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The influence of process parameters in friction stir welding of Al-Mg alloy and polycarbonate

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ABSTRACT

The Role of rotating and travelling speed of the friction stir welding (FSW) tool on the dissimilar lap-joining of an AA5058 aluminum alloy and polycarbonate (PC) sheets has been investigated. The Relation of the processing parameters with tensile, bending strength, material flow and hardness of the joints were studied to attain defect-free joints with proper mechanical strength. The results showed both the size and the contribution of PC and aluminum alloy on the formation of stir zone are strongly related to the tool's rotational speed. Tool's rotational speed mainly controls the joint strength and the fracture mode, while traverse velocity affects the size of aluminum fragments within the PC matrix. The most suitable dissimilar lap-joining microstructure is achieved at 1600 rpm and 45 mm/min tool speed. Under this condition, the maximum joint tensile and bending strengths attained are 68.2% (46 MPa) and 69.4% (60 MPa) of PC raw material respectively. Fractography indicated that during the tensile test, the rupture occurs below and in the middle of the stir zone on AA5058 alloy/PC interface during the bending test. The hardness of the PC after FSW decreased by the molecular weight reduction and AA5058 micro-hardness increased because of the fine grinding after suffering thermo-mechanical cycle.

1. Introduction

Recently, especially in automotive industries, widely used metals like steel are being replaced by the new lighter nonferrous materials such as magnesium and aluminum alloys [1]. In addition, polymer technology developments led into modern structures [2–4]. Modern thermoplastic materials as a specific type of polymer for having re-shaped properties, are used in different engineering applications, such as automotive and aerospace industries, due to their lower cost, high toughness and stress ratios compared to their weight [3]. These are one of the most commonly used materials in many industrial applications due to their easy manufacturing process [5]. Even though thermoplastic materials offer wider choice of design or process, manufacturing of bigger and complex parts frequently need joining to different materials and alloys [6,7]. These materials can be integrated with the polymer-metal hybrid technologies in a monadic component [8–10]. Studies and developments of such hybrid structures which led to the reduction of the weight of structures is increased in recent years. Lower fuel usage and CO_2 emission are the main factors that persuade the engineers to produce these lightweight structures [11,12]. Joining of polymer-metal hybrid structures is more difficult by traditional welding process due to their big difference in physical and chemical features [13]. Metal-polymer joining limitations such as surface treatments and adhesive bonding time, motivated novel joining techniques [14].

Amancio et al. classified various polymer-metal hybrid structures joining technologies from more conventional process like adhesive bonding to novel welding-based technologies like ultrasonic and inductive welding process [7,15,16]. Abibe et al. used a technology, based on staking and mechanical fastening which is called “injection clinching joining” to investigate the mechanical and failure behavior of the polymer-metal joints [17]. Lambiase and Paoletti joined thin aluminum sheets with Carbon Fiber Reinforced Polymer (CFRP) laminates by friction assisted clinching and showed that in this process the material formability increased and defect free joint was achievable even with sharp tool [18,19]. Blaga et al. investigated joining of the titanium grade 2 with the glass-fiber-reinforced thermoplastic composites by friction riveting technique [20]. Feasibility study, mechanical properties and optimization of ultrasonic spot welding of aluminum and carbon-fiber reinforced polymers (CFRP) is carried out by Balle et al. [21,22]. They also studied the process parameters to achieve the quasi-static tensile shear strength of up to two times higher than the weakest base alloy. Goushegir et al. investigated the weldability of AA2024 and CFRP using different post heat treatments, which resulted in joints with significant shear strength [23,24]. The feasibility of induction welding

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of steel and Al-Mg alloy with CFRP was investigated and by Mitschang et al. [25]. They also studied the effect of different metal surface pretreatments on the joint shear strength. However, due to the high manufacturing cost and equipment complexity of aforementioned welding methods, developing a new welding process is still needed [1]. Constant efforts are going on to develop and improve alternative joining techniques for these hybrid structures, such as the infrared welding, friction stir welding and the forced mixed extrusion technique [26]. One important advantage of the mentioned processes compared with the regularly used mechanical fastening or adhesive techniques is the higher assembly rates and consequently lower assembly costs. FSW is a rapidly developing solid state joining process with reduced material waste and without radiation or harmful gas emissions which are usually associated with the fusion welding techniques [27]. In FSW process, a hard rotating tool and a pin is inserted in the butting edges of the sheets traverse along the joint line [28]. Due to the friction and deformation between tools and surrounding materials, heat will be generated [29]. The tool rotation and traverse expedite material flow from the front to the back of the pin and welded joint are produced [30].

Accordingly, there are a number of researches on the possibility of using friction base process to join metals to polymers. Amancio-Filho et al. investigated on the feasibility of friction spot joining between AZ31 magnesium and CFRP composites and showed that metallurgical and physicochemical transformations of polymer take place during welding [4]. Yusof et al. studied on friction spot welding of AA5052 aluminum and PET and concluded that a successful joint produced with the aid of frictional heat energy generated from the FSSW process [30]. They showed that the plunge speed had a significant influence on the heat affected area while joined area was relatively reducing as the plunge speed increased. Goushegir et al. studied on the friction spot welding of AA2024 aluminum alloy and carbon-fiber reinforced poly (phenylene sulfide) composite [23]. They revealed that higher rotational speed of the tool lead to the highest shear strength of the formed joint. Lambiase et al. joined PVC and AA5053 aluminum alloy with friction assist joining [31–33]. They revealed that by controlling the plunge force, dwell time and clamping frame material, it is possible to achieve a joint with 97 percent of PVC strength. Lambiase and Paoletti also studied on friction assist joining of AA5053 aluminum alloy and poly etherether ketone (PEEK) [32]. They showed that with laser texturing of aluminum surface, achieving a joint with about 83% PEEK strength is possible. Khodabakhshi et al. studied the bonding mechanism, joint strength, and micro-hardness of friction stir welding of AA5059 aluminum alloy and high density polyethylene (HDPE) [34]. A maximum joint strength ratio improvement up to 50% with failure location from the interface of stir zone with aluminum alloy was reported. They examined the main bonding mechanisms and the nature of interface during dissimilar friction stir joining of aluminum and polymer with employing the scanning- (STEM) and high resolution-transmission electron microscopy (HR-TEM) [34]. As a result, mechanical interlocking and secondary Vander Waals interaction assisted by chemical bonding with formation of a thin alumina layer at the interface have been introduced as the main mechanisms. Liu et al. used friction lap welding for joining AZ31B Mg alloy and MC Polyamide 6 (Nylon 6). They showed that increasing welding speed, tool rotation rate and plunge depth will help to reduce the volume of bubbles in joint line and produce the strongest joint with area fraction of 8% bubbles [35]. Ratanathavorn et al. welded AA6111 aluminum alloy to polyphenylene sulphide (PPS) by FSW process. They indicated that the welding stir zone contained a blend of AA6111 aluminum alloy particles and chips which restricted by PPS matrix [36]. The sizes and shapes of the AA6111 alloy fragments in the stir zone are closely related to the travelling speed as rapid linear speeds tend to create coarser fragments. Shahmiri et al. studied on FSW of aluminum alloy to polypropylene sheets [37]. They indicated that shear strength of the joints decreased by the growth of the heat-input due to the increase in the thickness of the interaction layer. The maximum shear-tensile strength of this joint was about 20% of the shear strength of polypropylene. In the present study, the effects of tool's rotating and travelling speed of the overlap joint with AA5058 aluminum-magnesium alloy to transparent polycarbonate (PC) was investigated by using FSW. The tool used in this work generated aluminum fragments instead of plasticizing. Simultaneously, the PC melted and merged into the chipped zone to form a joint. Formation of joint mechanisms were studied in terms of the materials flow pattern as characterized using optical microscopy (OM) and scanning electron microscopy (SEM) equipped with energy dispersive X-ray spectroscopy (EDS) analysis. The prepared dissimilar FSW joints were evaluated in terms of joint strength, fracture behavior, hardness and microscopic examination of the weld cross-section to find out the optimum working window with maximum improvements in the mechanical performance.

2. Experimental procedure

An AA5058 aluminum-magnesium alloys and polycarbonate (PC) polymer sheets utilized as the raw base materials. These plates were cut in the dimensions of 200 × 50 × 3 mm by using water-jet machine. AA5058 alloy is commonly used for automobile sheet panels and PC is a special thermoplastic which shows good thermal and chemical stability that is usually being used for lighting systems and external parts of automobile body. These initial materials have potential application in automobile body structure. The physical properties of the selected initial materials are presented in Table 1.

The lap-joint design with placing the PC on top was examined during the friction stir welding for processing an AL-polymer bi-material structure from these dissimilar initial materials. A flexible clamping system made of carbon steel with two supporting plates was designed to clamp the raw sheets during the welding process in their proper positions. Single-pass friction stir welds were conducted using a milling machine, in position control, and FSW tool was made of tungsten carbide. The schematic view of plates and clamping system, tool plunge depth and tilt angle is shown in Fig. 1a and b, respectively.

Real thermal histories during FSW process were monitored by placing a 0.5 mm diameter *K*-type thermocouple (Omega Engineering, USA) inside the different regions of aluminum-side and 0.5 mm diameter *J*-type thermocouple (Omega Engineering, USA) in PC-side. The *J*-type thermocouple was attached into PC holes with Testor's cement for plastic material and held for 12 h before welding process to allow the glue to set. Thermocouples with 0.5 mm diameter were embedded into the interface of sheets at a distance of 5, 10, 15 and 20 mm from the joint center at aluminum side and 5, 10 and 15 mm from joint center in PC side. The schematic view of thermocouple places has been shown in Fig. 1c.

The maximum temperature obtained during the process was recorded at each rotational speed. A wide range of FSW tool speeds including the various tool rotating and travelling speed with constant tool tilt angle and tool plunge depth were assessed to establish a suitable working window for producing a defect-free dissimilar joint with

Table 1
The main physical properties of AA5058 aluminum alloy and polycarbonate (PC) polymer.

Base materials	AA5058	PC
Density (kg/m^3)	2685	1220
Ultimate tensile strength (MPa)	145	66.3
Elongation (%)	24	98
Bending strength (MPa)	240	88
Shear strength (MPa)	103	101
Microhardness (HV)	50	–
Hardness (Shore D)	–	90
Glass transition temperature (Tg)	–	147 °C
Melting point (°C)	591	225
Thermal conductivity at 25 °C (W/m.K)	193	0.22