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Formation of intermetallic structures at the interface of steel-to-aluminium explosive welds☆

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ABSTRACT

The formation of intermetallic structures at the interface of carbon steel to 6082 aluminium alloy explosive welds and their influence on the weldability of these two materials were studied. The morphology, the microstructure, the chemical and phase compositions of the welds were characterised by several types of microscopy techniques. The interface characterisation proved that explosive mixtures with a lower detonation velocity were revealed as being more suitable for achieving consistent welds since jet entrapment was prevented and continuous molten layers were not formed at the weld interface. It was also found that the physical properties of the intermetallic phases generated at the weld interface have a strong influence on the weldability of steel-to-aluminium explosive welds. Specifically, it was shown that the formation of aluminium-rich intermetallic phases at the weld interface increases the solidification time of the interfacial molten material, decreasing the weldability of these two materials. The formation of these intermetallic compounds should be avoided by reducing the interaction between the flyer and the baseplate as well as by avoiding excessive molten layers.

1. Introduction

Aluminium to steel (Al-Fe) joining has a very high economic and technical interest for many industries, since it makes possible to develop engineering solutions, which combine the lightweight and the high thermal and electrical conductivities of aluminium with the low cost and the high structural strength of steel. However, these metals are very difficult to join through the conventional welding techniques, because they present huge differences in their physical properties as well as having a very high susceptibility to generating brittle intermetallic phases. Sound joining of these materials requires that both the volume of the interacting material and the interaction time under high temperature are minimised. This may be achieved through explosive welding [1] and magnetic pulse welding [2], i.e. two impact-loading welding technologies, which, despite being conceptually different, share several operating principles. However, despite occurring in a very narrow region of the weld interface and for a very short time, the interaction of both materials also exists in these processes. So, it is crucial to characterise the morphological and the microstructural properties of the weld interface to understand the thermomechanical phenomena occurring at this zone, which have a decisive influence on the welding results [3].

The morphology of the Al-Fe weld interface has been characterised by many authors. Tricarico et al. [4], in explosive welding of AA5083 to ASTM A516 carbon steel plates, reported the formation of a wavy interface all along the weld length. However, most of the authors have reported the formation of a weld interface with a hybrid morphology, i.e. partially flat and partially wavy. Yu et al. [5], in magnetic pulse welding of AA3003 to AISI 1020 carbon steel tubes, reported the formation of an interface in which wavy regions were intercalated with flat regions along the weld length. In turn, Yu and Tong [6], in magnetic pulse welding of AA1060 to GB Q235 carbon steel base plates, instead of observing intercalated morphologies, detected both interface morphologies occurring simultaneously all along the weld length. A flat morphology was observed at the interface between the aluminium alloy and an Al-Fe mixed layer, which was formed between both welded metals, and a wavy morphology was observed at the interface between this layer and the steel plate.

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Some studies have already been performed to characterise the microstructure of the weld interface, and especially, the properties of the aforementioned Al-Fe layer, which is also denominated the transition or intermediate region. Li et al. [7], in explosive welding of AA5083 to GB Q345 low-alloy steel plates, reported the formation of discontinuous transition regions, which were intercalated with direct bonding zones. The transition regions were reported to present a molten morphology and to be composed of the intermetallic phases $FeAl_2$ and Fe_2Al_5. In turn, Aizawa et al. [8] reported the formation of two different transition regions in explosive welding of AA1100 to JIS SPCC carbon steel plates, which were formed at the rear and the front sides of the interfacial waves. In agreement with Li et al. [7], the rear side regions, in which dendrite branches, voids, and cracks were observed, were reported to result from localised melting and solidification. The intermetallic phases Fe_2Al_5 and $FeAl_3$ were identified in these regions. On the other hand, no evidence of local melting was observed on the front side transition zones, which were composed of a dispersion of Fe particles over an Al matrix. The authors reported that these regions were formed by Al-Fe mixing in a solid state.

A few recent studies have also addressed the crystallinity of the Al-Fe transition layer to further understand the metallurgical phenomena occurring at the weld interface. Fan et al. [9], in magnetic-pulse welding of AA1060 to AISI 1020 carbon steel tubes, reported the formation of an amorphous layer, with a few nanometres, at the Al/Fe interface. Although no intermetallic phases were detected, the interdiffusion of the Al and Fe elements across the interface promoted a composition gradient in this layer. According to the authors, the loss of crystalline structure within the interfacial layer was induced by the instability of the mechanical lattice during the high-strain-rate impact and by interdiffusion at temperatures below the melting temperature. The amorphisation of the transition layer was also reported by Yu et al. [10], in magnetic pulse welding of 5A02 aluminium alloy to AISI 304 stainless steel tubes. The transition layer was reported to be composed of an amorphous Al-rich matrix in which a nanoscale Fe-rich ordered phase was scattered.

Although some work on the weld interface characterisation has already been conducted, the influence of the formation of interfacial intermetallic structures on the Al-Fe weldability by impact welding remains unexplored. So, the aim of the present research is to study the formation of intermetallic structures at the interface of carbon steel to AA6082 explosive welds and their influence on the weldability of these materials. The morphology, the microstructure, the chemical and phase compositions of the welds were characterised using several characterisation techniques, such as optical microscopy, scanning electron microscopy (SEM), energy dispersive spectroscopy (EDS), electron backscatter diffraction (EBSD), and microhardness testing.

2. Experimental Procedure

Four series of Al-Fe explosive welds were produced by projecting 3 mm-thick plates of EN DC06 carbon steel over 15 mm-thick plates of AA6082-T6. The hardness values of the carbon steel and the aluminium alloy are 116 $HV_{0.2}$ and 111 $HV_{0.2}$, respectively. All the welds were produced in a full overlap joint configuration. Regarding the explosive mixture, two weld series were produced with an ANFO-based mixture and two series were produced with explosive emulsion-based mixtures (EE). The explosive emulsion mixtures were sensitized with hollow glass microspheres (HGMS) in one series and with expanded polystyrene (EPS) in the other series. The use of these sensitizers in explosive welding was studied in detail by Mendes et al. [11]. Different explosive to flyer mass ratios (explosive ratios) were used in the four weld series. The stand-off distance was the same in all welds. The welding conditions are summarised in Table 1. As displayed in the table, the nomenclature used for labelling the welds identifies the explosive mixture and ratio. For example, the EE-PS5 weld was produced with the explosive emulsion sensitized with EPS, using an explosive ratio of 0.53, and the AF-9 weld was produced with ANFO, using an explosive ratio of 0.93.

Table 1
Welding parameters of the EE and AF welds.

	Welds			
	EE-PS5	*EE-HG6*	*AF-9*	*AF-6*
Flyer plate alloy	EN DC06 steel	EN DC06 steel	EN DC06 steel	EN DC06 steel
Base plate alloy	AA6082-T6	AA6082-T6	AA6082-T6	AA6082-T6
Configuration	Full overlap	Full overlap	Full overlap	Full overlap
Explosive	EE + EPS	EE + HGMS	ANFO	ANFO
Flyer plate thickness	3 mm	3 mm	3 mm	3 mm
Base plate thickness	15 mm	15 mm	15 mm	15 mm
Explosive ratio	0.53	0.68	0.93	0.69
Stand-off distance	4.5 mm	4.5 mm	4.5 mm	4.5 mm

The detonation velocity of the explosive mixtures was measured following the procedure reported in Mendes et al. [12] for all the weld series. After welding, samples were removed longitudinally to the welding direction and prepared for metallographic analysis according to ASTM E3-11. A Leica DM4000M LED optical microscope was used to observe the welds. The microstructural characterisation was complemented by SEM, using a field emission scanning electron microscope, Zeiss Merlin VP Compact. This equipment was provided with EDS, which was used to analyse the chemical composition of the weld interface. The phase composition of the weld interface was analysed by EBSD, using a field emission scanning electron microscope, FEI Quanta 400FEG ESEM/EDAX Genesis X4M. The indexing of the EBSD patterns was conducted using Genesis and Delphi software applications. The mechanical properties of the welds were characterised by microhardness testing, which was conducted using Struers Duramin equipment. Measurements with a testing load of 25 g were performed at the weld interface.

3. Results and Discussion

3.1. Welding Parameters and Weldability Window

Table 2 shows the values measured for the detonation velocity (V_d) and the values calculated for the impact velocity (V_p) and the collision angle (β). V_p and β were computed using the Gurney equation for a dimensional problem in parallel configuration (Eq. (01)) [13, 14] and with a relation between both velocities and β (Eq. (02)) [13].

$$V_p = \sqrt{2E}\cdot\sqrt{\frac{3R^2}{R^2+5R+4}} \tag{01}$$

$$\beta = 2\cdot\arcsin\left(\frac{V_p}{2\cdot V_d}\right) \tag{02}$$

R is the explosive ratio (dimensionless) and $\sqrt{2E}$ is the Gurney characteristic velocity of the explosive ($m\cdot s^{-1}$). This parameter was estimated through an empirical correlation obtained by Cooper [15] for ideal explosives, $\sqrt{2E} = V_d/2.97$.

Table 2
Values of detonation velocity, impact velocity and collision angle for the EE and AF welds.

Welds	V_d (V_c) ($m\cdot s^{-1}$)	V_p ($m\cdot s^{-1}$)	β (°)
EE-PS5	3172	372	7
EE-HG6	3514	497	8
AF-9	2300	404	10
AF-6	2072	296	8