, *Explosive welding of metal plates.* Journal of materials processing technology, 2008. **202**(1-3): p. 224-239.

[8] Mousavi, S.A. and S. Al-Hassani, *Finite element simulation of explosively-driven plate impact with application to explosive welding.* Materials & Design, 2008. **29**(1): p. 1-19.

[9] Wronka, B., *Testing of explosive welding and welded joints: joint mechanism and properties of explosive welded joints.* Journal of materials science, 2010. **45**(15): p. 4078-4083.

[10] Mousavi, A.A. and S. Al-Hassani, *Numerical and experimental studies of the mechanism of the wavy interface formations in explosive/impact welding.* Journal of the Mechanics and Physics of Solids, 2005. **53**(11): p. 2501-2528.

[11] Aydın, K., Y. Kaya, and N. Kahraman, *Experimental study of diffusion welding/bonding of titanium to copper.* Materials & Design, 2012. **37**: p. 356-368.

[12] Arik, H., et al., *Weldability of Al4C3–Al composites via diffusion welding technique.* Materials & design, 2005. **26**(6): p. 555-560.

[13] Blazynski, T.Z., *Explosive welding, forming and compaction*. 2012: Springer Science & Business Media.

[14] Crossland, B., *Development of exlosive welding and its application in engineering.* Metals materials, 1971. **5**(12): p. 402-413.

[15] Sherpa, B.B., et al., *Explosive Welding of Al-MS Plates and its Interface Characterization.* Explosion Shock Waves and High Strain Rate Phenomena, 2019. **13**: p. 128-133.

[16] Aceves, S.M., et al., *Comparison of Cu, Ti and Ta interlayer explosively fabricated aluminum to stainless steel transition joints for cryogenic pressurized hydrogen storage.* International Journal of Hydrogen Energy, 2015. **40**(3): p. 1490-1503.

[17] Mastanaiah, P., et al., *An investigation on microstructures and mechanical properties of explosive cladded C103 niobium alloy over C263 nimonic alloy.* Journal of Materials Processing Technology, 2014. **214**(11): p. 2316-2324.

[18] Corigliano, P., et al., *Full-field analysis of AL/FE explosive welded joints for shipbuilding applications.* Marine Structures, 2018. **57**: p. 207-218.

[19] Crossland, B., F. McKee, and A. Szecket, *An experimental investigation of explosive welding parameters*, in *High-Pressure Science and Technology*. 1979, Springer. p. 1837-1845.

[20] Cowan, G., O. Bergmann, and A. Holtzman, *Mechanism of bond zone wave formation in explosion-clad metals.* Metallurgical and Materials Transactions B, 1971. **2**(11): p. 3145-3155.

[21] Wang, Y., et al., *Numerical simulation of explosive welding using the material point method.* International Journal of Impact Engineering, 2011. **38**(1): p. 51-60.

[22] Bondar, M. and V. Ogolikhin, *Plastic deformation in the joint zone with cladding by explosion.* Combustion explosion and shock waves, 1985. **21**(2): p. 266-270.

[23] Kriventsov, A. and V. Sedykh, *The role of plastic deformation of metal in the weld zone in explosion welding'.* Fiz Khim Obrab Mater, 1969. **1**: p. 132-141.

[24] Krupin, A., et al., *Explosive Deformation of Metals.* Metallurgiya, Moscow, 1975.

[25] Gul'Bin, V. and A. Kobelev, *Plastic deformation of metals in explosion welding.* Welding international, 1999. **13**(4): p. 306-309.

[26] Borchers, C., et al., *Microstructure and mechanical properties of medium-carbon steel bonded on low-carbon steel by explosive welding.* Materials & Design, 2016. **89**: p. 369-376.

[27] Sabirov, I., M.Y. Murashkin, and R. Valiev, *Nanostructured aluminium alloys produced by severe plastic deformation: New horizons in development.* Materials science and engineering: A, 2013. **560**: p. 1-24.

[28] Gloc, M., et al., *Microstructural and microanalysis investigations of bond titanium grade1/low alloy steel st52-3N obtained by explosive welding.* Journal of Alloys and Compounds, 2016. **671**: p. 446-451.

[29] Bazarnik, P., et al., *Mechanical and microstructural characteristics of Ti6Al4V/AA2519 and Ti6Al4V/AA1050/AA2519 laminates manufactured by explosive welding.* Materials & Design, 2016. **111**: p. 146-157.

[30] Sherpa, B.B., et al., *Neuro-Fuzzy Technique for Micro-hardness Evaluation of Explosive Welded Joints.* Transactions of the Indian Institute of Metals, 2020. **73**(5): p. 1287-1299.

[31] Sherpa, B.B., et al., *Study of the Explosive Welding Process and Applications*, in *Advances in Applied Physical and Chemical Sciences-A Sustainable Approach*. 2014, Krishi Sanskriti: New Delhi. p. 33-39.

[32] Blazynsky, T., *Explosive forming, welding and compaction*. 1983, Elsevier Science, New York.

[33] Crossland, B. and J. Williams, *Explosive welding.* Metallurgical Reviews, 1970. **15**(1): p. 79-100.

[34] Abrahamson, G.R., *Permanent periodic surface deformations due to a traveling jet.* Journal of Applied Mechanics, 1961. **83**: p. 519-528.

[35] Loureiro, A., et al., *Effect of explosive mixture on quality of explosive welds of copper to aluminium.* Materials & Design, 2016. **95**: p. 256-267.

[36] Mendes, R., J. Ribeiro, and A. Loureiro, *Effect of explosive characteristics on the explosive welding of stainless steel to carbon steel in cylindrical configuration.* Materials & Design, 2013. **51**: p. 182-192.

[37] Manikandan, P., et al., *Control of energetic conditions by employing interlayer of different thickness for*

explosive welding of titanium/304 stainless steel. Journal of materials processing technology, 2008. **195**(1-3): p. 232-240.

[38] Bahadur Sherpa, B., et al., *Low Velocity of Detonation Explosive Welding (LVEW) Process for Metal Joining.* Propellants, Explosives, Pyrotechnics. 2020;**45**(10):1554-1565

[39] Hanliang, L., et al., *Joining of Zr60Ti17Cu12Ni11 bulk metallic glass and aluminum 1060 by underwater explosive welding method.* Journal of Manufacturing Processes, 2019. **45**: p. 115-122.

[40] Arab, A., et al., *Joining AlCoCrFeNi high entropy alloys and Al-6061 by explosive welding method.* Vacuum, 2020. **174**: p. 109221.

[41] Tanaka, S., A. Mori, and K. Hokamoto, *Welding of Sn and Cu plates using controlled underwater shock wave.* Journal of Materials Processing Technology, 2017. **245**: p. 300-308.

[42] Mori, A., M. Nishi, and K. Hokamoto, *Underwater shock wave weldability window for Sn-Cu plates.* Journal of Materials Processing Technology, 2019. **267**: p. 152-158.

[43] Tao, C., et al., *Microstructure and mechanical properties of Cu/CuCrZr composite plates fabricated by explosive welding.* Composite Interfaces, 2020: p. 1-12.

[44] Kaya, Y. and G. Eser, *Production of ship steel—titanium bimetallic composites through explosive cladding.* Welding in the World, 2019. **63**(6): p. 1547-1560.

[45] Durgutlu, A., B. Gülenç, and F. Findik, *Examination of copper/stainless steel joints formed by explosive welding.* Materials & design, 2005. **26**(6): p. 497-507.

[46] Kahraman, N., B. Gülenç, and F. Findik, *Joining of titanium/stainless steel by explosive welding and effect on interface.* Journal of Materials Processing Technology, 2005. **169**(2): p. 127-133.

[47] Manikandan, P., et al., *Underwater explosive welding of thin tungsten foils and copper.* Journal of Nuclear Materials, 2011. **418**(1-3): p. 281-285.

[48] Durgutlu, A., H. Okuyucu, and B. Gulenc, *Investigation of effect of the stand-off distance on interface characteristics of explosively welded copper and stainless steel.* Materials & Design, 2008. **29**(7): p. 1480-1484.

[49] Jandaghi, M.R., et al., *Microstructural Evolutions and its Impact on the Corrosion Behaviour of Explosively Welded Al/Cu Bimetal.* Metals, 2020. **10**(5): p. 634.

[50] Wittman, R. *Use of explosive energy in manufacturing metallic materials of new properties*. in *Proceedings of the Second International Symposium, Marianski Lazne, Czechoslovakia*. 1973.

[51] Cowan, G.R. and A.H. Holtzman, *Flow configurations in colliding plates: explosive bonding.* Journal of applied physics, 1963. **34**(4): p. 928-939.

[52] Vaidyanathan, P. and A. Ramanathan, *Computer-aided design of explosive welding systems.* Journal of materials processing technology, 1993. **38**(3): p. 501-516.

[53] Abrahamson, G.R., *Permanent periodic surface deformations due to a traveling jet.* journal of applied mechanics, 1961. **28**(4): p. 519-528.

[54] Zakharenko, I. and B. Zlobin, *Effect of the hardness of welded materials on the position of the lower limit of explosive welding.* Combustion, Explosion and Shock Waves, 1983. **19**(5): p. 689-692.

[55] Grignon, F., et al., *Explosive welding of aluminum to aluminum: analysis, computations and experiments.*

International Journal of Impact Engineering, 2004. **30**(10): p. 1333-1351.

[56] Acarer, M., B. Gülenç, and F. Findik, *Investigation of explosive welding parameters and their effects on microhardness and shear strength*. Materials & design, 2003. **24**(8): p. 659-664.

[57] Kacar, R. and M. Acarer, *Microstructure–property relationship in explosively welded duplex stainless steel–steel.* Materials Science and Engineering: A, 2003. **363**(1-2): p. 290-296.

[58] Kacar, R. and M. Acarer, *An investigation on the explosive cladding of 316L stainless steel-din-P355GH steel.* Journal of Materials Processing Technology, 2004. **152**(1): p. 91-96.

[59] Rybin, V., E. Ushanova, and N.Y. Zolotorevskii, *Features of misoriented structures in a copper-copper bilayer plate obtained by explosive welding.* Technical Physics, 2013. **58**(9): p. 1304-1312.

[60] Habib, M.A., et al., *Cladding of titanium and magnesium alloy plates using energy-controlled underwater three layer explosive welding.* Journal of Materials Processing Technology, 2015. **217**: p. 310-316.

[61] Fronczek, D., et al., *Structural properties of Ti/Al clads manufactured by explosive welding and annealing.* Materials & Design, 2016. **91**: p. 80-89.

[62] Lazurenko, D., et al., *Explosively welded multilayer Ti-Al composites: Structure and transformation during heat treatment.* Materials & Design, 2016. **102**: p. 122-130.

[63] Saravanan, S., K. Raghukandan, and K. Hokamoto, *Improved microstructure and mechanical properties of dissimilar explosive cladding by means of interlayer technique.* Archives of Civil and Mechanical Engineering, 2016. **16**: p. 563-568.

[64] Zhang, T., et al., *Microstructure evolution and mechanical properties of an AA6061/AZ31B alloy plate fabricated by explosive welding.* Journal of Alloys and Compounds, 2018. **735**: p. 1759-1768.

[65] Zhang, T.-T., et al., *Molecular dynamics simulations and experimental investigations of atomic diffusion behavior at bonding interface in an explosively welded Al/Mg alloy composite plate.* Acta Metallurgica Sinica (English Letters), 2017. **30**(10): p. 983-991.

[66] Carvalho, G., et al., *Microstructure and mechanical behaviour of aluminium-carbon steel and aluminium-stainless steel clads produced with an aluminium interlayer.* Materials Characterization, 2019. **155**: p. 109819.

[67] Kaya, Y., *Investigation of copper-aluminium composite materials produced by explosive welding.* Metals, 2018. **8**(10): p. 780.

[68] Paul, H., L. Lityńska-Dobrzyńska, and M. Prażmowski, *Microstructure and phase constitution near the interface of explosively welded aluminum/copper plates.* Metallurgical and Materials Transactions A, 2013. **44**(8): p. 3836-3851.

[69] Amani, H. and M. Soltanieh, *Intermetallic phase formation in explosively welded Al/Cu bimetals.* Metallurgical and Materials Transactions B, 2016. **47**(4): p. 2524-2534.

[70] Kaya, Y., *Microstructural, mechanical and corrosion investigations of ship steel-aluminum bimetal composites produced by explosive welding.* Metals, 2018. **8**(7): p. 544.

[71] Carvalho, G., et al., *Explosive welding of aluminium to stainless*

steel. Journal of Materials Processing Technology, 2018. **262**: p. 340-349.

[72] Sherpa, B.B., et al., *Examination of Joint Integrity in parallel plate configuration of explosive welded SS-Al combination.* Materials Today: Proceedings, 2017. **4**(2): p. 1260-1267.

[73] Sherpa, B.B., et al., *Interface Study of Explosive Welded AL-Steel Joint Using Ultrasonic Phased Array Technique*, in *31st International Symposium on Ballistics*. 2019, DEStech Publications, Inc. p. 2280-2290.

[74] Stivers, S. and R. Wittman, *Computer selection of the optimum explosive loading and weld geometry.* High Energy Rate Fabrication. University of Denver Research Institute, Colorado. 1975, 4. 2-4. 2. 16, 1975.

[75] Wylie, H. and B. Crossland. *Explosive cladding with thick flyer plates*. in *Proc. Conf. on The Use of High-Energy Rate Methods for Forming, Welding, and Compaction, Leeds*. 1973.

[76] Carpenter, S., R. Wittman, and R. Carlson, *Relationships of explosive welding parameters to material properties and geometries factors, proc. first int. conf. of the center for high energy forming, university of Denver*. 1967, June.

[77] Shribman, V. and B. Crossland. *An experimental investigation of the velocity of the flyer plate in explosive welding*. in *Second international conference of the center for high energy forming, Proceedings*. 1969.

[78] El-Sobky, H. and T. Blaznski, *Proc. 15th Int. MTDR Conf.* 1974.

[79] Findik, F., *Recent developments in explosive welding.* Materials & Design, 2011. **32**(3): p. 1081-1093.