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Steel to aluminium key-hole laser welding

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Abstract

The laser joining of a low carbon steel to a 6000 series aluminium alloy was realised in key-hole welding mode in a steel-on-aluminium overlap configuration and was investigated in a three-fold approach: (1) process optimisation, (2) material characterisation and (3) mechanical testing. No-defect welds, composed of a solid solution of aluminium in iron and richer aluminium "white solute bands" of FeAl phases were obtained when limiting steel penetration in aluminium to below 500 μm. Embrittlement of the joining zone was observed, mainly located on the weld–aluminium interfaces composed of Fe_2Al_5 and/or $FeAl_3$ phases with thicknesses between 5 μm and 20 μm. Limiting penetration to below 500 μm allowed to restrict steel to aluminium dilution in order to confine the hardness of the welds. With such penetration depths, up to 250 N/mm in linear strength could be achieved, with failures located in the weld–aluminium interfaces. Increasing penetration depth led to a change in the assembly weak points (in the weld and on the steel–weld interfaces) and induced a severe decrease in strength.

Keywords: Aluminium alloy; Steel; Laser welding; Intermetallic compounds

1. Introduction

New antipollution and energy-saving laws impose a reduction in fuel consumption for vehicles of the automotive industry. This reduction may be obtained through the lightening of vehicles by making car-bodies out of aluminium instead of steel, by using high elastic limit steels or by making some components out of light alloys as aluminium or magnesium alloys instead of steel. Manufacturing car bodies with steel and aluminium components implies joining steel to aluminium, that is why nowadays several studies are focused on the steel to aluminium assembling by new joining methods, with or without steel melting.

The main issues of the steel to aluminium fusion welding come from the large difference between their melting points, the nearly zero solid solubility of iron in aluminium and the formation of brittle aluminium-rich intermetallic compounds such as Fe_2Al_5 and $FeAl_3$.

Until today the dissimilar materials were joined by mechanical means of assembling like screwing, riveting or clinching, but also with solid state processes like explosion welding [1] or friction welding [2,3]. On the other hand, despite the difficulty of assembling steel to aluminium by liquid state processes, many studies have been done on this topic by conventional processes as arc welding [4,5], resistance spot welding [6,7], or brazing [8].

During the last 5 years, new processes have also been envisaged for steel to aluminium assembling: friction stir welding process which allows the reaction between a fluid-like plastic state aluminium created with a rotating pin to adhere to the steel surface [9,10], and different methods involving laser process [11–16]. Preliminary studies with laser process favoured metallurgical reactions between solid steel and liquid aluminium, by heating steel with the laser beam to melt the aluminium by heat conduction between two overlapped sheets [11–13]. With this joining technique, good mechanical properties could be achieved, provided intermetallic thickness growth was kept below 10 μm. By using Al–12Si filler wire [14,15] on flanged joints, reaction layers could be maintained below 2 μm and provided good mechanical properties to the joints. With this brazing technique, Mathieu et al. [15] also obtained good joints with

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Table 1
Chemical composition of DC 04 low carbon steel, 6056 and 6016 aluminium alloys

Alloy	Element	Al	Fe	Mg	Si	Cu	Mn	P + S	C
DC 04	Wt.%	–	Bal.	–	–	–	0.4	0.06	0.08
6056	Wt.%	Bal.	0.5	0.6–1.2	0.7–1.3	0.5–1.1	0.4–1	–	–
6016	Wt.%	Bal.	0.5	0.3–0.5	1–1.3	0.2	0.2	–	–

the use of Zn–Al filler wires between galvanized steel and aluminium alloy. Lastly, Katayama and Mizutani [16] succeeded in joining liquid low carbon steel or stainless steel to liquid aluminium by a well-known key-hole laser welding process, where the laser energy is absorbed in volume at the walls of a vapour capillary generated by laser-material interaction at high intensity regime. With this key-hole technique rather good mechanical properties were obtained by irradiating steel placed on aluminium sheet, and limiting aluminium to steel mixing by a reduced steel penetration in aluminium. One of the advantages of the laser process versus other fusion processes, is the ability to provide very short interaction times between liquid steel and liquid aluminium, to limit intermetallic compounds which are detrimental to the steel/aluminium assembling. Also taking into account that key-hole welding is the most common laser welding method, and that high welding speeds are usually achievable with high power YAG lasers, the objective of this work was to investigate steel to aluminium joining by this key-hole technique. The different aims of the present work were:

(1) first, to optimise experimental conditions (laser power, welding speed, clamping device, focal length) for the realisation of galvanized – or not – low carbon steel DC 04-6000 aluminium assemblies, using a dedicated experimental set-up, with specific attention paid to the video analysis of the melt pools;
(2) to investigate steel-on-aluminium and aluminium-on-steel welding configuration and to improve the understanding of the liquid steel–liquid aluminium interaction by metallurgical analysis of the assemblies;
(3) to characterise the mechanical properties of the assemblies with a usual transverse tensile test and a specifically developed tearing-off test.

Table 2
Mechanical data of DC 04 steel, 6056-T4 and 6016-T4 aluminium alloys [17]

Mechanical properties	σ_Y (MPa)	σ_{UTS} (MPa)	ε (%)
DC04 steel	160	280	37
6016-T4 alloy	140	230	28
6056-T4 alloy	400	420	12

2. Materials and experimental procedure

2.1. Materials

The materials used for these investigations were a 1.2 mm thick low carbon steel DC 04 mostly used for automotive applications, defined by the European normalisation NF EN 10130 and two Al–Mg–Si aluminium alloys: a 6056-T4 and a 6016-T4 aluminium alloy with a wide range of applications in aeronautical and automotive fields. Their chemical composition and mechanical properties are respectively reported in Tables 1 and 2. The microstructures of the parent materials are shown in Fig. 1. The average size of the ferritic grains (Fig. 1a) is 40 μm for the rolling direction and 20 μm for the transverse direction. For the 6056-T4 alloy (Fig. 1b), the average size of the grains is 80 μm for the rolling direction and 20 μm for the normal direction. On the other hand, 2.5 mm thick 6056 aluminium sheets were used with an angled geometry already proposed by Katayama and Mizutani [16] to reduce the thickness to 1.3 mm at the joint location, and 1 mm thick 6016 aluminium sheets.

2.2. Laser experimental procedure

Two kinds of assemblies were realised: (1) with steel sheet placed on aluminium and (2) with aluminium placed on steel sheet in an overlap configuration. The DC 04 steel, 6016 and

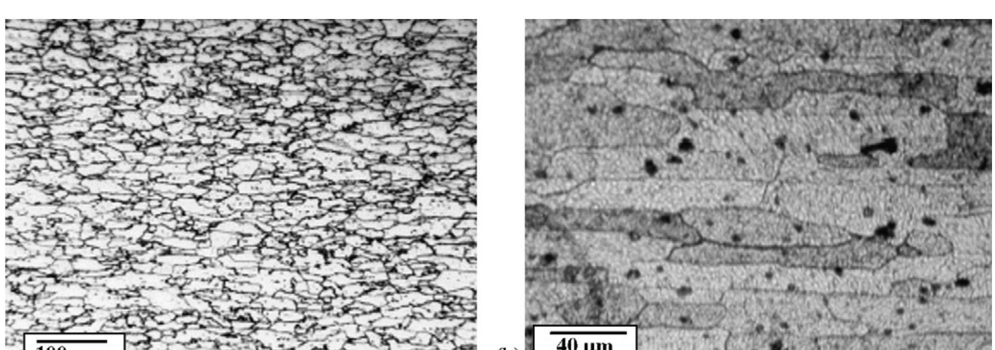
(a) (b)


Fig. 1. Microstructure of the parent materials: (a) DC 04 steel and (b) 6056-T4 aluminium alloy.