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Preliminary study on the feasibility of friction spot welding in PMMA

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KEYWORDS

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ABSTRACT

In this work the feasibility of Friction Spot Welding of thermoplastics was investigated on poly (methyl methacrylate) plates. Preliminary results have shown that the weld strength is comparable to other available welding techniques, while joining times are equal or shorter. Light optical microscopy and Vickers microhardness measurements showed the presence of a heat affected zone and a thin, consolidated stir zone, where physical-chemical transformations related to thermo-mechanical processing led to changes in local mechanical strength. The work has demonstrated for the first time that the welding of thermoplastic materials by Friction Spot Welding is feasible.

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1. INTRODUCTION

Modern thermoplastic materials are used in an expanding range of engineering applications, such as in the automotive industry, due to their enhanced stress-to-weight ratios and toughness. Although plastics offer high degrees of design freedom and processing ability, the fabrication of larger and complex parts usually requires joining technologies, such as welding. In the last decade, efforts have been made to improve the present processes and develop new polymer joining techniques [1].

In this preliminary work, the feasibility of the new technology Friction Spot Welding (FSpW) of thermoplastic is evaluated using Poly(methyl methacrylate), PMMA. Joint microstructure, shear strength and process properties relationships are discussed. The PMMA is an amorphous thermoplastic widely used in the automotive sector as a substitute for glass (a denser material) or polycarbonate (an expensive plastic) parts. In addition of its reputation for being easy to process, PMMA can be welded by different techniques [2]. Furthermore, PMMA is a good candidate for exploratory studies on joining technology, due to its high transparency allowing an initial non-destructive investigation of the weld. Finally, the large availability of information regarding the PMMA properties permits a direct comparison of FSpW to other joining processes.

2. MATERIAL AND METHODS

Three-millimeter PMMA cast plaques (Plexiglas GS – Evonik) were cut to produce 25 x 100 mm length welding specimens. This PMMA grade offers a tensile strength of 80 MPa and a T_g of about 107°C, along with good dimensional stability and excellent weather and UV resistance [3].

Single lap joints were produced in friction spot welding equipment (RPS 100, Harms & Wende, Germany). Microstructure was evaluated by reflective light optical microscopy. Local mechanical properties were analyzed by Vickers microhardness (50 g of load, 15 s indentation time and 300 µm indentation distance). Lap-shear testing was performed in accordance with ASTM D1002-5 [4] at room temperature and 2 mm/min.

3. FRICTION SPOT WELDING OF PMMA

Friction Spot Welding is a new technology, primarily developed for metal applications [5]. Due to its positive features in metal welding, such as short joining cycles and improved performance, the feasibility of FSpW in thermoplastics requires investigation. Figure 1 summarizes the main steps of the FSpW procedure. Two process variants are possible, the “Sleeve-Plunge” and the “Pin-Plunge” [5]. Since the only functioning difference of both variants is the plunging action, only the former is described in this work. The main advantage of the Sleeve-Plunge variant is the formation of larger weld zone, resulting in joints with superior shear strength [6]. However the Pin-Plunge variant is easier to perform, because it demands less power from the machine.

Work pieces are first fixed in the welding machine (Figure 1 A). Next the sleeve and pin begin to rotate in the same direction; the sleeve (Figure 1 B) is forced against the upper joining partner generating frictional heat. The temperature increases and a volume of softened/molten polymer is created. While the sleeve is inserted into the partners the pin is retracted, creating a cavity where the softened material will flow into. When the desired plunge depth is reached, the sleeve and the pin return their original position (Figure 1 C); this will force the softened polymer in the cavity to refill the keyhole left behind by the sleeve. By the end of the welding cycle the tool is retracted and the joint consolidates under pressure, to avoid thermal shrinkage (Figure 1 D).

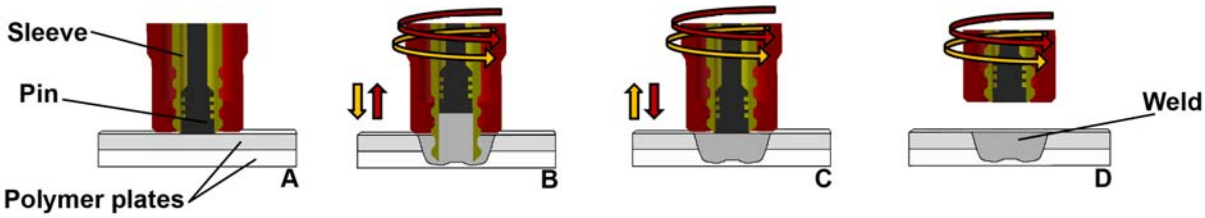


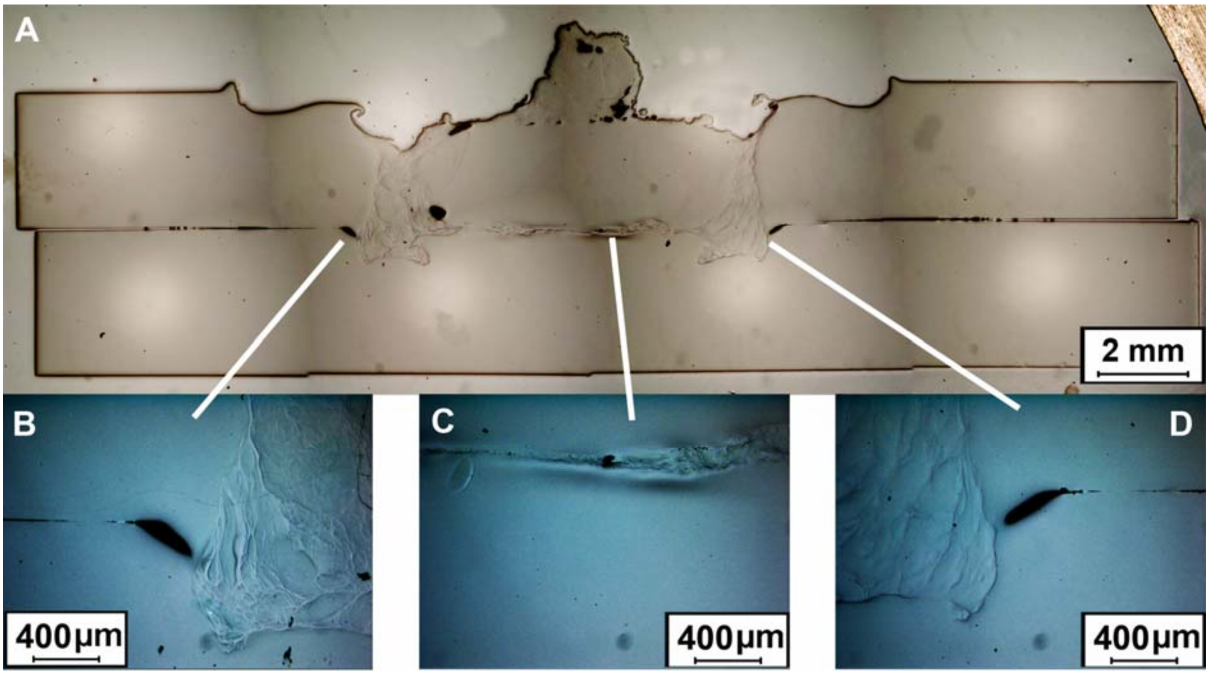
Figure- 1- Illustration of the FSpW process: (A) to (D) the main steps with the Sleeve-Plunge variant.

When welding thermoplastics by FSpW, a higher amount of thermal energy is required to achieve the desired plasticizing volume, due to the low thermal conductivity of polymers. For this reason heat losses should be reduced. $TiAl_6V_4$ titanium alloy was selected as the tool material due its low thermal conductivity [7]. The dimensions and geometries of the tool comprised a threaded sleeve, pin and a clamping ring of Φ 9, 6 and 14.5 mm, respectively.

4. RESULTS AND DISCUSSIONS

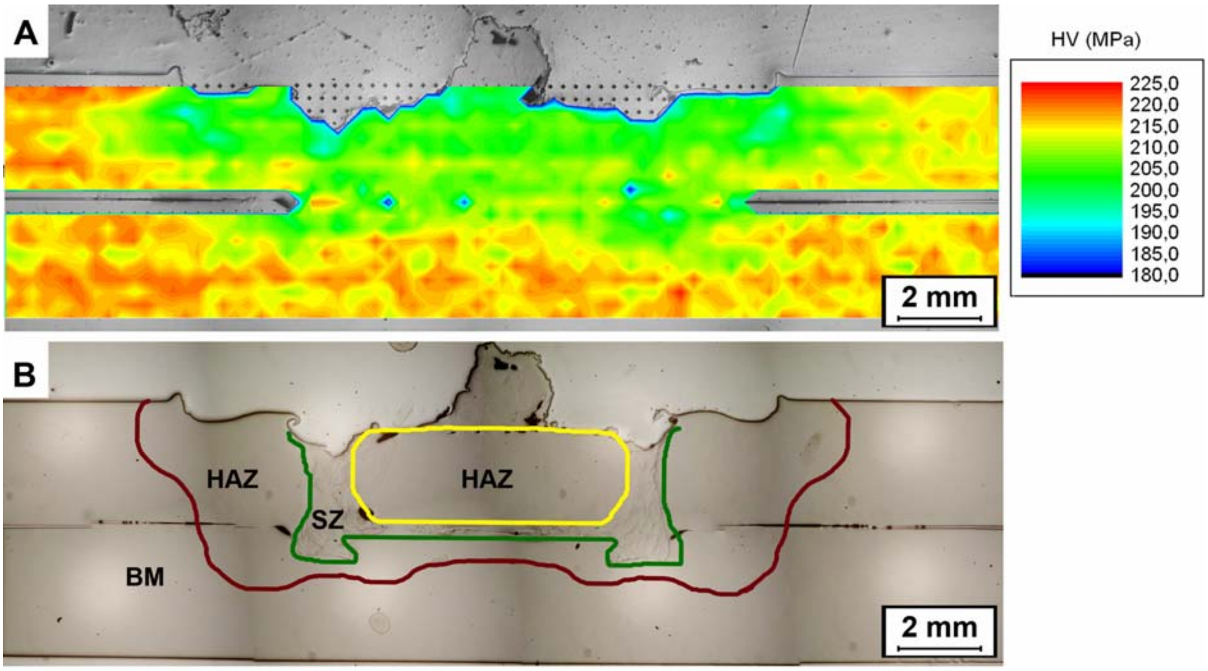
Joints were successfully produced within the following ranges: rotational speed of 500-2000 rpm, welding times of 5.5 - 12 seconds, joining pressure of 3 bar and plunge depths of 3.5 - 4 mm [8].

In this preliminary work, selected results of PMMA FSpW joints are presented. A cross-section view from the weld center can be observed in Figure 2 A. Figure 2 B and Figure 2 D show the refilled region with consolidated polymer. Figure 2 C the bonding line between the upper and lower plates can be seen. It is possible to observe the presence of few voids along the weld seam. Although the mechanisms of void formation in FSpW of thermoplastics are still under investigation, it is believed that these defects can be related to thermal shrinkage, entrapped air or some physical-chemical structural changes, such as structural water evolution. Figure 3 A shows the microhardness distribution and Figure 3 B the microstructural zones found in a typical PMMA FSp weld ("sleeve plunge" at 500 rpm/ 5.5 s/ 3 bar/ 4 mm). Thermo-mechanical polymer degradation may also occur [8].



Figure– 2 – Microstructure of a PMMA joint of FSpW ("sleeve plunge" at 500 rpm/ 5.5 s/ 3 bar/ 4 mm): (A) Cross-sectional view from the weld center; (B) and (D) Details of the consolidated plasticized polymer; and (C) The central region of the spot, showing the bonding line between upper and lower plaques.

.A region in the center of the joint with an average decrease in hardness of about 5-10% from the PMMA base material can be identified in Figure 3 A. Depolymerization in PMMA starts at about 250°C by chain scission [9]. This stage is not significant and a considerable decrease in molecular weight will only take place above 250°C. Surface temperatures of 140-160^{o}C within short heating times (5 to 12 s) are typically observed in PMMA FSp joints [8]. From the slight decrease in hardness in the weld (Figure 3 A), it can be assume that the temperature in the rubbing area may have achieved the degradation-commencement temperature (250°C) of the PMMA. At lower joining temperature and dwell times, thermal degradation is reduced and any loss in strength becomes insignificant. Further studies are in progress, aiming to better understand the microstructural changes in PMMA joints.



Figure– 3 – (A) Microhardness distribution and (B) Proposed microstructural weld zones of a typical FSp joint on PMMA.

Based on the present state of knowledge, the microstructural weld zones present in FSpW are presented in Figure 3 B. The *Heat Affected Zone (HAZ)* comprises the regions where no visual strucutural changes can be observed; a reduction in microhardness in comparison to the *Base Material (BM)* has been observed (see Figure 3 A). The *Stir Zone (SZ)* is the region where the softened (plasticized) material refilled the hole created by the tool insertion. In the top central portion of the weld (above the HAZ in Figure 3 B), a small consolidated plasticized zone, resulting from contact with the heated pin, can be seen. This thermo-mechanically altered region does not affect the weld strength and can be further removed by machining if required.

Average joint lap-shear strengths of up to about 9.5 MPa were achieved. Figure 4 A shows the average shear strength for two joints welded with different plunge depths (3.5 and 4 mm) at

500 rpm, 5.5 s, and 3 bar. A nominal circular welded area, calculated from the sleeve's external diameter was considered. This is the normal procedure adopted for spot joints. Higher plunge depths resulted in greater joint strength (Figure 4 A). This can be explained by an increase in the welded area at higher plunge depths, due to higher heat input and material mixing. Similar trends were observed when increasing the Rotational Speed and Joining Time [8] parameters.

A comparison was attempted with the available literature data on the strength of PMMA spot welds. Figure 4 B summarizes examples of maximum lap-shear strengths of different PMMA welded joints. Yussuf et al. [10] obtained shear strength of 6.8 MPa in microwave welded specimens of 2 mm thickness using 15 seconds. Sood [11] obtained maximum lap-shear strength of 2.35 MPa in his thermally bonded specimens (100°C for 120 seconds). Souza [12] observed average strengths of 1.1 MPa in ultrasonic welded PMMA (at a welding pressure of 0.095 MPa, 0.4 seconds and holding time of 0.15 s). It is worth mentioning that FSpW total joining time (clamping, welding and specimen removal time) is normally comparable with or faster than the compared published data.

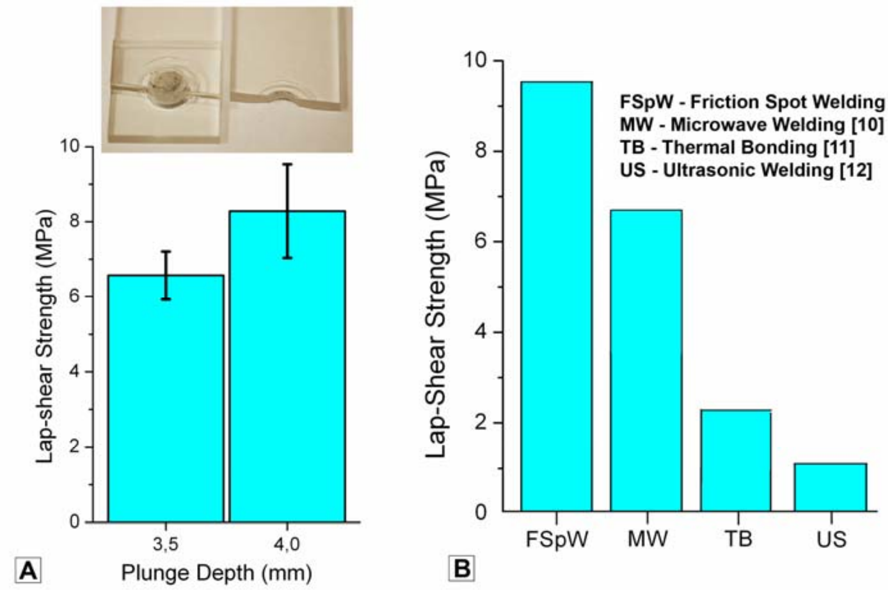


Figure 4 – (A) average strength of PMMA FSpW joints (3 replicates) for two different plunge depths. An example of a fractured lap-shear specimen can be seen at the top of A; (B) Maximum weld strengths of PMMA joints welded by different techniques.

5. CONCLUSIONS

The feasibility of the FSpW of thermoplastics was successfully demonstrated in this work. Preliminary results on 3 mm PMMA cast material have shown that current friction spot weld strength is comparable to other welding techniques available. However, further work must be carried out in order to better understand the structural phenomena controlling microstructure and joint performance. The development of new and improved tool geometries, as well as the selection and testing of adequate tool materials, will lead to a decrease in weld imperfections and higher strengths.

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