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Microstructure-property characterization of a friction-stir welded joint between AA5059 aluminum alloy and high density polyethylene

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ABSTRACT

Aluminum alloys and high density polyethylene are utilized in a wide variety of industrial applications. In the present work the feasibility of friction stir butt welding between AA5059 alloy and high density polyethylene sheets is examined. The bonding mechanism, joint strength, and microhardness are considered in this study. Various welding parameters and tool alignment were investigated until sound joints were achieved by positioning approximately 85% of the rotating tool in the aluminum material on the advancing side (1.4 mm offset) at constant spindle speed and traverse speed of 710 rpm and 63 mm/min, respectively. The results indicate that AA5059 aluminum and high density polyethylene sheets can be successfully joined with a combination of secondary bonding and mechanical interlocking of the materials, which provides a potential alternative to adhesive bonding or mechanical fastening.

1. Introduction

Global trends in CO_2 emission and gas price have forced automotive/aerospace manufacturer to produce lighter, safer and more environmental friendly vehicles [1,2]. In particular, selection and development of light materials (i.e. aluminum, magnesium and polymers) can significantly result in reduction in the vehicle weight. In the new class of vehicles, the current design of hybrid structures in which different classes of materials (metals or polymers) are present, often require *joining* of the components. High strength, excellent heat and electrical conductivity are among common properties in light-weight metals (i.e. aluminum). On the other hand, polymers, high density polyethylene (HDPE) for instance, offer desirable strength-to-weight ratios, corrosion resistance and insulation properties [3–5]. Therefore, dissimilar material joints between polymer and metal can combine different properties so that the resulting hybrid material can offer structural performance which is a compromise between either of the two constituent materials independently. For instance, enhanced weight-to-strength performance of transportation components is one of the key advantages of polymer–metal joining.

In recent years, HDPEs have attracted more attention in the automotive and aerospace industries due to the fact that they can be easily produced in many different forms to offer a high degree of design freedom [4,6,7]. In 1996, the front end of the Audi A6 automobile was produced for the first time using a hybrid structure combining sheet steel with elastomer-modified polyamide [8]. Currently, polymer/metal hybrids are among the best candidate for replacing all-steel structures in automotive front-end modules [8]. In addition to their aforementioned use in the front-end components, polymer/metal hybrids are currently being used in door modules, instrument-panel and bumper cross-beams, and tailgate applications as well as in other functions, varying from appliance housings to bicycle frames [8].

Adhesives (glues), screws and riveting are the main joining techniques between polymers and metals. However, these joining processes are quite undesirable due to environmental concerns and difficulties of mass production [9]. Therefore other joining processes (i.e. welding) need to be considered for joining metals to polymers. Due to the widely varying physical, chemical, and mechanical properties of metals versus polymers, applying conventional welding processes to join these materials is nearly impossible. The simple explanation is that the plasticizing temperatures to achieve mixing with the harder metallic material during welding are generally excessive and cause the softer polymer to oxidize and degrade. Therefore, there is a niche for novel and innovative joining techniques (i.e. solid-state welding) designed for this purpose. Among solid-state welding techniques, friction stir welding (FSW) is a promising, rapidly growing, and environmental friendly joining method which offers great capability to join dissimilar materials with completely different properties (i.e. metals and non-metals) [10–14]. Since FSW does not involve bulk melting of the components (since the peak temperature in FSW is about 0.6–0.9 of the melting point of aluminum alloys in Kelvin) [15–18], and hence it is among the most convenient

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Table 1
Physical and mechanical properties of HDPE [42].

Molecular weight	Density	Young's modulus	Hardness	Melting point	Thermal conductivity	Softening temperature
28.0 g	0.930–0.965 g/cm^3	1035 N/mm^2	55–70 (Shore D Scale)	135 °C	0.40–0.47 W/m K	112–130 °C

welding techniques for joining dissimilar materials. However, such temperatures open the possibility of melting most polymers in the case of a dissimilar joint with aluminum.

Dissimilar FSW between dissimilar alloys of aluminum as well as joining with other metals has been addressed broadly in previous literature [19–24]. For example, the effect of weld parameters such as the position of each material relative to the tool, plunge depth, and dwell time has been compared to the lap shear fracture load of friction stir spot welded dissimilar lap joints between AA2024 and AA5754 studied by Bozkurt et al. [19]. The experimental results showed that by positioning of AA5754 sheet on the top, a higher joint strength was achieved. Meanwhile, the failure mode was strongly affected by the plunge depth, dwell time and tool tilt angle. In the study of İpekoğlu and Çam [20], dissimilar AA7075-O/AA6061-O and AA7075-T6/AA6061-T6 butt joints were produced by FSW, and post-weld heat treatment was applied to the joints obtained. It was demonstrated that sound dissimilar joints can be produced for both temper conditions. Strength overmatching in the weld zone was achieved in joints between 'O' temper (annealed) materials, and this result is contrary to the majority of results revealing undermatching in joints produced using material in a peak-aged (i.e., T6 temper) condition. In the research of Zhang et al. [21], based on the potential industrial applications of Al/Cu metallic couple, a feasibility investigation was performed involving lap joining of AA6061 alloy to pure copper using submerged (under water) FSW, since this will help to reduce the peak temperature and increase the cooling rate of the joint.

The majority of prior work on dissimilar FSW has focused on dissimilar metals, such as AA5052 aluminum alloy and AZ31 magnesium alloy [22]. In this work, sound joints could be produced with a rotational speed of 600 rpm and welding traverse velocity of 40 mm/min, and it could be noted that the range of processing parameters is far narrower compared to joining of the same metal or alloy. To understand the issues which limit joining, one can consider the work of Grujicic et al. [23,24], where the effects of various FSW process parameters on the heat and mass transport of the material, and microstructure evolution were examined. These results showed that with proper modeling of the material behavior under high-temperature/severe-plastic-deformation conditions, much better agreement can be attained between the computed and measured material-strength distributions and post-weld residual stresses.

Friction stir welding and processing of polymer sheets (i.e. polyethylene and poly methyl methacrylate) are quite well documented [3,4, 25–27]. However, there are very few publications on polymer–metal welding (i.e. FSW, friction stir spot welding, and laser direct joining). Amancio-Filho and dos Santos [26] reviewed different joining technologies for polymer–metal hybrid structures including mechanical fastening, adhesive bonding, and welding processes (i.e. ultrasonic welding and induction welding). Amancio-Filho et al. [5] also studied the feasibility of friction spot joining of AZ31 magnesium to fiber-reinforced and to glass fiber polymer composites. They showed that metallurgical and polymer physical–chemical transformations take place during joining. They concluded that the joining is accomplished by a mixed regime of surface mechanical interlocking (through micro- and macro-constraints related to the metallic nub) and adhesion between the metallic and consolidated polymeric layers, as well as direct partial fiber attachment on the metallic plate. Yusof et al. [28] studied laser joining of polyethylene terephthalate (PET) and AA5052 aluminum alloy. They showed that the shear strength of the joints increases with increasing heat input and pulse duration. In the other study, Yusof et al. [29] assessed joining parameters and mechanical properties of friction stir spot lap joining for dissimilar joint between AA5052 aluminum sheets and PET. They concluded that a successful joint is produced with the aid of frictional heat energy generated from the friction spot welding process and showed that the plunge speed has a significant influence on the heat affected area while joined area was relatively small as plunge speed increased.

Goushegir et al. [30] studied the process temperature and the microstructure of a single-lap friction spot joint of aluminum AA2024 and carbon-fiber reinforced poly(phenylene sulfide) composite. They demonstrated a correlation between the joining area and the lap shear strength of the joint; the higher the rotational speed of the tool is, the larger is the joining area. Wahba et al. [2] successfully achieved lap joints between AZ91D Mg alloy and PET sheets using the laser direct joining method. They considered the process under different processing parameters and lapping configurations and obtained tight bonding in the microsize at the interface between AZ91D Mg alloy and PET due to the induced pressure from generation and expansion of gas bubbles inside PET specimens. Bergmann and Stambke [31] investigated laser-based joining of polymer (Polyamide 6.6)–metal (DC01 steel) hybrid joints. They showed that there is no correlation between the standardized surface roughness parameter and the shear strength of the joint. In their experiments, the failure of the joint occurred within the base material (Polyamide 6.6). Katayama and Kawahito [9] and Kawahito

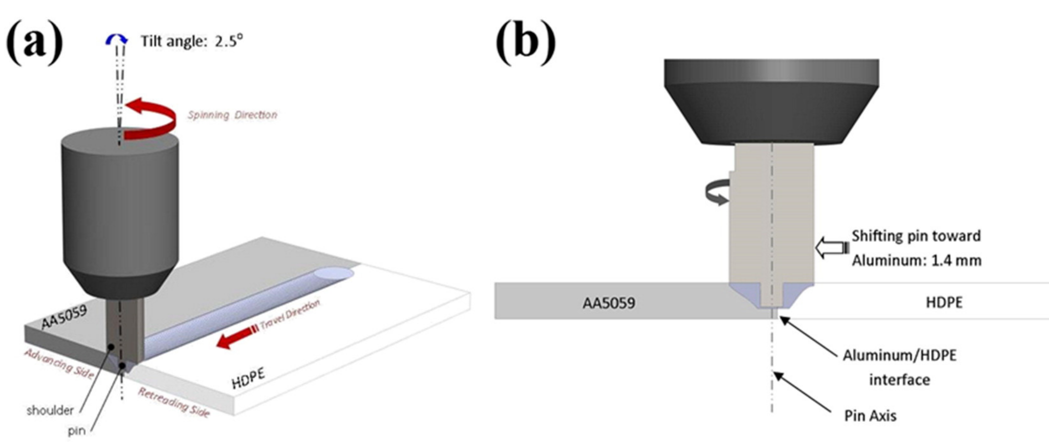

Fig. 1. Schematic of the process: (a) friction stir welding in butt-joint configuration and (b) position of the rotating pin in present study.