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Experimental and thermomechanical analysis of the effect of tool pin profile on the friction stir welding of poly(methyl methacrylate) sheets

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ABSTRACT

Effects of frustum, cubic and triangle tool pin profiles on the friction stir welding (FSW) of poly(methyl methacrylate) (PMMA) were studied by experimental analysis and thermomechanical simulations. It is shown that employing pins with a low contact surface area form macrocracks and voids along the joint line. Edged-type pins locally stir the polymer and cause tunnel defects which are formed at the root of the joint. In contrast, pins with relatively smooth and large surface area would yield a defect-free weldment if an appropriate processing condition is employed. Mechanical examinations in longitudinal (LS) and transverse (TS) directions indicate that the highest tensile strength (LS = 59 MPa and TS = 43 MPa) of the joint is attained for the frustum pin. The result of Izod test also determines a higher impact energy of the joint for the frustum pin as well. Fractographic studies indicate that cracks are initiated from internal defects and voids, propagating through the material to cause brittle rupture. Interestingly, the effect of pin geometry on the tensile strength and impact energy is different than that hardness (in ShoreD scale).

1. Introduction

Friction stir welding (FSW) is relatively a new semi-solid joining processes for thermoplastic polymers with many advantages over conventional methods that can be used for similar- and dissimilar- material welding [1,2]. So far, FSW of different polymeric materials such as high and low density polyethylene (LDPE and HDPE) [3,4], polyamide 6 (PA6) [5], polytetrafluoroethylene (PTFE) [6], polypropylene (PP) [7], acrylonitrile butadiene styrene (ABS) [8], polycarbonate (PC) [9], and poly(methyl methacrylate) (PMMA) have been examined [10]. Common problems in FSW of polymers are related to the pore and cavity formation in the treated area, lack of consolidation, material expelling from the welding line, and low joint strength. These shortcomings may be overcame by employing appropriate processing conditions. For instance, for successful FSW of HDPE, the imposed frictional heat should finely be tuned to avoid polymer melting and defect formation [4]. Under optimized condition, the strength of welded HDPE may reach to ~75% of the base polymer [11]. Friction stir spot welding of HDPE is also challenging and processing parameters such as tool rotation speed, plunge depth, and dwell time affect the tensile and shear strength of the joint [12,13]. Through proper controlling of these parameters, the joint strength may reach to ~48% of the base material [14]. For successful FSW of PE, selecting an appropriate tool tilt angle, employing specially designed tool shoulder (stationary tool shoulder called "shoe"), and pre-heating are recommendable in order to control material expelling from the join line [15–20]. Meanwhile, the effect of tool plunge depth on the strength has been found marginal [21]. Underwater FSW of cast nylon 6 by a double-pin tool at a low tool rotational speed and short dwell time may yield successful weldments having a shear strength of ~58% of the base material [5]. For FSW of PTFE, ABS and PC, utilizing stationary heated shoe and employing relatively low tool traveling/rotational/plunging speeds avoid squeezing of the melted polymers from the joint line and yield higher strengths [22–25].

Recently, FSW of PMMA has received attention of researchers because of its wide usage in automotive sector [26]. Material flow during FSW of PMMA was studied using Arbegast model to predict suitable processing window [27,28]. Friction stir spot welding (FSSW) of PMMA and PMMA composites reinforced with silica have indicated that the tool rotational speed should be controlled in a the range of 1000–3000 rpm in order to avoid formation of volumetric defects in the stir zone (SZ) [29,30]. Through fine tuning of processing parameters, the strength of the weldment reaches to the same level of other joining processes [31]. Further studies [32,33] have shown that not only

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defect-free PMMA weldments can be attained through controlled conditions, but also dissimilar joining (PMMA/ABS) is feasible.

Albite the existing knowledge on the role of pin profile on FSW of metals and composites, for example [34–41], few studies have notified this role for polymers. For FSW of PP, it has been found that a threaded cylindrical conical tool yields better surface quality and higher shear strength due to controlled material flow in the welding zone [42]. Similar results have been reported for different pin geometries (square, triangular, threaded and tapered) at a wide range of rotational speed and traverse velocity [43]. It has been showed that several defects such as pores, lack of consolidation, cavities and inclusions may be formed, which might be prevented by employing an appropriate tool geometry (threaded tool pin profile for PP). For instance, by using a specially designed left-hand threaded tool and employing a counter-clockwise direction for FSW of nylon 6 PA, defect-free weldments with improved joint strength were attained [44]. Meanwhile, the tool shoulder diameter is also important for gaining high strength welded polymers. Researches showed that the shear strength of PC significantly varied with the shoulder diameter [45,46].

Although FSW of PMMA has been reported in a number of studies, the effect of tool design has been lacked behind. For this purpose, we systematically studied the effect of FSW pin profile on the material flow of PMMA during FSW. A joint experimental analysis and simulations were performed to investigate the generated heat and development of temperature/pressure profiles during FSW of PMMA. The mechanical strength of the weldments were also measured and linked to the processing parameters and defect formation. Finally, a proper working window for successful FSW of PMMA was established.

2. Experimental procedure

To prepare PMMA sheets for FSW, 4 mm thickness raw materials were cut into 200 × 100 mm^2 plates by a water jet machine. The physical and mechanical properties of PMMA is reported in Table1. Three different non-consumable tools with cone frustum, square frustum, and triangle frustum tool pin profile were made of high speed tool steel (HSS). A schematic image of the pins is shown in Fig. 1a, b and c, respectively. A TABRIZ/4301 milling machine modified with tool and clamping setup attachments was employed as FSW system. During welding process, the tool rotation direction was counter-clockwise (CCW). The processing parameters are presented in Table 2. A non-contact infrared camera (Raytec Ltd, Ashington, Northumberland, UK) was used to measure the surface temperature of the workpiece during welding. During the test, IR camera was placed at an angle of almost 45° with respect to the PMMA sheet at a distance of 280 mm. An acquisition rate of 30 Hz was adopted. Due to the low heat transfer of PMMA, no preheating was employed and no covering layer (like covering with graphite layer) was applied on the clamping frame. The emissivity of the PMMA surface was measured by comparing the IR measurements with surface K-type thermocouple (Omega, UK). The value of the transmittance of the PMMA sheet was about 97% of the incoming radiation.

Tensile specimens in longitudinal (LS) and traverse (TS) directions were prepared from the welded plate to examine the mechanical properties of the joints depending on the processing conditions. The tensile specimens had a gauge length of 25 mm and cross-sectional area of 6 × 32 mm^2 (in accordance with ASTM D638 standard). A servo-controlled universal testing machine (SANTAM, Co. Tehran, Iran) with a load cell of 400 kN was utilized. The loading velocity was 1 mm/min. The IZOD impact test was carried out according to ASTM D256 standard on samples prepared from the weldments. Images of the specimens used for mechanical testing are shown in Fig. 1d. Hardness was measured in Shore D scale according to ASTM D2240 Standard. Three replicates were performed for each conditions and the average values were reported. For visualizing of the longitudinal and lateral material flow in FSWed joints, the processed samples were sectioned from the stir zone in cross and traverse sections. The sectioned planes were then mechanically polished using different grades of emery papers. Because of the transparency of PMMA, the analysis of the flow patterns was carried out by an optical camera. In order to examine possible variation of the polymer, differential scanning calorimetry (DSC) was employed. The samples (~16 mg) were heated under nitrogen atmosphere up to 500 °C with a rate of 10 °C/min and held for 10 min. From the exothermic peak appeared in the range of 330 to 339 °C, the amount of crystalized polymer was recorded as a function of temperature.

Table 1
Properties of the commercial PMMA sheet used in this study. For comparison, the reported values in literatures [49–53] are shown.

Property	Measured values	Reported values
Density (g/cm^3)	2.57	2.58
Tensile Strength (MPa)	69.8	70
Young Modulus (GPa)	72	72.3
Elongation (%)	4.73	4.8
Poison's Ratio	0.2	0.2
Melting pint (°C)	160	160
Glass Transition (°C)	90	92

3. Process modelling

The 3D CFD approach used to simulate the FSW process based on the commercial Fluent CFD code. The computational domain (base material and tool) set after the welding process reaches to steady state. In other words, the process is solved as a steady-state behavior flow regardless of the tool plunge and exit stage. The three dimensional plastic flow is represented by the momentum conservation equation [47]:

$$\rho S_i S_{i,j} = -P_{,j} + (\mu S_{i,j})_j - \rho V s_{j,1} \tag{1}$$

where s is the material velocity, ρ the density of base material, V the tool velocity speed, and P the pressure. Indexes i or j = 1, 2 and 3 represent x, y and z directions, respectively. μ is non-Newtonian viscosity that can be determined from flow stress and effective strain rate as follows [48]:

$$\mu = \frac{\sigma_e}{3\dot{\varepsilon}} \tag{2}$$

σ_e is base material flow stress and $\dot{\varepsilon}$ effective strain rate, given by [49]:

$$\dot{\varepsilon} = \sqrt{\frac{2}{3}\varepsilon_{ij}\varepsilon_{ij}} \tag{3}$$

where ε_{ij} is strain rate tensor:

$$\varepsilon_{ij} = \frac{1}{2}(u_{i,j} + u_{j,i}) \tag{4}$$

The properties of poly(methyl methacrylate) including the viscosity-shear rate relationship and variation of heat capacity and thermal conductivity with temperature were deduced from Ref [49–53]. and presented in Fig. 2a–c. The thermal properties of the FSW tool were extracted from Ref [54]. as:

$$C_p = 468.3 - 8.5T + 3.0 \times 10^{-4}T^2 + 1.8 \times 10^{-7}T^3 \tag{5}$$

$$K = 3.8 + 0.092T - 1.8 \times 10^{-4}T^2 + 7.8 \times 10^{-8}T^3 \tag{6}$$

The pressure field was obtained by solving the following continuity equation iteratively with the momentum equations for incompressible single phase flow [55]:

$$S_{i,i} = 0 \tag{7}$$

S_i is the velocity of plastic flow. The single phase momentum conservation equation with reference to a co-ordinate system attached to