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Full Length Article

Friction stir welding of polypropylene sheet

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A B S T R A C T

Friction stir welding (FSW) is a growing technology in the manufacturing industries because of its numerous contributions involving the welding of light-weight materials such as aluminium and magnesium. The process has been recently implemented for joining thermoplastics. The present paper has been dedicated to investigate the application of the FSW process to join the thermoplastics. The article has been divided into two parts; the first part outlines the importance of the thermoplastics through their wide applications and the principle of the FSW process has been described. A detailed literature study regarding the effect of process parameters, pin profile, defects and weld zones during the FSW of thermoplastics has been conducted. The second part has been focused on the experimental investigation carried out to analyse the effect of tool pin geometry on FSW of 6 mm thick polypropylene sheets. The variation of the Z-load with time has been utilised to understand the occurrence of various stages of the welding. Also, a comparison between the thermoplastic and metal concerning the variation of Z-load with time has been performed to emphasis the process difference between them. Further, the effect of tool rotational speed and welding speed on the average force during FSW of thermoplastics has been shown. In order to investigate the weld quality, three different tools having cylindrical, square and conical pin geometry have been employed. Three different tool rotational speeds and traverse speeds were selected for carrying out the experiments. The effect of the shoulder diameter has also been studied. The tensile strength of the welds has been determined and correlated with pin profile. Results obtained proved the potential of square pin in achieving high quality welds. The process parameters have been found to have a significant effect on the tensile strength of the welds.

1. Introduction

There exists a mismatch between the demand for natural resources such as fuel and its supply which has created a pressure on the manufacturers to involve efficient production processes that would lead to resource conservation. As such various light-weight materials and improved processes have been discovered. Alloys of aluminium, magnesium, copper etc. are being widely used nowadays in automobiles, aerospace, shipbuilding and railway industries. Thermoplastics being light-weight with high specific strength, design flexibility and low manufacturing cost have drawn the attention of manufacturers to explore these properties in leading industries [1]. Some of the applications of thermoplastics are the clutch pedal and centre console manufactured from polyamide 6 (PA 6) which has significantly reduced the weight of the component [2], use of various fibre reinforced plastics (FRP) as structural components and clips and brackets of aerospace structures made of thermoplastics which aid to weight savings [3]. Adhesive bonding, mechanical fastening and the fusion bonding methods are the techniques which have been employed for joining of polymeric materials [4]. Adhesive bonding method has been employed in many industrial applications but has adverse environmental effects because of the chemicals used; and the process needs surface preparation. Moreover, the joints can neither be examined qualitatively nor the forecasting of failure. Mechanical fastening is another alternative but it leads to further weight addition because of the rivets, clamps etc. being used and moreover residual stresses are developed [5]. Thus, the preferred method to join is welding. Traditional welding methods degrade the material and thus we need a method which would not only provide better efficiency with

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reduced cost but also be environmentally friendly. One of the solutions to this issue can be FSW. The major significance of FSW is that it does not involve melting of the base material.

This innovative joining process takes place in solid state without generating any toxic fumes and requires no filler material. It was patented by The Welding Institute (TWI), UK in 1991 for joining aluminium alloys [6]. It utilises a rotating tool with a specially designed pin which plunges into the substrate to be welded maintaining zero root gap and travels along the joint line. The schematic image of the process has been shown in Fig. 1. The ease with which the tool can travel over the joint line is controlled by the parameter termed tilt angle. The tool is normally tilted towards the trailing edge and as such the front edge of the tool is a little above the surface of the work-piece. It helps to ensure the contact between the shoulder and the work-piece and also ensures better flow of material across the edges of the tool. Literature shows that the butt joint and lap joint configurations are the need of the hour. This process can be employed for other geometries as well. Continuous research on this technology has been carried out which has contributed significantly to the manufacturing industries. Since a few years, the process has been employed to weld thermoplastic materials [7].

TWI reported the successful welding of Polypropylene plates (PP) with a reciprocating tool (‘‘Reciprocating friction stir welding joins thermoplastics.“, 2000) [8]. The scope of FSW against other joining methods for plastics was analysed and studied (Strand, 2003) [9]. The author also presented the comparative data among various plastic joining methods in terms of energy requirement and the cost incurred which further leverages FSW. Various tools for FSW of thermoplastics have been developed and the degradation of top surface of the material caused by the traditional FSW tools has been reported [10]. Nevertheless, a wide range of works have been carried out using traditional tools. These works serve as the foundation and have inspired other researchers to contribute more to this field [7,11–29]. Table 1 approximately shows the various thermoplastic materials in percentage which have been the interest of researchers till date.

It has been observed that as the tool plunges into the plates to be welded, the soft material gets deformed. The shoulder rotation over the top helps to throw out this softened material. A new variant of the traditional FSW tool called the ‘‘heated shoe" was used to weld the PP plates [11]. It consists of a stationary shoulder having a rectangular cross sectional area and is referred as the shoe. A heating coil is placed inside the shoe which was held responsible for providing the necessary heat to the base metals. The long shoe exerted force on a large area and restricted the material to come out from the joint line. Stationary shoulder was employed to weld ABS plates and superficial finished joints without any external

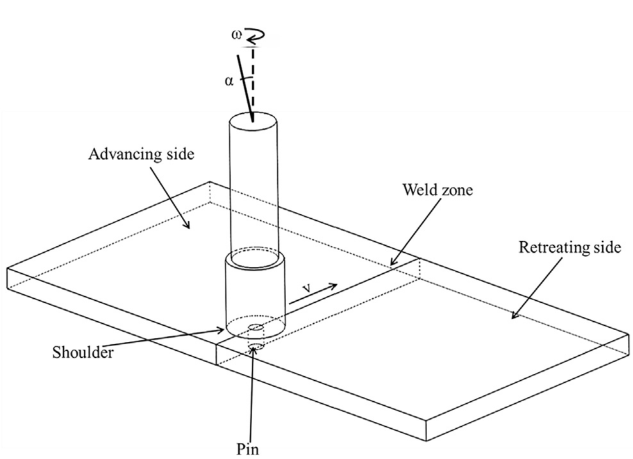

Fig. 1. Schematic view of friction stir butt welding process.

Table 1
Thermoplastic materials used in research.

Sl no	Thermoplastic	Use of the thermoplastic in FSW (%)
1	HDPE	36
2	ABS	24
3	PP	20
4	PC	8
5	PMMA	4
6	UHMW-PE	4
7	NYLON 6	4

(PP- Polypropylene, PC- polycarbonate, PMMA- polymethyl methacrylate, HDPE- high density polyethylene, UHMW-PE- ultra high molecular weight polyethylene, ABS- acrylonitrile butadiene styrene)

heating were obtained [21]. A tool with two stationery shoulders to weld ABS plates with a convex pin and a simple pin was developed [23]. The use of stationary shoulder aids in achieving good welds in case of polymeric materials because the material present at the top surface are not destroyed while the softened materials inside the abutting edges solidify firmly without any loss of strength. Further, the loss of the material from the work-piece as in case of the traditional tool was not only reduced with the use of two stationary shoulders but also the root defects arising during the welding process were eliminated. In case of traditional FSW tools, threaded pin profile has proven to be better for welding of polymeric materials. Two tools with left hand threaded pin to weld Nylon-6 were developed which were fed in clockwise and anti-clockwise directions separately [24]. They observed that the threads in the pin are creating a path for the soft material to flow along the edges of the tool. Thus, feeding the tool in clockwise direction resulted in loss of material. However, good welds were created in case of anti-clockwise direction. A study on welding of PP composites in a lap configuration using four different tools was performed [18]. They reported that the conical pin is one of the poorest designs in welding of the polymeric materials because its profile failed in achieving the homogenization of the material.

Thermoplastic materials have properties very different from that of the metals. One of the major features being the low thermal conductivity, because of which the heat developed in the advancing side and retreating side is not uniform which leads to defects. Tool rotational speed, traverse speed and tilt angle are the effects that have been studied. The welding parameters are found to have significant effects on the mechanical properties of the welds. Lower rotational speed created cavities as it was unable to generate the required heat to deform the material while higher rotational speed was constantly degrading the top surface of the work-piece. In the case, where traverse speed of the tool was at lower values, it presented good appearance, rough surfaces otherwise. The tool tilt angle effect has also been studied by several researchers [12,16,25]. They observed that a tilt in the tool is assisting in obtaining higher strength. This is because the tilting helps in plunging and better mixing of the material. But a higher tilt in the tool will result in plunging of tool more inside and cannot ensure mixing. The UHMW-PE sheets were pre-heated prior to welding and this technique helped to achieve adequate heat and also reduced the need of high tool rotational speeds [14]. Moreover, it is suggested that it is wise to remove the samples after they reach room temperature so that they do not distort thereby ensuring better results [25]. The FSW process succeeded in eliminating the defects occurring in a traditional welding method but has given rise to other defects. The occurrence of root defect was found while welding PP plates with a heated shoe with conical pin [11]. A longer pin will result in melting of the material while a shorter pin length will result in root defects. The peeling defect was also observed while welding PP plates with a traditional FSW tool [26]. This defect was observed by other researchers as well while