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Technical Paper

Tool geometry optimization in friction stir spot welding of Al-steel joints

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ABSTRACT

The necessity to reduce the weight of transport structures, such as cars and airplanes, has become more important due to gas emission regulations. In this regard, the use of hybrid structures made of steel and aluminum is a way to achieve this goal. Joining aluminum to steel is a great challenge and Friction Stir Spot Welding (FSSW) has become as a new potential welding technique to produce dissimilar joints. Despite Friction Stir Welding has been studied on different similar joints, the information related to the influence of FSSW parameters on the evolution of aluminum-steel joints is scarce. So, the effect of the tool geometry and its penetration depth during FSSW of AA5052–LCS (Low Carbon Steel) joints, has been studied. During FSSW, axial load and consumed electrical current were recorded in order to improve the understanding of the welding process. Macro and microstructural characterization was done on the cross section of the welded spots. The mechanical properties of the joints were determined by microhardness profiles and by Peel and Cross Tension tests. The fracture loads increased when the tool penetration depth goes up. The tool geometry optimization also increased the fracture loads.

1. Introduction

Fuel efficiency, lowering carbon emissions and passenger safety have been the main drivers in designing automobiles for the past twenty years. In this sense, vehicle weight reduction was identified as a key strategy to minimize fuel consumption [1]. Lightweight materials such as aluminum and magnesium, when properly designed, can be used to replace equivalent steel assemblies with approximately half the weight [2]. The main use of this material on cars structures has been on closure panels such as hoods, doors and lift gates to reduce weight and improve vehicle fuel economy [2]. Current closure panel joining techniques include Resistance Spot Welding (RSW), Self-Pierce Riveting, and clinching [2]. However, the disadvantages of these methods to weld aluminum sheets include weld electrode dressing, high energy consumption, and the use of consumables that add weight to the structures. The welding method used for aluminum sheets is one of the key technology drivers to enhance weight reduction in the automotive industry, and hence, Friction Stir Spot Welding (FSSW) is being considered as an alternative joining technique [2]. The use of aluminum parts in cars structures implies the joining of aluminum and steel sheets. Joining dissimilar materials may present the advantages of both materials, offering solutions to specifics engineering problems but often presenting more difficulties. Joining of Al to steel sheets has become very important in the industry and several joining methods including fusion arc welding processes, laser beam welding, resistance welding, mechanical joining, brazing, Cold Metal Transfer, hot bonding or even hybrid joining techniques have been considered [3].

Several aspects have to be considered when a dissimilar joint is going to be designed. The main are: joint geometry, sheets thicknesses, thermal distortions, galvanic corrosion, residual stress because of welding and joint mechanical properties. Depending on the specific process, other aspects have to be also considered: melting points, formation of intermetallic compounds and the effect of the thermal cycle during welding on the microstructural evolution of the base materials [4]. The main problem when welding aluminum with steel is the metallurgical evolution of the joint related to the formation of Inter Metallic Compounds (IMC). The thermal cycle during welding may form different intermetallic compounds in the interface between both materials and during solidification

Abbreviations: FSSW, friction stir spot welding; RSW, resistance spot welding; IMC, inter metallic compounds; TPD, tool penetration depth; PT, peel test; CT, cross tension; BM, base material; HAZ, heat affected zone; TMAZ, thermo mechanical affected zone; SZ, stir zone; SEM, scanning electron microscope; LCS, low carbon steel.

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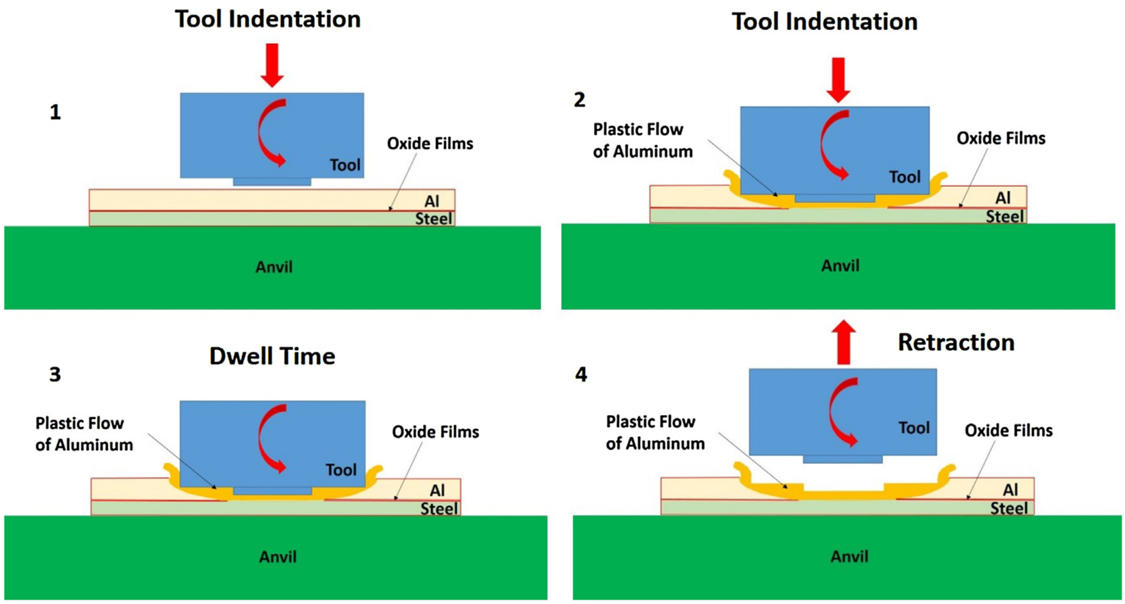

Fig. 1. Friction Stir Spot Welding of Aluminum to steel sheets.

Table 1
Chemical composition of the materials used (wt%).

Material	C	Si	Fe	Cu	Mn	Mg	Zn	S	Cr	P
AA5052-H32	–	0.06	0.25	0.01	0.01	2.38	0.005	–	0.16	–
LCS	0.08	0.10	Bal.	–	0.40	–	–	0.025	–	0.025

of the diluted zones. Formation and growth of IMC may occur during conventional fusion welding processes and even in solid state joining processes. When the heat input is increased, the thickness of the intermetallic layer that grows in the interface between the materials being joined also rises [4].

FSSW technique was invented by Mazda [2]. It is a solid state welding process which has three main steps, as it may be appreciated in Fig. 1. In first place, a rotating non consumable tool with a pin is plunged into the two sheets that are going to be welded in a lap configuration (steps 1 and 2 in Fig. 1). At the same time, a backing plate, or anvil, contacts the lower sheet from the bottom and supports the axial load made by the welding tool during the welding cycle. Also, in this first step, the geometry of the tools shoulder gives compressive force to the materials. In the third step, when the tool penetration depth is reached, the downward movement stops ant the welding tool is held in that place for a certain period of time, known as dwell time. In this step, heated and softened material due to the welding action causes plastic flow. Finally, in the fourth step, the welding tool is retracted from the sheets while a solid state joint has been made between the upper and lower sheet. This technology was first used in Mazda RX-8 aluminum rear door panel spot welding in 2003 [2].

Since the required heat input in a solid state joining process, such as FSSW, is much less than that of the RSW, nowadays FSSW has been regarded as one of the most available method for the dissimilar welding of Al to steel alloys [5].

The appropriate selection of the welding parameters of FSSW would control the microstructural evolution of the joint and may produce sound joints with low thermal cycles. Tool geometry, tool rotation speed, dwell time and tool penetration depth are considered as the main FSSW welding parameters [6–10]. Finally, another critical factor in the joint strength in aluminum/steel friction stir joining is the tool penetration depth (TPD) into the steel sheet [11,12]. According to [11,12], as much as the tool penetrates the steel sheet, lower is the thickness of the intermetallic layer and higher is the inter mix between sheets, improving welds strength. Previous works, have shown that when the tool slightly runs into the steel surface, the joint strength is greater than that when the probe tip does not reach the steel surface [6,7]. However, more complex tool materials with much higher strength than steel, such as carbides or other ceramics like Polycrystalline Cubic Boron Nitride, have to be used. Nevertheless, it is possible to use cheaper tool materials and still promote bonding via diffusion without penetrating the tool into the lower sheet [10]. In Fig. 1 the main steps of this welding process are shown.

Joining Al/St sheets is still of great interest, especially when welding thin sheets without inter mix between Al and steel, with cheap welding tools. According to [9], tool design is a key factor when welding Al/St thin sheets by FSSW. It has been appreciated that a plastic instability occurs, when welding with high levels of TPD, on the aluminum sheet, causing high deformations of it and weld defects. It has been previously reported that Al/St thin sheets may be joined using a tool made of a common H13 [13]. However, the shoulder remains relatively far from the interface and mechanical properties were not high enough [13]. It has been previously reported that the optimal TPD is 0.85 mm when welding with a tool shoulder and probe diameter of 10 and 2 mm, respectively [14]. However, for high levels of TPD a plastic instability of the aluminum sheet was also appreciated [9,14]. On the other hand, it has been observed that the optimal mechanical properties are achieved when the shoulder of the welding tool gets closer to the joint interface [15]. It is worth noticing that previous works have used long dwell times of 5 s [9,14] up to 15 s [16]. These dwell times are too high taking into account the productivity of an assembly process and its optimization is a pending matter.

The aim of this work was to design FSSW tools able to weld Al/St thin sheets without defects. Moreover, the effects of tools geometry and its penetration depth on the weldability and mechanical