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Laser spot welding of laser textured steel to aluminium

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ABSTRACT

Laser welding of dissimilar metals (steel and aluminium) was investigated with the aim to increase the maximum tensile shear load of the Fe-Al joints. The increase was achieved by texturing the surface of steel prior to the laser spot welding process which was performed in a lap-joint configuration with the steel positioned on top of the aluminium and with a texture faced down to the aluminium surface. This configuration enabled an increase of the bonding area of the joints, because the molten aluminium filled in the gaps of the texture, without the need of increasing the process energy which typically leads to the growth of the intermetallic compounds. Different textures (containing hexagonally arranged craters, parallel lines, grid and spiral patterns) were tested with different laser welding parameters. The Fe-Al joints obtained with the textured steel were found to have up to 25% higher maximum tensile-shear load than the joints obtained with the untextured steel.

1. Introduction

One of the challenges in the automotive industry is to reduce the carbon emission of manufactured vehicles (Church, 2015; Havrilla, 2014; Lesemann et al., 2008). This can be done by incorporating lightweight metallic alloys, such as aluminium alloys, with more generic automotive modulus often made of uncoated mild steel in order to reduce the total mass of a vehicle. Unfortunately, joining these two dissimilar metals is difficult due to the chemical reactions between aluminium and steel that lead to the formation of intermetallic compounds (IMC) at the metals' interface during the welding process and thus the mechanical properties of the welds are deteriorated (Martinsen et al., 2015).

A thin sheet of steel (DC04 grade) can be successfully welded to an aluminium alloy (6111-T4) using a conduction mode laser spot welding process (Pardal et al., 2014). This novel welding technique relies on the incidence of a defocused laser beam on the top surface of steel and the generation of heat resultant from the laser-material interaction that is conducted to the aluminium through the steel. In this process the welding parameters need to be controlled in order to melt only the aluminium at the interface. The backing bar underneath the Al alloy is used to facilitate the heat extraction and minimise the IMC growth (Borrisutthekul et al., 2007). This technique differs from regular laser welding because here only aluminium is melted whilst steel remains in solid state. Although this approach helps to minimise the mixing of Al with Fe, due to a maximum solubility of 12% Al in Fe, a thin IMC layer is still produced which leads to a reduction in weld strength. As reported by (Pardal et al., 2014), the thickness of the IMC layer depends on the temperature profile generated by the laser spot and the heat distribution across the interface. However, the thermal field is also responsible for geometry of the fusion zone of the aluminium and thus the dimension of the bonding area. Previous results reported by (Meco et al., 2015) suggest that when a larger bonding area is created the joints have higher maximum shear load. One would expect a linear evolution of the tensile-shear load of dissimilar metal joints with the bonding area. However, this trend is not observed in dissimilar metal joining because the IMC layer becomes thicker simultaneously with the growth of the bonding area.

Resistance spot welding (RSW) can also be used for joining thin sheets of steel to an aluminium alloy, as demonstrated by (Zhang et al., 2011) and (Qiu et al., 2009a,b). The first of these papers reported welding of a 1 mm thick galvanized high strength steel to 1.5 mm thick 6008 aluminium alloy and obtained the Fe-Al joints with the maximum tensile-shear load of 3.3 kN. By correlating the mechanical strength of the joints with the process parameters, it

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Table 1
Chemical composition in weight% of Al 5083 and CR4 steel according to the standards BS EN 573-3:2009 and EN10130-2006, respectively.

Element	Al	Fe	Mn	Ti	Mg	Cu	Si	Zn	Cr	C	P	Other
Al 5083	Bal.	0.4 max	0.4–1.0	0.05–0.25	4.0–4.9	0.1 max	0.0–0.4	0.0–0.1	0.05–0.25	–	–	0.0–0.15
CR4	–	Bal.	0.6 max	–	–	–	–	–	–	0.12 max	0.045 max	

was found that the tensile-shear load of the joints increased with the increasing welding current and time. Detailed examination of the joints provided evidence that the increase of the process parameters leads to the increase of the weld nugget diameter as well as to the growth of IMC. The second of these papers (Qiu et al., 2009a,b) described use of the RSW process with a cover plate to join 1 mm thick SPCC steel to 1 mm thick 5052 aluminium alloy. This welding approach enabled the generation of the Fe-Al joints with the maximum tensile-shear load of approximately 5 kN. Although the authors confirmed that the tensile-shear load increases with the increasing weld nugget diameter, they also provided evidence that the presence of the IMC layer reduces the maximum load of the dissimilar Fe-Al joints compared to the Al–Al joints. Under similar welding conditions, the maximum tensile-shear load of the Al–Al joints was about 6 kN, and hence a 1 kN higher than that obtained with the Fe-Al joints. The use of metallic inserts was also investigated in RSW for joining 0.8 mm thick low carbon steel to 1 mm thick 5XXX series aluminium alloy (Oikawa and Saitoh, 1999). The insert metal sheets were aluminium clad steel sheets manufactured by hot rolling with a direct resistance heating process. These inserts were positioned between the steel and the aluminium sheets with the steel side of the insert facing the steel and the aluminium side of the insert facing the aluminium sheet. This metallic combination was found to be stronger than that without the metallic insert (3.3 kN compared to 2 kN).

An alternative approach to join thin sheets of galvanized steel to 6061 aluminium alloy by spot welding has been investigated using a variant of arc welding process called Cold Metal Transfer, also known as CMT (Cao et al., 2014). In this study, 4043 aluminium wire was used to create a spot plug by filling in a hole previously machined on the metallic sheet which was positioned on the top of the lap-joint. The material stacking configuration and welding variables were investigated in terms of microstructure and mechanical strength. The authors found that when the steel was positioned on the top there was no presence of IMCs in the middle on the surface of the fractured joint. On the other hand, when aluminium was positioned on the top, the molten aluminium was deposited onto the steel surface and the reaction between Fe and Al occurred, forming $FeAl_3$ and Fe_2Al_5 at the joint interface. The fracture load of the joints with the aluminium on the top was about 5 kN which was higher than when the steel was on the top or even when the joint was produced between the coupons of aluminium (3 kN). The reason for these results was the nugget diameter that in the steel-aluminium joint was smaller than that in the aluminium-steel joint configuration.

A modified friction stir spot welding (FSSW), called abrasion circle FSSW was used by (Chen et al., 2012) to join 6111-T4 aluminium alloy to DC04 low carbon steel. The authors showed that IMCs were not formed on the joint and the maximum tensile-shear load registered was near 4 kN. The abrasion circle FSSW enabled the increase of the bonding area by translating the tool through an orbital path.

In this paper, an alternative spot welding approach to increase the bonding area between steel and aluminium alloy without modifying the laser-generated temperature profile is proposed and investigated. A nanosecond pulsed laser is used for texturing the surface of steel prior to laser spot welding in order to locally increase the bonding area between these two dissimilar metals. The aim of this work is to investigate the impact of various laser-generated textures on the mechanical properties (strength) of the Fe-Al welds as well as to understand the mechanism of their formation.

Table 2
Mechanical strength of Al 5083 and CR4 steel.

	Ultimate tensile strength, MPa	Yield strength, MPa	Hardness, HV
Al 5083	275–350	125 min	87
CR4	270–410	280 max	105

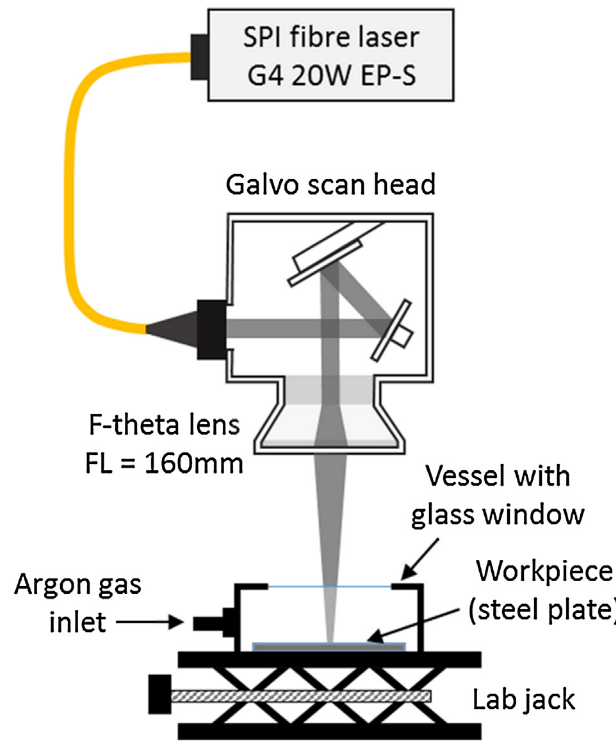

Fig 1. Schematic of the laser system used for texturing the surface of steel.

2. Experimental procedure

2.1. Material

A 1 mm thick 5083 aluminium alloy and 0.85 mm thick CR4 grade mild steel were used in the experiments. The steel and aluminium coupons were 100 mm long and 40 mm wide. Tables 1 and 2 show the chemical composition and the mechanical properties of these two metals.

2.2. Laser texturing of steel

2.2.1. Methodology and experimental setup

Fig. 1 shows a schematic of the laser machining system used for texturing the steel coupons. The laser source was a pulsed SPI 20 W fibre laser (G4 EP-S) that provided 220 ns long pulses (full width 10% maximum) with a pulse repetition frequency of 28 kHz, wavelength of 1064 nm and maximum pulse energy of 0.71 mJ. The low cost, high flexibility and acceptable absorption of this wavelength make