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Technical Paper

Experimental investigation on flexural behavior of friction stir welded high density polyethylene sheets

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ABSTRACT

Flexural strength is one of the main criteria in evaluation of the mechanical properties of polymeric joints. The flexural strength of thermoplastics, such as high density polyethylene (HDPE) sheets, is influenced by friction stir welding parameters. The determination of the welding parameters plays an important role in the weld strength. In the present study, the response surface method (RSM) was used as a statistical design of experiment technique to set the optimal welding parameters. The designed tool was consisted of a rotating pin, a stationary shoulder (shoe) and a heating system inside shoe. Rotational speed of the pin, tool traverse speed and shoe temperature were considered as varying parameters. Obtained results show a significant relationship between considered properties and processing parameters through an analysis of variance (ANOVA) study and the response surface method. It was found that welding at a high level of rotational speed and a lower level of tool travel speed increases weld flexural strength by reducing size of defects.

1. Introduction

Nowadays, developing of materials with enhanced stress-to-weight ratios and toughness as well as low cost such as thermoplastic materials, is much under attention in automotive and aerospace industries [1,2]. Among the most important and versatile of the hundreds of commercial thermoplastics is polyethylene. Moreover, polyethylene is utilized in a wide variety of industrial applications because, based on its natural structure, it can be easily produced in many different forms. Even though thermoplastic materials such as polyethylene offers a high degree of design freedom and processing ability [3], the construction of larger and more complex parts usually requires joining methods [4].

Plastic welding processes can be divided into two main groups: processes involving mechanical movement to produce heat (ultrasonic welding, friction welding, vibration welding) and processes involving external heating (hot plate welding, hot gas welding and resistive and implant welding) [5]. All plastic welding techniques consist of three common stages: (a) formation of a layer of molten material on the surfaces to be joined, (b) bond formation by application of pressure, (c) the melt is allowed to cool, and in this stage pressure should be maintained in order to prevent forming voids inside the weld zone [6]. Friction stir welding (FSW) is a new joining method which has great capability to compete with established plastic welding practices [6,7]. FSW produces welds by using a nonconsumable rotating tool with specially designed shoulder to locally soften a workpiece, through heat produced by friction and plastic dissipation, thereby allowing the tool to stir the joint surfaced. The reduced welding temperature during this process makes possible dramatically lower distortion and residual stresses, enabling improved fatigue performance, new construction techniques, and making possible the welding of very thin and very thick materials [8].

Since its discovery in 1991, FSW has evolved as a technique of choice in the routine joining of aluminum components; its applications for joining difficult metals and metals other than aluminum are growing, albeit at a slower pace [9]. It is now used on a wide variety of materials, including copper [10], magnesium alloys [11], titanium and its alloys [12], steel [13], metal matrix composites [14] and dissimilar metal and alloy systems [15,16]. Recently, FSW and FSP have been applied to join and process thermoplastic materials [5,17–21].

When conventional FSW is used to joining polymeric materials, it is very difficult to achieve the high mechanical and surface properties [22,23]. Central to the FSW process is the design of welding tool [24], so developing various tools has been considered in recently published literatures [7,22,25–27]. Research group at BYU invented a method for FSW of polymers, called hot shoe, with the purpose of containing the melted material, improving surface quality, and aiding in the fusion process [27]. By utilizing this method Strand [28] investigated the mechanical

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and microstructure properties of polypropylene (PP) friction stir welded sheets. They reported that to achieve minimal disruption of polymer microstructure, welds should be made at low feed-rate, high shoe temperature, long pressure time and large pin diameter.

Arici and Sinmazçelýk [5] studied the effects of double passes of the tool on friction stir welding of polyethylene. TWI researchers developed a tool using a vertical reciprocating blade to prevent formation of voids along the length of the weld [22]. Erica Anna Squeo et al. [29] perused a modification of the traditional friction stir welding by adding a heating step of the pin and the samples to join. They declared that in order to make the process more robust and gain higher strengths and obtain more process repeatability, heating the plastic material is a good way using a hot tool process. Mustafa Aydin investigated the effect of pre-heating in friction stir welding of UHMW-polyethylene and compared it with conventional FSW. He finally came into conclusion that application of pre-heating to improve and accelerate the creation of the friction stir welding temperature of plastic materials improved the joining characteristics of the welded joint and enhanced its tensile strength [30].

In another study, Rezgui et al. [25] utilized a fixed "scraper" instead of shoulder of the tool in order to contribute to a better distribution of temperature in the weld cordon and retard the cooling of welded plates. Applying a factorial DOE and an optimization using Taguchi approach, they declared that rotational speed, welding speed, pin diameter and holding time at the beginning of welding influence flow stress and maximum temperature of welded samples and do not have any significant effect on yield stress [25]. In another work reported by Payganeh et al. the effect of tool pin geometry on weld appearance and tensile strength was investigated experimentally to select a proper tool design to produce high quality welds. Also, the effects of tool rotational speed, work linear speed and tool tilt angle on tensile strength of the welds were also studied [31].

It appears that there are few publications concerning polymer FSW applications. No publication has been found on the role of FSW process parameters on the basis of flexural strength. As known by the authors [23,28] flexural strength is one of main criteria in evaluation of polymeric joints performance. Furthermore, very few studies on the optimization of FSW process parameters of polyethylene sheets using RSM method have been reported. Response surface method (RSM) is a collection of mathematical and statistical technique useful for analyzing problems in which several independent variables influence a dependent variable or response and the goal is to optimize the response [32].

Considering the above fact, the aim of this research was to investigate the effect of critical process parameters (pin rotational speed, shoe temperature and traverse speed of the tool) on the flexural strength of friction stir welded joints of the HDPE and achieve maximum strength by optimizing these parameters using RSM. In this work, high density polyethylene (HDPE) sheets were welded using the hot shoe tool due to its advantages.

2. Experimental procedure

2.1. Materials and methods

In the present work, the commercial high density polyethylene (HDPE) plates with 10 mm thickness were utilized and samples were cut in 100 × 200 mm size. The tool used in this study was consisted of a stationary shoe shape shoulder, a rotating pin and a heater which located at the shoulder and equipped with closed-loop thermo-controller. Through an indicator, this device shows the approximate temperature of the melting area and with a thermal potentiometer, the heat output of the electric heater could be adjusted. The schematic and photograph pictures of tooling system are shown in Fig. 1. As it can be seen in Fig. 1, a thrust bearing separated the pin from the shoulder and its main purpose is to hold the shoulder stationary relative to pin. The tool pin was made of H13 hot-working steel and shoulder's material was 7075 aluminum owing to its high thermal conductivity and mechanical strength. Pin diameter (part of pin that will be inserted into work-pieces) and its' thread was $M10 \times 1$. Pin has a length equal to thickness of HDPE sheets with a 0.5 mm gap. The shoulder's width and length were 28 and 250 mm, respectively. The shoulder's surface was coated with PTFE (Teflon).

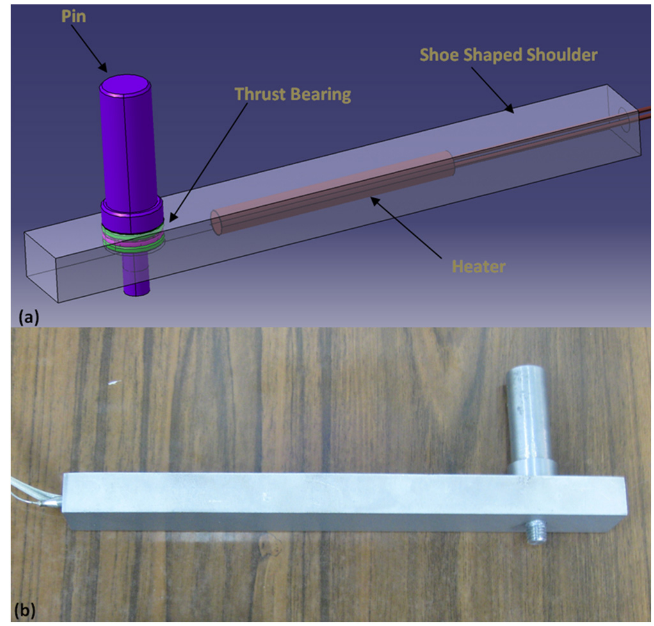

Fig. 1. Schematic and photograph pictures of tooling system.

As it can be seen in Table 1, rotational speed of pin, tool traverse speed and shoulder temperature was considered as the processing parameters and from the preliminary experimental results three levels of welding parameters was selected. A Box–Behnken response surface design was used to probe the effects of operating parameters (see Table 2). Furthermore, an ANOVA study was performed in order to determine the significance of process parameters and the relationship between them and the flexural strength of the welds.

After processing parameters were set according to the conditions of DOE, in order to perform welding process, the HDPE sheets were placed into the designed fixture which is illustrated in Fig. 2. The fixture was designed to provide sufficient horizontal and vertical forces to the work-pieces and hold them stationary during welding operation. Moreover, designed fixture is required to play as a guideline role and prevent any vibration of tool shoulder during welding. In order to prevent outpouring of melted material from the bottom of the welding area, a 0.5 mm gap was required between bottom of rotating pin and backing plate.

In initial step of welding process, dwell step requires for at least 15 s. In other words, when full depth (with predefined offset) was achieved, the tool was allowed to heat the material in order to create a pool of semi-molten polymer, and then the tool traverses along

Table 1
Table of processing parameters.

Symbol	Welding parameters	Unit	Level 1	Level 2	Level 3
A	Temperature	°C	70	110	150
B	Rotational speed	rpm	710	1120	1400
C	Traverse speed	mm/min	25	50	100