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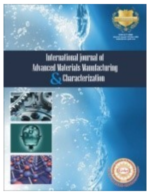

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Evaluation Of Microstructure And Mechanical Properties Of Explosively Welded Aluminium Alloy And Low Carbon Steel Plates

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ABSTRACT

In the present paper joining of aluminium alloy-AA1100 and low carbon steel (LCS) plates has been carried out using explosive welding technique. Welding parameters were optimized in order to achieve uniform and good quality welds. Optical and scanning electron microscope (SEM) were employed to observe the morphology and microstructure at the interface boundary. Mechanical properties of weld joints have been evaluated by carrying out ram tensile and hardness test. After successful joining of plates, the bonding interface had laminar morphology free from major cracks. No delamination was observed at the interface of the clad plate when subjected to chisel test. The bonding strength of the weld joint was more than the strength of weaker material.

Keywords: *Low carbon steel, AA1100, explosive welding*, *interface*

1. Introduction

Explosive welding is generally used to join a wide variety of both similar and dissimilar combinations of metals and alloys with varying physical and mechanical properties. It is a solid state metal joining process that produces a weld joint by high velocity impact, aided by controlled detonation with an explosive [1-2]. Since the welding time is very short the processes of diffusion and crystallization are not essential in explosive welding [3]. Classically explosive welding is a process in which when the metal surfaces are brought into sufficiently close contact, the valence electrons can overcome the repulsive forces and result in sharing of their orbits [4]. This would result in a cold weld through metallurgical bonding from a solid-phase process. Explosive welding has several advantages over other competing processes. There are no heat-affected zones, no diffusion and only minor melting. Any combination can be joined provided the material retains its integrity during explosion shock. As reported by Wang et al. [5] up to now, over 260 various similar and dissimilar metal and alloy combinations can be welded by using explosive welding technique. Acarer et al. [6-7] has reported papers about explosive joining of similar materials i.e. steel to steel plates and investigated their effects on microstructure, microhardness and shear strength in original and heat-treated samples. In this work, different welding interfaces (straight, wavy and continuous solidified-melted) were obtained with changing explosive welding parameters like stand-off distance, explosive loading and anvils. In addition tensile-shear and bending tests of those joints were performed and fracture samples were examined. It was shown that the bonding interface changed from a straight to a wavy structure when the explosive loading and stand-off distance were increased.

Kacar and Acarer [8] reported on the explosive cladding of 316L stainless steel-DIN-P355GH steel. In this study, 316L stainless steel and DIN-P355GH grade vessel steel were cladded by explosive welding technique. Microstructure, hardness, tensile shear strength and fracture toughness of the cladded metals were estimated. The bond interface showed a wavy morphology and hardness was also increased near the bond interface. The impact toughness of the cladded metals was also found significantly higher than that of parent plate alone. Consequently,

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mechanical properties of the low carbon steels can be increased by explosive cladding with austenitic steel. An investigation of mechanical and metallurgical properties of explosive welded aluminium-dual phase steel was performed by Acarer and Demir [9]. Dual phase steel was produced by intercritical annealing and water quenching from 1.45Mn-0.2Si-0.186C HSLA (high strength low alloy) steel. Hardness, tensile shear strength, tensile strength, toughness and microstructure of explosively welded aluminium-HSLA steel and aluminuim-dual phase steel were evaluated. Both bimetal had a straight bonding interface. It was also found that plastic deformation of dual phase steel was higher than HSLA steel near the interface. Tensile and tensile shear strength tests showed that aluminuim-dual phase steel was superior to aluminium-HSLA steel. Han et al. [10] has investigated the effect of interlayer thickness on shear deformation behavior of AA5083 aluminium alloy/SS41 steel plates manufactured by explosive welding. In this study AA5083 aluminium alloy plate and an SS41 steel plates were cladded by an explosive welding method using AA1050 aluminium alloy as an interlayer plate. Variations of the interface morphology and the shear deformation behavior depending on the interlayer thickness were investigated. It was concluded that by increasing the thickness of the interlayer, the thickness of the generated interfacial zone increased, and the maximum shear strength gradually decreased. The microstructural characteristics and mechanical properties of the explosively welded various metals and their alloys have been studied by several investigators as reviewed by Findik [11] in his paper in which he has reviewed developments in explosive welding for the last four decades. However, there is lack of information about explosive welding of aluminium alloy AA1100 to low carbon steel and effect on the bonding interface in terms of microstructure and mechanical behaviour after explosive welding. There is a need for large surface area joining of AA1100 to low carbon steel plates by explosive welding process for various industrial, military and aerospace applications. Such joining is not possible by conventional manufacturing and welding processes because of the vast difference in physical and mechanical properties of AA1100 and low carbon steel taken under study. Therefore, in the present study, incompatible metals AA1100 and LCS plates have been joined by explosive welding process and detailed characterization of weld joint has been carried out as to examine their metallurgical and mechanical properties.

2. Experimental Work

2.1 Material and Methods

The metals used under study were aluminium alloy (AA1100) having dimensions 300 x150 x 5 mm and low carbon steel (LCS) plates with dimensions 300 x150 x 25 mm. The chemical compositions of AA1100 and low carbon steel are given in Table1. AA1100 was taken as flyer plate and LCS as base plate.

***Table 1**: The chemical composition of Aluminium and Low Carbon Steel*

Chemical Composition (weight %)									
Element	Cu	Si	Mn	Zn	C	P	S	Al	Fe
AA1100 (Flyer)	0.06	0.8	0.03	0.05	-	-	-	Bal.	-
LCS (Base)	-	0.22	1.07	-	0.08	0.02	0.02	-	Bal.

2.2 Explosive welding

The explosive material used was based on Trimonite -I powder explosive and inert material was added to the explosive mix as a way to reduce the detonation velocity of the explosive. The density of the explosive material was 1.1 g cm^{-3}. Detonator along with booster charge was used to initiate the explosive. A parallel arrangement was used for the experimental set-up of explosive welding, as schematically revealed in figure 1.

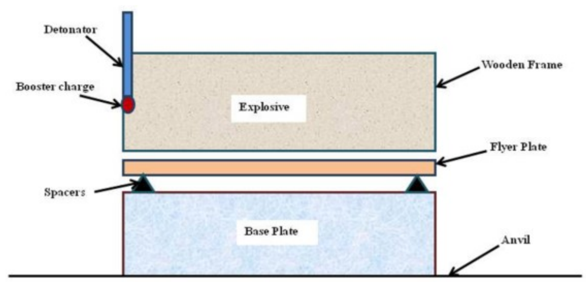


Fig. 1 Schematic illustration of experimental assembly for explosive welding

The clads were assembled in the firing area where the base/parent plate was placed directly on the flat sandy floor of the firing area and the flyer plate supported above it on small equal height collapsable metallic spacers. The gap between the flyer plate and the base plate (standoff distance) was kept 5 mm, over which distance the plate will develop a substantial portion of its terminal velocity. The main explosive mixture in powder form was poured on the cladding plate surface protected by buffer layer inside a surrounding wooden frame. Explosive type, thickness and composition were selected to yield a specific energy release so as to get acceptable weld. The explosive powder was applied in two increments with light tamping to give uniform density of the charge and care was taken that the explosive fully fills the corners and edges of the container. Initiation of the main explosive was done using a booster charge of high velocity explosive to ensure that the main charge immediately propagates at full velocity and detonator placed at the center of an edge. After firing, the clad was removed from the firing area, washed down and examined for defects.

2.3 Microstructural Characterization

Microstructure evaluation of the weld sample was carried out using optical microscope (Leica, Germany, DM 2700P) and scanning electron microscope (Carl Zeiss, USA, EVO15). Energy-dispersive X-ray analysis (EDX) was also done. The samples were fabricated from the welded plate. The sample was made flat by rough grinding on belt surfacer. Since the welded sample consist of two metallic materials having different mechanical properties, the grinding and polishing of the surface is a bit difficult. The hardness of AA1100 is lower than LCS, therefore, while grinding aluminium gets grinded easily and to greater extent as compared to LCS. Therefore, the sample was grinded using different grit size emery papers carefully by taking into account this issue. Finally, the cloth polishing of the sample was done on velvet cloth to remove the minor scratches. The polished sample was observed under optical microscope to analyze the welded interface of the two materials before and after etching. The samples were also observed in scanning electron microscope having EDX facility for revealing diffusion of atoms across the interface.

2.4 Mechanical Testing

Vicker's microhardness tester (Radical, India, RMHT201) was used for measuring the hardness distribution across the weld interface so as to examine the change in mechanical properties occurring after explosive welding. The specimen was sectioned to the required size from the joint and polished using different grades of emery papers. During the test, 100 and 300 g loads were applied with a dwell time of 15s on AA1100 and LCS respectively. For each sample, seven different measurements were taken at intervals of 150, 300, 450, 600, 750, 900 and 1050 µm from the interface and the average values are presented.

An electromechanical test machine equipped with 100 kN load cell (FIE UTE-100,) was used to evaluate the joint strength of the weld. Ram tensile test was carried out in which the specimens were prepared in accordance with MIL-J-24445A [12]. Three specimens were tested and the average value is presented.

3. Results and Discussion

The experimental results indicated that successful welding of AA1100 on LCS was achieved by explosive welding method (Figure 2a, 2b).

(a)

(b)

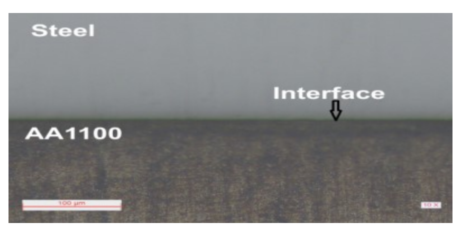
Fig 2: The plates after detonation of the explosive (a) welded plate after detonation (b) Welded plate after machining

3.1 Microstructural Analysis

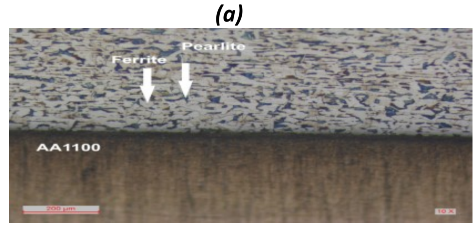
3.1.1 Optical analysis

Figure 3a shows the optical micrographs of magnified (100X) interface analyzed under optical microscope. The laminar structure was observed at the interface with smooth bonding line. The figure 3a appeared to be free of major voids or cracks.

As the sample consists of two metallic materials aluminium and steel, it is very difficult to reveal the microstructure of both the materials using a single/same etchant. Therefore, Nital solution (98 ml ethanol and 2 ml Nitric acid) was used as an etchant to reveal the microstructural features of LCS. Low carbon steel microstructure consisted of randomly oriented grains of ferrite and pearlite (Fig 3b).



(a)



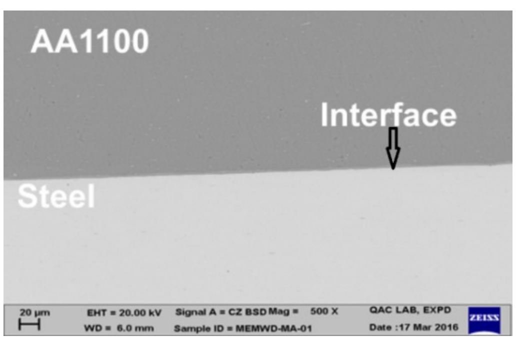
b

Figure 3: Microstructure analysis of weld interface by optical microscopy at 100X (a) Micrograph before etching displaying the laminar interface of welded sample (b) Micrograph of the welded sample after etching revealing the microstructure of LCS

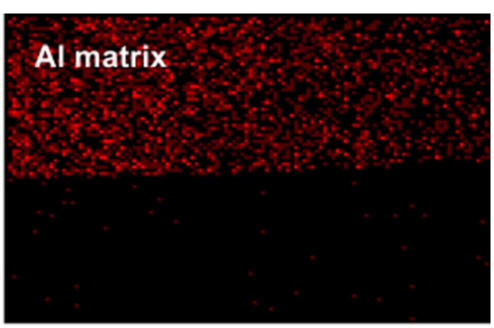
3.1.2 SEM analysis

The sample of same configuration as used for optical microscopy was prepared by grinding and polishing and analyzed by SEM. Fig 4a shows the back scattered electron image (BSI) in which aluminium appears dark and LCS as bright. SEM also corroborated optical microscopy results as interface is seen as defect free, without any major cracks or melting voids, indicating that plates were bonded over the entire surface of collision even at microscopic level. This confirms successful joining of metal plates by explosive welding process.

EDX analysis was carried to study the diffusion of elements i.e. aluminium and iron present in AA1100 and LCS plates respectively into each other. The red and green represent the high abundance of aluminium and iron respectively and black areas no concentration of each element. It was observed that there was not much diffusion of aluminium into iron and vice versa (Fig 4b, 4c) validated by carrying out dot mapping of the welded material. The reason behind this may be as explosive welding is a microsecond phenomenon, therefore atoms didn't get sufficient time for diffusion during welding. In spite of the high temperatures generated at the vicinity of the contact point in a very narrow zone, high velocity of the process and immediate heat transfer to the bulk of the materials which normally are at room temperature, do not allow melting or diffusion.



(a)



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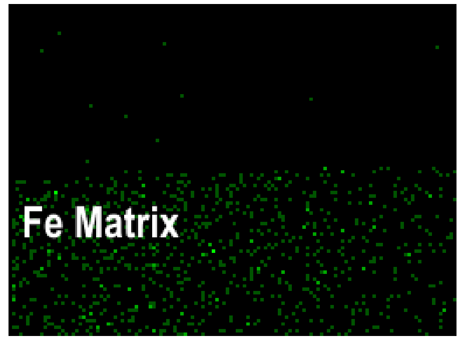


(c)

Figure 4: SEM image and EDX analysis of weld interface (a) Weld interface at 500X (b) EDX derived dot mapping of AA1100 showing distribution of aluminium (c) EDX derived dot mapping of LCS showing distribution of iron.

3.2 Mechanical Characterization

3.2.1 Microhardness measurement

Figure 5 details the microhardness variation across the weld interface. It is evident that the hardness of both metals increased after explosive welding. The average hardness of original materials, i.e. LCS and AA1100 were 145 HV and 38 HV respectively. After explosive welding, average hardness of LCS increased to 170 HV and that of AA1100 as 45 HV. The maximum hardness obtained at the areas nearest to interface in the explosively welded joint may be attributed to high degree of deformation due to high pressure during the explosive welding operation. As the distance gets increased from the interface, the microhardness value becomes smaller and smaller because of lesser plastic deformation occurring further.

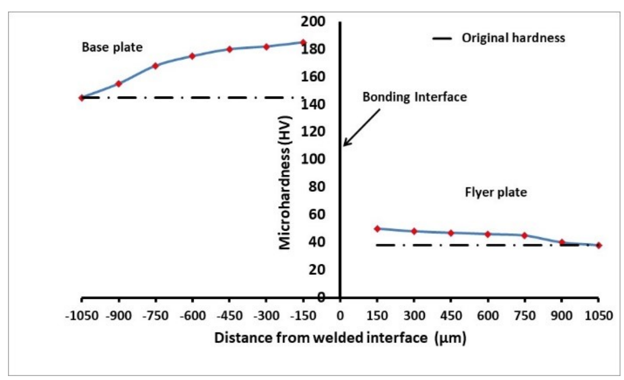
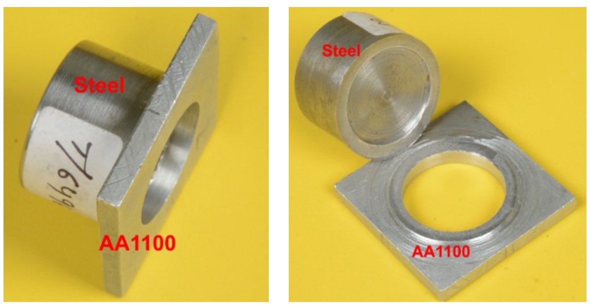


Fig. 5: Microhardness profile near the LCS/Al bonding interface

3.2.2 Ram tensile test

The bond strength of the weld joint is a significant determining factor for evaluation of the quality of the bonding. Therefore, the tensile strength of the weld was measured using the tensile testing set up and Ram tensile test was conducted. The test specimens were prepared as per MIL-J-24445A standard as shown in fig 6a. The test results showed that average ram tensile strength of the weld specimen was 55 MPa which was approximately 60% of the ultimate tensile strength of AA1100 (90 MPa) that was obtained by a conventional tensile test. Actually the tensile strength values cannot be related to the tensile strength of the component metals because the welded interface is much more constrained than in a conventional tension specimen and furthermore the weld specimen is subjected to a pealing action in addition to the tensile strength [14]. Fig 6b shows the photograph of a tested specimen, fracture was found to occur on the interface.

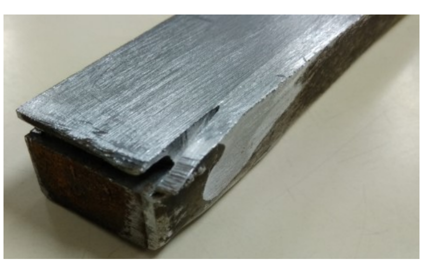


(a) (b)

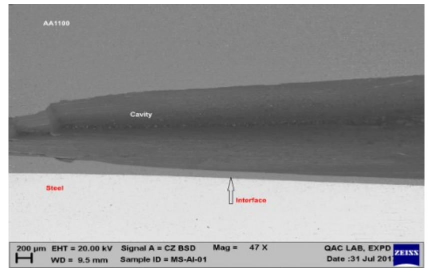
Figure 6: Ram tensile testing of welded plates (a) Ram tensile specimen before test (b) Ram tensile specimen after test.

3.2.3 Chisel test

A simple qualitative test of bond quality is to chisel the interface of a sample of the clad by applying the force at the interface. The test confirmed successful joining as no delamination occurred as shown in figure 7a. SEM analysis of the sample after chisel test also indicated that separation was not occurred in the interface, but breaking off was only observed in the aluminium side as cavity was created (Figure 7b). EDX analysis also corroborated SEM results (Fig 7c). Therefore, AA1100 got parted within itself rather than at the interface. It is reported that a soundly bounded specimen will part in the softer metal rather than at the interface [15].



(a)



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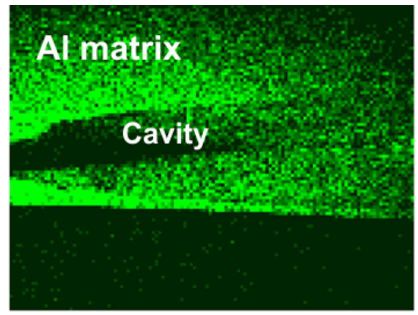

(c)

Figure 7: Chisel test of welded plate (a) Welded sample after chisel test (b) SEM image of welded sample after chisel test (c) EDX derived dot mapping of AA1100 showing cavity on aluminium side

4. Conclusions

1. Aluminium alloy (AA1100) and low carbon steel (LCS) plates were joined successfully using explosive welding method. The interfacial profile of the weld obtained had laminar morphology at the interface free from major cracks as well as no melting voids or intermetallic compounds were observed as characterized by SEM and optical microscopy.
2. The hardness of welded plates was higher than the original materials near the welding interface due to deformation hardening during the explosion.
3. The average ram tensile strength of the weld specimen was 55 MPa which was approximately 60% of the ultimate tensile strength of AA1100 (90 MPa).
4. Chisel test confirmed successful bonding as no delamination was observed at the interface.

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