Metallurgical characterization of an explosion welded aluminum/steel joint

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Explosion welding is an effective method to join very dissimilar metals, which in the last years is adopted in many field of transportation industry to obtain a good compromise among the involved materials properties. In this work a commercial bar made of ASTM A516 low carbon steel, clad by explosion welding with A5086 aluminum alloy and provided with an intermediate layer of pure aluminum, has been investigated. Results of metallurgical characterization and mechanical surveys (Vickers microhardness, tensile and FIMEC test) confirmed the bar is suitable for structural applications. Although precipitation of intermetallic compounds and deformation hardening has been observed at the interfaces, the tensile behavior of the whole joint (deformed along the orthogonal direction to the interfaces) maintains characteristics of high ductility.

KEYWORDS: EXPLOSION WELDING - ALUMINUM-STEEL JOINT - DISSIMILAR METALS - STEEL-ALUMINUM INTERFACE - INTERMETALLIC COMPOUNDS - TRANSITION JOINT - MECHANICAL PROPERTIES

INTRODUCTION

Ships and offshore structures need materials with high mechanical properties, which ensure also low weight and satisfactory protection against marine corrosion within a reasonable budget. Unluckily no single material shows all these requirements, so a variety of materials has to be considered according to their specific characteristics.

Aluminum superstructures are widely used in shipbuilding together with common steel hull, in order to exploit the peculiar properties of the two materials and achieve important weight savings, as the overall deadweight reduction and centre of gravity lowering. In these constructions connections were traditionally performed by riveting, with the draw back of corrosion phenomena leading to limited operational durability and replacements every few years. More in general joining aluminum or titanium to steel is a goal of great interest in transportation industry, in developing aeronautic and aerospace parts and other emerging applications.

Dissimilar material joining is a significant challenge, due to the difference in chemical and mechanical characteristics of metals and alloys involved. The usual processes as fusion welding may become applicable only under restricted conditions and defect-free welds can be obtained only thanks to an appropriate selection of welding parameters. Fusion welding between Al and steel generally forms intermetallic compounds along the interface which reduce dramatically fracture toughness, thus their formation should be as much as possible suppressed.

Nowadays friction stir welding (FSW) [1] and explosion welding [2] appear as promising techniques to produce transition joints. In particular explosion welding, patented since 1962 [3], is considered for its capability to join directly a wide variety of dissimilar metals (as the aluminum-steel, copper-steel or titanium-steel systems) with thickness greater than what could be obtained by FSW.

By explosion welding, the metals surface to be joined are brought in close contact by an explosive charge detonated against them. So steel sheets clad with aluminum or steel/aluminum bars can be produced with thicknesses over than 20 mm. Surely, at present, no alternative commercial technology is available to realize such a direct bonding with these great thicknesses [4].

Explosion welding occurs under oblique collision of plates: explosive loading and flyer metal are placed together, spaced slightly away from backing metal and positioned at a characteristic collision angle [5]. Due to the explosion wave, flyer and base plates collide resulting in electron-sharing metallurgical bonds at the

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interface of metals. Plates are joined under the influence of a very high pressure that causes considerable local plastic deformation at the interface [6]. Therefore straight or wavy interfaces could be formed depending on the quantitative of explosive: increasing in explosive loading, the impact energy of flyer plate increases, causing the transition from the straight to the wavy form [7]. Moreover the temperature distribution and heat transfer behavior have great influence on the interface morphology, microstructures and local stress distribution [8].
Usually explosion welded plates and bars are then fusion welded with Al and steel components at the respective sides. It results in further problems, because heating the interface between metals with different chemical compositions gives rise to alloying elements diffusion and consequently metallurgical changes that might alter mechanical properties and corrosion behavior [9]. In particular it has been experimented that bonds quality of aluminum alloy / steel transition joints is improved by using an interlayer of commercially pure aluminum. By this way steel bars clad with aluminum alloy have been successfully produced and utilized in shipbuilding.
Aim of this work is the metallurgical and mechanical investigation of a bar made of ASTM A516 low carbon steel, clad by explosion welding with A5086 aluminum alloy and provided with an intermediate layer of commercially pure aluminum. Metallographic samples of the interface have been characterized by optical and scanning electron microscopy (SEM) observations, moreover energy dispersive spectroscopy (EDS) has been performed in order to investigate the presence of intermetallic precipitates. Vickers microhardness surveys are carried out across the clad line to check any local hardening and embrittlement. Mechanical properties are investigated by means of tensile test and locally by FIMEC test (Flat-top cylinder Indenter for MEchanical Characterization), that through instrumented indentation is able to estimate the yield stress in a small portion of material.

MATERIALS AND METHODS

Commercial transition joints, in form of plates or bars for shipboard uses, are composed of an Al alloy (AA 5000 series) welded by explosion to a low C - Mn structural steel with an intermediate layer of commercial pure Al (AA 1100 series) to ensure maximum toughness.
A commercial bar, made of ASTM A516 Gr 55, AA 1050 (interlayer) and AA 5086, has been considered in this work (fig. 1a). Composition of the different metals are given in table 1.

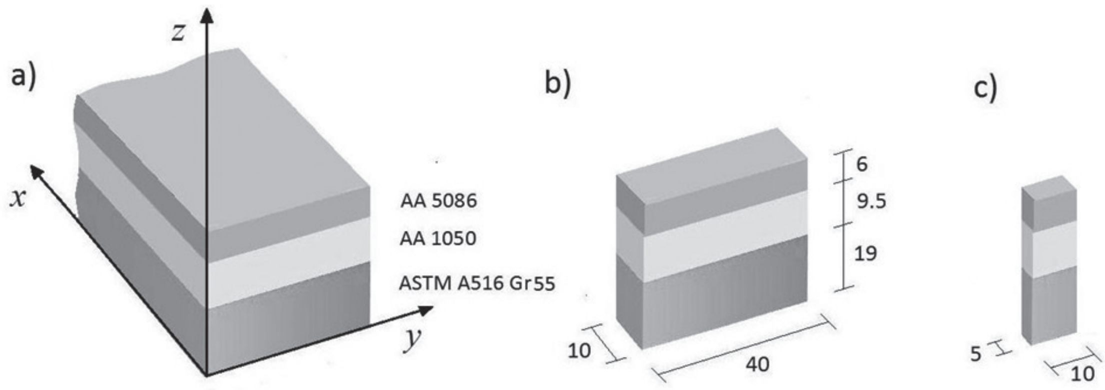


Fig. 1 - Transition joint geometry: a) commercial bar (length 3800 mm along the x axis), b) specimen for metallographic investigations, c) specimen for tensile test.

Tab. 1 - Compositions of the transition joint (weight %).

ASTM A516 Gr 55								
C	Mn	P	S	Si	Fe			
0.2	0.6-1.2	0.035	0.035	0.035	Bal.			
AA 1050 (interlayer)								
Si	Fe	Cu	Mn	Mg	Zn	Ti	Al	
0.25	0.4	005	0.05	0.05	0.07	0.05	Bal.	
AA 5086								
Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
0.4	0.5	0.1	0.2-0.7	3.5-4.5	0.05-0.25	0.25	0.15	Bal.

Specimens 10 mm thick were cut from bar, duly polished and metallographically prepared.
Metallographic observation were performed by an optical microscope and by SEM equipped with EDS device.
Vickers microhardness surveys were carried out on metallographic samples along transversally to the interface, along the z axis (fig. 1b). The test loads were 200 g and 25g to measure hardness near the interfaces.
Tensile test were carried out on specimens 10 mm wide and 5 mm thick (fig. 1c), by deforming along the z axis at a rate of 10^{-3} s^{-1}.
The indentation test FIMEC, with a cylindrical probe (diameter 1.5 mm) and advancing speed (0.1 mm/min), was performed in the three regions of the transition joint. During the FIMEC test load values are plotted in function of penetration depth. The specific pressure values are calculated as the ratio load / probe cross section area.
The specific pressure vs. penetration depth curves differ from load vs. penetration depth ones only for a scale factor. These curves are characterized first by an elastic stage until a pressure p_L is reached, followed by a plastic deformation stage with an almost linear trend up to a pressure p_y, where larger plastic deformation starts with a sharp variation of slope. Here a protrusion of material occurs around the indentation, followed by a constant slope deformation with a remarkable plastic flow.
When the penetration speed is lower than 0.1 mm/min, FIMEC test gives indications about mechanical behavior of material submitted to static tensile test with a rate of $10^{-3}s^{-1}$. Under these conditions the following relationship can be applied to estimate the yield strength (σ_y) from the load p_y:

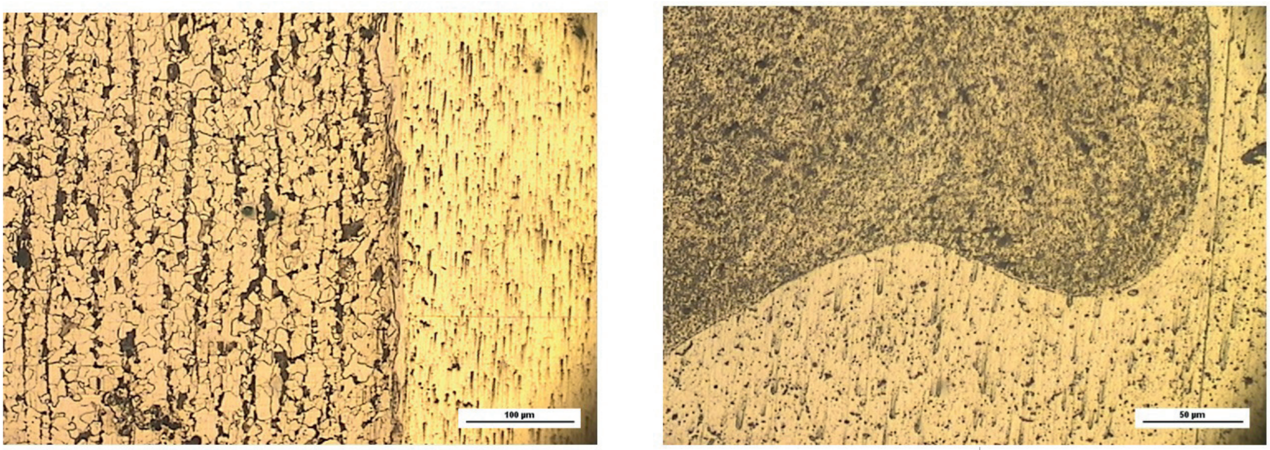
(1) $$\sigma_y \approx p_y/3$$

This relationship, successfully tested for a lot of metals and alloys [10, 11, 12], is considered particular useful to check locally mechanical properties of steel or Al alloy welded joints [13, 14]. So in this work it has been utilized to estimate the yield strength in the different zones of the transition joint.

RESULTS AND DISCUSSION

Metallographic observations

Optical observations on ASTM A516 steel have shown the typical microstructure of rolled products with ferrite and perlite consisting of small sized grains stretched along the rolling direction (respectively lighter and darker constituent in figure 2a). At low magnification, the welding interface steel/aluminum appears as an almost straight and very narrow film, being wide not more than 20 µm.
Instead the interface aluminum/aluminum alloy is wavy (fig. 2b), as a consequence of the great plasticity of both the two metals. The waves formation produces an increase of the interfacial area with an improved bonding efficiency.
It is worth to notice that straight or wavy interfaces could be formed by explosion, according to metals involved and to process parameters: increasing in explosive loading increases the impact energy of flyer causing the transition from straight to wavy form [9].
As concern the steel / aluminum interface, the particles observed by SEM at high magnification in (fig. 3a) can be ascribed to the formation of a narrow film of intermetallic compounds, due to the element interdiffusion consequent to the explosion heating. Such interpretation is confirmed by the EDS mapping in fig. 3b, where the interfacial film appears mainly consisting of Al atoms (red color), with the presence of Fe atoms as well (green color).
The intermetallic compounds, that make the interfacial film very brittle, are responsible of cracks, as showed in figure 3, whose formation is caused by thermal gradients arising during the cooling stage that follows the explosion.



a) b)

Fig. 2 - Optical micrographs: a) interface between low carbon steel (on the left) and Al (on the right), b) interface between Al interlayer and Al alloy.

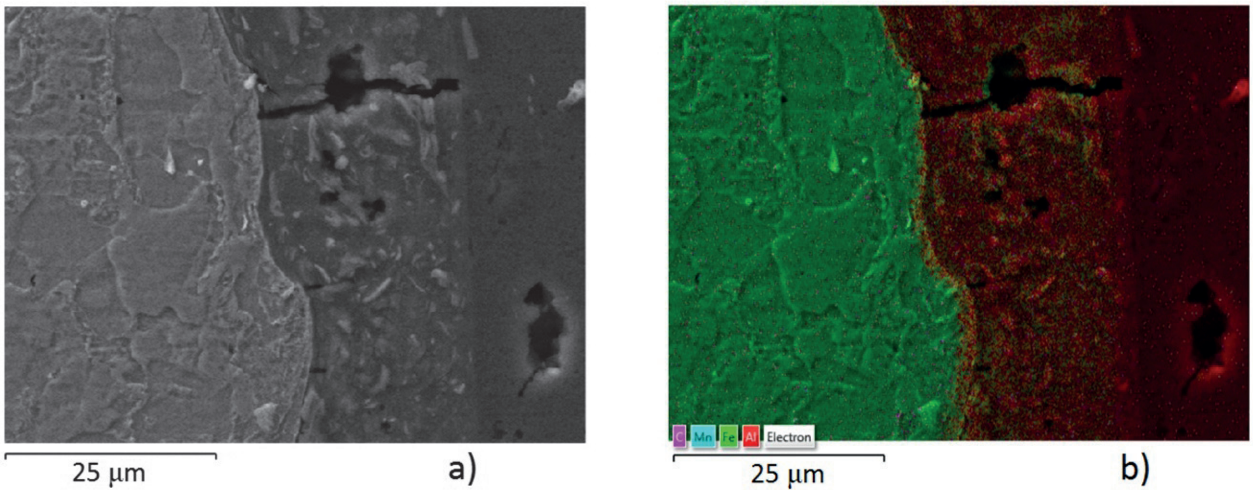


Fig. 3 - Detail of clad line between low carbon steel (on the left) and Al interlayer (on the right): a) SEM micrograph, b) EDS mapping.

Microhardness test

The original hardness of the three metals involved, measured far from the interfaces, are: 175 HV for ASTM A516 Gr 55, 28 HV for AA 1050 interlayer and 90 HV for AA 5086. However microhardness increases significantly near the interface.

The microhardness profile recorded across the interface is shown in figure 4: it is evident an increase of values due to the deformation hardening of metals caused by the explosion, above all at the steel side.

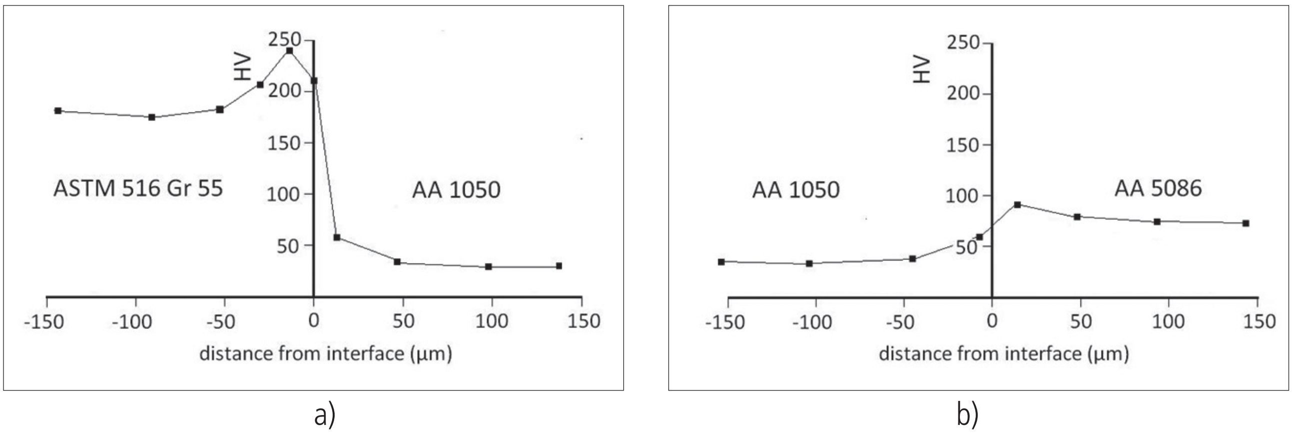
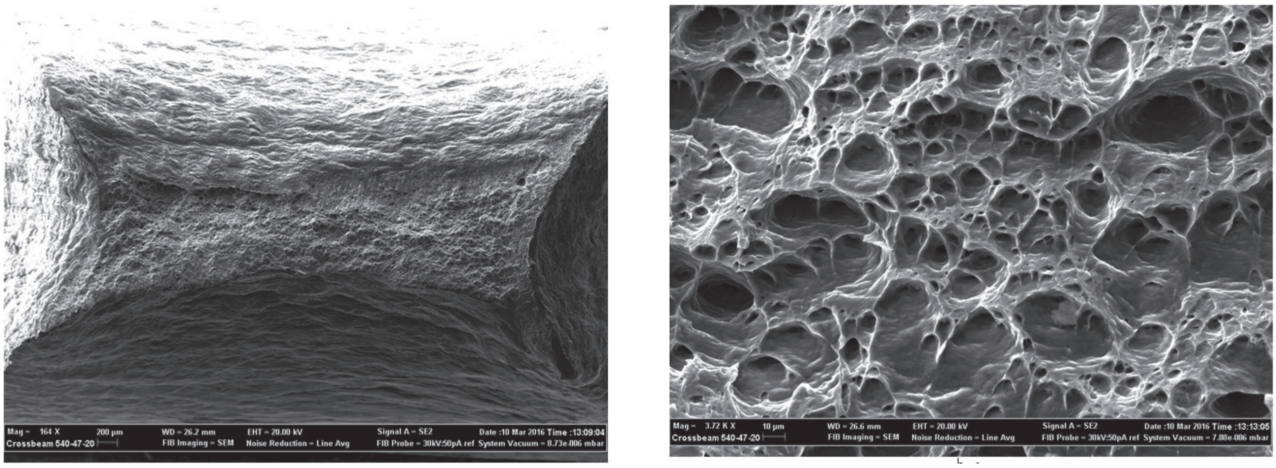


Fig. 4 - Microhardness profiles: HV values vs. distance from the interface, along the z axis.

Tensile test

During tensile test, all the specimens fractured in correspondence of the aluminum interlayer in a ductile way after a long deformation stage with an ultimate strength of 75 MPa.

Samples exhibit clearly necking in the typical form of flat geometry and fracture surface is characterized by dimples formation (fig. 5).



a) b)

Fig. 5 - SEM fractographic images: a) fracture surface (Al interlayer), b) detail of fracture surface.

FIMEC test

FIMEC surveys were performed on a metallographic specimen in zone of the three metals far from the interfaces. Results are shown in figure 6 as specific pressure vs. penetration depth curves.

The arrows indicate values of p_y. The resulting data of $p_y/3$ (table 2) are in the range of the yielding loads (σ_y) of the three materials.

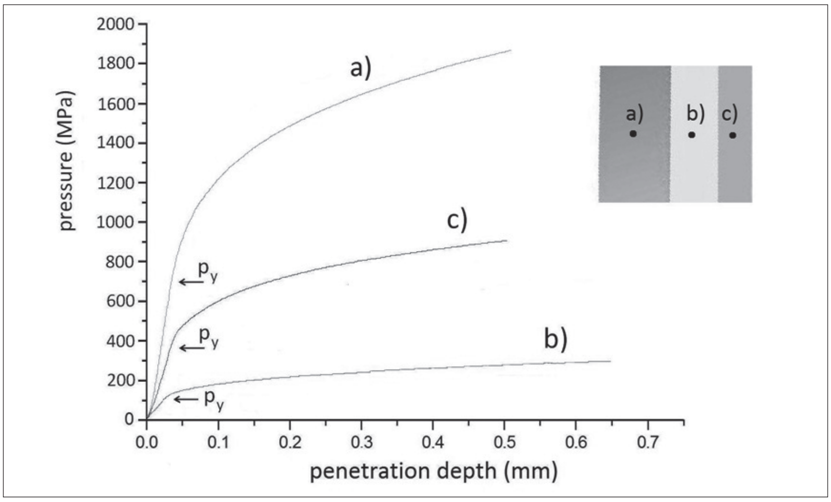


Fig. 6 - Diagram of pressure vs. penetration depths obtained by FIMEC test:
a) ASTM A516 Gr 55, b) AA 1050 (interlayer), c) AA 5086 (the arrows indicate load values considered to calculate p_y).

Tab. 2 - Results of FIMEC test.

	p_y (MPa)	p_y / 3 (MPa)	σ_y (MPa)
a) ASTM A516 Gr 55	650	217	205 *
b) AA 1050 (interlayer)	105	35	28-145 **
c) AA 5086	370	123	115-255 **

*) minimum value requested, see ref. [15]; **) yielding loads range, according to treatment conditions [16, 17]

CONCLUSION

Results confirm that the investigated low carbon steel / Al / Al alloy commercial bar, produced by explosion welding, is suitable for structural applications.

The Al / Al alloy interface, observed by optical microscopy, has a wavy feature that indicates a high degree of plastic deformation of the involved metals. Instead a very narrow and straight film takes place at the steel / Al interface. By means of SEM observations and EDS microanalysis, this film was recognized rich of diffusion products as the Fe-Al intermetallic compounds. Although the explosive detonation produces heat, the thinness of this film proves that there wasn't time for heat transfer to the metal surfaces. Thus no appreciable temperature raised in metals and consequently very little diffusion occurred at the interface.

Microhardness surveys showed, close to both the interfaces, a deformation hardened layer, wide only some tens of microns. In particular at the steel / Al interface the formation of intermetallic compounds could locally results in toughness reduction. FIMEC test gave values in agreement with the yielding load of the three materials. In any case specimens showed a very ductile behavior during tension test, with fracture in the Al interlayer after a clearly observable necking.

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