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# Laser welding of steel to aluminium: Thermal modelling and joint strength analysis

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## ABSTRACT

The integrity of steel-aluminium dissimilar alloy joints is dependent on the thermal cycle applied during the joining process. The thermal field has a direct influence on the growth of the intermetallic compounds (IMC), which result from the reaction between iron (Fe) and aluminium (Al), but it also determines the size of the bonding area of the joint. A finite element (FE) thermal model was developed to predict the transient thermal cycle at the Fe-Al interface for different levels of applied energy by changing the power density and interaction time. The time-temperature profiles were correlated to the weld geometry, IMC layer thickness and mechanical strength. The experimental results showed that having a small bonding area is equally detrimental to the mechanical strength of the joint as having a thick IMC layer. The FE model suggested that comparing to time, the temperature is more important in laser welding of steel to aluminium as this is the factor which most contributes to the growth of the IMC layer and the formation of the bonding area. However, it was not possible to identify a thermal field able to produce simultaneously a large bonding area and a thin IMC layer to optimize the joint strength.

## 1. Introduction

In automotive and maritime industries hybrid structures using different metals have been a research focus for a long time. The main driving force for this is the complementary properties of the metals and the development of design efficient structures. However, for many metallic combinations joining can be difficult due to dissimilarities in physical properties or poor chemical compatibility. In particular, when joining steel to aluminium the reaction between atoms of iron (Fe) and aluminium (Al) during the joining process form brittle intermetallic compounds (IMCs) (Bouche et al., 1998; Springer et al., 2011). The mechanical strength of the joint is limited by the presence of these IMCs and therefore the amount of these compounds should be minimised.

Studies have been carried out either aiming to understand the mechanism of formation and growth of the Fe-Al IMC layer or to maximise the mechanical strength of joints produced with different joining processes and then correlating the IMC layer thickness with the joint strength (Bouche et al., 1998; Shahverdi et al., 2002). The outcome of this research showed the composition and morphology of Fe-Al IMCs, the theoretical diffusion equations calibrated against experimental validation which determine the growth rate of these IMCs, and most important, the key parameters in the formation and growth of the IMCs, time and temperature.

All fusion joining processes occur in transient conditions and it is not possible to control temperature and time independently. The IMC layer thickness and the weld geometry (in particular weld width) are determined by the thermal cycle applied to the joint. Therefore, to control these two factors it is necessary to understand the thermal cycle and their dependency on it. FEA is a useful tool to estimate the thermal cycle under different welding conditions, i.e. different energy levels.

The main advantages of laser conduction welding compared to arc welding are (1) the control of the melt pool geometry and dimension by varying the laser metal interaction, flexibly which would be hard to achieve by an arc source e.g. GTAW; (2) minimal heat affected zone due to higher energy density of the laser process; (3) high cooling and solidification rates restricts diffusion an important aspect for such jointing; (4) laser energy can be applied in the most focused and directional manner which would allow more control on the heat input and thereby IMC formation. What is furthermore important is that with TIG it would not be possible to control the temperature gradient in a manner that only sufficient heat reaches near the interface to melt the aluminium alloy and wet the steel. Such control would not be possible

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**Table 1**
Chemical composition of base metals.

| Material | Elements (wt.%) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Al | Fe | C | Si | Mn | P + S | Ni | Ti | Cu | Mg | Zn | Cr | Other |
| XF350 | 0.047 | Bal. | 0.059 | 0.021 | 0.610 | 0.025 | 0.020 | 0.001 | 0.03 | – | – | 0.030 | 0.255 |
| 5083-H22 | Bal. | 0.400 | – | 0.400 | 0.500 | – | – | 0.150 | 0.100 | 2.600–3.600 | 0.200 | 0.300 | – |

by traditional non-consumable processes such as TIG or plasma.

In laser welding there are only a few research papers published where the IMC layer thickness is correlated with time and temperature. Fan et al. measured the thermal cycle at the interface between steel and aluminium and correlated the laser power with the peak temperature, cooling time and with the IMC layer thickness (Fan et al., 2011). However, the authors have not considered the two other important laser processing parameters, travel speed and laser beam diameter. The results showed that the IMC layer thickness was dependent on both peak temperature and cooling time. It is important to refer that in fusion joining processes as temperature and time are inter-dependent parameters, therefore when temperature increases, the time that the material is above a certain temperature also increases. FEA was used by Borrisutthekul et al. to predict the transient thermal cycle at the interface of the lap joints (Borrisutthekul et al., 2007). In this case the authors only assessed the influence of welding speed (or travel speed) and the material of the backing bars (heat sink) on the IMC layer growth. They showed that higher travel speeds and backing bars made of high thermal conductive materials minimise the IMC layer thickness. Once again, the authors have not considered the effect of laser power and laser beam diameter in the IMC layer growth. In equilibrium conditions, Wang et al. studied the formation of IMCs in Fe-Al alloys by heat treatment and also concluded that the IMC layer grows with both temperature and time (Wang et al., 1998). The authors also showed that time, as opposed to temperature, does not change the IMC composition.

In published work only IMC layer thickness has been correlated with mechanical strength of the joints whereas the dimension of the bonding between the steel and aluminium has been disregarded. One would expect the mechanical strength to follow a linear evolution with bonding area. However, the linear trend is not observed due to the continuous IMC layer formed at the joint interface. Also, Schubert et al. and Ozaki et al. estimated that an IMC layer thickness up to 10 µm would produce strong Fe-Al hybrid joints (Schubert et al., 1997; Ozaki and Kutsuna, 2009). However, if there is a positive effect in using very low energy in the joining process to suppress growth of the IMC layer, it is also true that this results in a small bonding area which reduces the joint strength. The temperature profile during the joining process determines both IMC layer thickness and bonding width. Therefore, it is important to characterise the evolution of these factors in terms of time and temperature so that the process can be optimised to achieve the best possible combination of mechanical strength and toughness. Previous research by Meco et al. showed that by increasing the amount of energy, by increasing power density, interaction time or laser beam area, both IMC layer thickness and bonding area were increased in laser welded joints (Meco et al., 2014). A larger bonding area contributes to a stronger joint but conversely, a thicker IMC layer is detrimental to the joint. It is therefore important to find a balance between these two parameters to obtain optimized joint strength. Mathieu et al. have discussed the importance of global geometry of fillet welds in laser brazing applied to steel to aluminium joints (Mathieu et al., 2007). The authors concluded that the geometry of the weld (concavity and wetting) plays an important role in the mechanical strength of the joint after observing samples with IMC layer thickness less than 10 µm but still showing poor mechanical properties.

The fundamental laser material interaction parameters, including power density or intensity (Eq. (1)), interaction time (Eq. (2)) and specific point energy (Eq. (3)) are used in this work. These parameters fully determine the way the material responds to the laser energy independent of the laser system in use (Suder and Williams, 2012) and determine the thermal cycle and cooling rate and thus, the weld geometry and microstructure changes (Williams and Suder, 2011). Therefore, the results obtained in this work can be applied or interpreted for any laser system.

- Power density, $MW.m^{-2}$ $$PD = P.\ A_{beam}^{-1} \quad (1)$$
- Interaction time, s $$t_i = D_{beam}.\ TS^{-1} \quad (2)$$
- Specific point energy, kJ $$E_{sp} = PD \times t_i \times A_{beam} \quad (3)$$

Power density is defined by the ratio of laser power and laser beam area projected on the substrate. In continuous laser mode, interaction time is defined as the ratio of beam diameter and travel speed. The specific point energy is the product of power density, interaction time and laser beam area and represents the total energy transferred to the work piece through the irradiated area.

The aim of this work is to understand how the IMCs and bond area affect the mechanical strength of the joints and how temperature and time affect these two parameters individually.

## 2. Materials and methodology

### 2.1. Materials

Plates of 2 mm low carbon steel (XF350) and 6 mm 5083-H22 aluminium alloy were used. The chemical composition and mechanical properties of the materials are detailed in Tables 1 and 2, respectively. The plates were 150 mm long and 138 mm wide, these dimensions were according to the standard for shear testing resistance seam welds (British Standard Institurion, 2001).

All plates were cleaned before welding. The steel was ground and the aluminium was linished to remove any oxide layer from the surface. Afterwards all plates were degreased with acetone.

### 2.1.1. Laser welding

The joints were produced in a lap configuration with an overlap of 46 mm, with steel positioned on the top of aluminium (Fig. 1a). Laser welding in conduction mode was used because of the characteristic weld shape with low depth-to-width ratio. This welding mode is necessary for the joint configuration used in this work to avoid the mixing of the steel and aluminium in liquid state. This welding mode also avoids any vapourisation effects which leads to poor quality welds. In this manner, the heat produced when the laser beam irradiates on the steel surface is smoothly conducted through the thickness of the steel

**Table 2**
Mechanical properties of the base materials.

| Material | Yield strength [MPa] | Ultimate tensile strength [MPa] | Total elongation at failure [%] |
|---|---|---|---|
| XF350 | 368 | 474 | 23 (at 80 mm of gauge length) |
| 5083-H22 | 250 | 337 | 8 (at 50 mm of gauge length) |