Explosive welding of Aluminium Alloy With Low Carbon Steel Plates and Weld Interface Characteristics

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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 methodology. Optical and scanning electron microscope (SEM) were used to observe the morphology and microstructure at the interface boundary. Mechanical properties of weld joints have been evaluated by carrying out, chisel test, Ram tensile and hardness tests. After successful joining of plates, the bonding interface had laminar morphology free from voids/cracks. No separation was observed at the interface of the welded plates after conduct of chisel test indicating good quality weld.

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, micro hardness 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, 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 aluminium-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 aluminium-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

Aluminium alloy (AA1100) having dimensions 300 x 150 x 5 mm and low carbon steel (LCS) with dimensions 300 x 150 x 25 mm were used as flyer plate and base plate respectively. The chemical compositions of AA1100 and low carbon steel are presented in Table 1.

<table>
<thead>
<tr>
<th>Chemical Composition (weight %)</th>
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<tbody>
<tr>
<td>Element</td>
</tr>
<tr>
<td>---------</td>
</tr>
<tr>
<td>AA1100 (Flyer)</td>
</tr>
<tr>
<td>LCS (Base)</td>
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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 explosive mixture had density 1.1 g cm$^{-3}$. As illustrated in figure 1, the explosive welding experiment was conducted in a parallel geometry. Detonator along with booster charge was used to initiate the explosive.

![Fig. 1 Schematic illustration of experimental assembly for explosive welding](image)

2.3 Microstructural Characterization

The samples for microstructure evaluation of the weld interface were cut from the welded plate. Metallographic examination was carried out using optical microscope (Leica, Germany, DM 2700P) and scanning electron microscope (Carl Zeiss, USA, EVO15) in conjunction with EDX (Energy-dispersive X-ray) analysis. 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

The hardness variation across the weld interface was studied by Vicker’s microhardness tester (Radical, India, RMHT201) so as to observe 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. Hardness was measured at intervals of 150, 300, 450, 600, 750, 900 and 1050 µm for each sample from the interface and the average values are presented.

The tensile strength of the weld joint was estimated by an electromechanical test machine equipped with 100 kN load cell (FIE UTE-100) and Ram tensile test was conducted and 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

After explosive welding trial, the visual examination of the welded plates revealed that welding of AA1100 on LCS was achieved (Figure 2a, 2b).

![Image](image1.png)

(a)

![Image](image2.png)

(b)

Figure 2: The explosively welded plates (a) welded plate just after explosive welding trial (b) Welded plate after machining

3.1 Microstructural Analysis

3.1.1 Optical analysis

Figure 3a shows the optical micrographs of magnified (100X) interface analysed under optical microscope. The straight interface structure was observed with smooth bonding line and free of major cracks or voids.

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).

![Image](image3.png)

(a)

![Image](image4.png)

(b)

Figure 3: Optical microscope images of weld interface 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. The SEM analysis was performed in the back scattered electron (BSE) mode and aluminium appeared dark and LCS as bright (Fig 4a). SEM validated optical microscopy results as laminar, defect free, interface was revealed without any cracks or melting voids even at microscopic level. Thus structural investigations by SEM indicated successful welding of plates over the entire surface of collision.

The diffusion of elements i.e. aluminium and iron present in AA1100 and LCS plates respectively into each other was investigated by EDX analysis. The red and green represent the high abundance of aluminium and iron respectively and black areas no concentration of each element. No significant diffusion of aluminium into iron and vice versa (Fig 4b, 4c) was observed as studied 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.
Figure 4: SEM (BSE) image of the interface and EDX analysis (a) Weld interface at 500X (b) EDX map analysis of AA1100 showing distribution of aluminium (c) EDX map analysis 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. Increase in hardness of flyer as well as base metal was observed compared to original material hardness. The average hardness of materials i.e. LCS and AA1100 in initial state, were 145 HV and 38 HV respectively. Average micro hardness of LCS increased to 170 HV and that of AA1100 as 45 HV after welding. As the distance gets increased from the interface, the micro hardness value becomes smaller and smaller because of lesser plastic deformation occurring further. The maximum hardness obtained at the areas nearest to interface in the explosively welded joint may be because of high degree of plastic deformation during the explosive welding operation.

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.

3.2.3 Chisel test
For assessing the quality of weld joint, a typical destructive test i.e. chisel test was conducted. Efforts were made to break the interface by hammering the chisel placed at the interface. The test confirmed successful joining as no separation was found at the interface as shown in figure 7a. Failure started from softer aluminium side and interface remained intact. 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). It is reported that a soundly
bounded specimen will part in the softer metal rather than at the interface [15].

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

4. Conclusions
1. Successful joining of aluminium alloy (AA1100) and low carbon steel (LCS) plates was achieved using explosive welding process. The weld interface obtained had laminar morphology without any cracks/voids as well as melting voids as revealed by metallographic examination.
2. The hardness of welded materials was higher close to the welding interface.
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. A good quality weld was obtained as revealed by chisel test as no separation was observed at the interface.

5. References: