Influence of Critical Process Parameters on the Quality of Friction Stir Welded Nylon 6

M. S. Youssif¹, M. A. El-Sayed², A. M. Khourshid³

Abstract – Friction Stir Welding (FSW) is a relatively refreshing joining approach developed in the early nineties. Although originally intended for aluminum alloys, the research of FSW has now extended to a variety of materials including steels and polymers. The work presented here was to evaluate the effect of process parameters such as tool rotational speed and traverse speed on the tensile strength of friction stir welded Nylon 6. The results showed that a combination of high speed and low feed rate would result in the best ultimate tensile strength of the weldments. Optimized welding conditions of 1250 rpm rotational speed and 10 mm min⁻¹ feed rate resulted in the highest UTS of the FSW joint which was equivalent to 48% that of the base material.

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I. Introduction

Friction stir welding was invented at The Welding Institute (TWI), Cambridge, United Kingdom by Wayne Thomas as a solid state joining technique in December, 1991 [1].

This technique was initially applied to aluminum alloys such as those of series 2XXX and 7XXX [2]-[6], which were generally considered unweldable or difficult to weld at that time. Ever since, it has been generally acknowledged as one of the most significant developments in the area of welding [1]-[33].

In this process, a non-consumable rotating tool with a specially designed profile pin and shoulder is driven into the edges of sheets or plates and traversed along the weld joint line, as shown in Fig. 1.

The tool has three main functions; these are: (1) heating of the workpiece, (2) movement of the material from one side to another to produce the joint and (3) containment of the hot material under the tool shoulder. FSW has several advantages allowing it to be a very attractive welding process. By avoiding melting, several metallurgical problems usually encountered with conventional fusion welding, such as porosity, shrinkage, distortion and splatter, could be eliminated. Also, no flux or shielding gas is used.

In addition, the process is distinguished with its low energy consumption and does not require the use of filler material. Furthermore, it does not need skilled labor, and can be easily automated. This process is applied mostly to butt and lap weld joints but other joint geometries can be welded as well [7]. Nowadays, a wide variety of materials is joined using FSW method ([31]-[33]), including steel [8], magnesium alloys [9], metal matrix composites [10], titanium and its alloys [11], copper [12], dissimilar metals [13] and thermoplastics.

It was noticed, that most of the studies published on FSW of polymers were concerned with a very narrow range of polymers, more precisely, polyethylene (PE) [14], high density polyethylene (HDPE) [15], polypropylene (PP) [16], acrylonitrile–butadiene–styrene (ABS) [17], PMMA [18] and the polyamide Nylon 6 [19]. For instance, Bozkut [20] used a FSW tool, with a 6 mm diameter pin and a 18 mm diameter shoulder, for welding of high density polyethylene (HDPE). In his experiments, the tool rotational speed and the welding speed ranged from 1500 to 3000 rpm and 45–115 mm/min, respectively. Temperature variation across the weldment was measured using an infrared thermometer device to be between 120 and 165 °C (the melting point of the polymer is 132 °C). He observed root cracks and voids in the welding area, which were the main reasons for the low tensile properties of the welded joint.

Saedy and Givi [14] also investigated the effect of critical process parameters on FSW of medium density polyethylene plate.

![Fig. 1. Friction stir welding and its elements](image-url)
They tested two welding parameters: the tool rotation speed and the tool tilt angle, which ranged between 1400 and 2000 rpm, and 1° and 2°, respectively. They obtained an optimum weld strength value of 70% of the parent material strength at welding conditions of 1600 rpm and tool tilt angle of 1°, thus reflecting the essential role of process parameters on controlling the mechanical properties of FSW weldments.

FSW of polyethylene plates was also studied by Arici and Sinmaz [21], who employed a double pass butt welding strategy to eliminate root crack defects areas at the bottom of the joint (that are not welded). Rotation speeds of 600, 800 and 1000 rpm and traverse speeds of 12.5, 25, 40 and 60 mm/min and tool angles of 0° and 1° were investigated. They reported that below 1000 rpm rotational speed the heat generated was insufficient to soften the material. They also observed that the specimens welded with a tool angle of 1° were better than those welded with 0°.

Squeo and Quadrini [22] studied the effect of preheating of the weld joint during FSW of polyethylene.

The pin rotational speed was changed from 3000 to 20000 rpm, the feed rate from 10 to 44 mm/min, and the pin diameter from 1 to 3 mm. They claimed that the worst results were observed with the larger pin. Furthermore, they reported that preheating insured sufficient heating even at low rotation speeds. Welds surface morphology and mechanical properties were also appointed to be improved by preheating, which improved the welds quality. They suggested that achieving optimum FSW conditions still requires additional research of process parameters.

Panneerselvam and Lenin [23] employed different conventional FSW tools to analyze the effects of pin profile geometry on FSW quality. They used PP plates as base material. Triangular, square, tapered, and threaded pin geometries were tested.

The rotation speeds ranged from 1500 to 2250 rpm and traverse speeds from 30 to 60 mm/min. They reported several defects, such as porosity, lack of consolidation, inclusions, and cavities. They also obtained poor joining, mainly at the retreating side of the welds. They claimed that the threaded tool pin profile resulted in the best welding results. Panneerselvam and Lenin [24] continued FSW tests using a threaded tool pin profile during welding of Nylon 6 polyamide. A specially designed left hand threaded tool pin profile was used and operated at rotational and traverse speeds of 1000 rpm and 10 mm/min, respectively, to evaluate the effect of tool rotation direction on weld quality. They observed that the FSW joints produced via a tool rotated in a counter-clockwise direction had improved strength and were free of defects, compared with the joints welded with clockwise tool rotation.

They suggested that the reason for the poor quality of the former welds was the removal of the stirred material from the weld seam.

Due to the practical importance of Nylon 6 polymer [25], the current research endeavor will be concerned with investigating the influence of critical process parameters on FSW of Nylon 6. In particular, the effect of pin rotational speed and travelling speed of the tool on the mechanical properties of FSW joints of Nylon 6 will be of main concern.

II. Experimental Work

In this work a universal milling machine was adapted to carry out the FSW experiments. The machine has a rotational speed range from 80 to 1250 rpm and was equipped with a stepping motor to control the traverse welding speed with a range from 0 to 80 mm/min.

A backing anvil, made of 25 mm thick mild steel, was used for fixation of the specimen on the machine table, as shown in Fig. 2. It consists of a base (1), left and right shoulders (2), and fasteners (4 and 5). The backing anvil base must be flat and rigid to withstand stresses during welding and to prevent any movement of the specimen. Six bolts M10 (4) were used to fix the base to the machine table (3), as shown in Fig. 2. The shoulders were used for fixation of the specimen to the backing anvil base. The lower face of the shoulder was stepped by 3 mm to allow better fixation of the specimen. Finally, Six bolts M10 (5) were used for fixation of shoulders to the back anvil base.

Nine experiments with different welding parameters were carried out, with an aim to investigate the effects of critical process parameters, namely rotational speed and feed rate, on the mechanical properties of FSW weldments of Nylon 6, as shown in Table I.

![Fig. 2. Backing anvil assembly](image)

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>Experimental Work Plan</th>
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<tbody>
<tr>
<td>Exp. No.</td>
<td>Feed rate (mm/min)</td>
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<tr>
<td>2</td>
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The FSW tool used is shown in Fig. 3. It was made of medium carbon steel, and it was hardening at 900 °C after fabrication. The main parts of the tool are the pin and the shoulder; the pin was threaded with right hand thread M6 and its length was 11.6 mm, whereas the tool shoulder was 18 mm in diameter. The tool was clamped to the machine by the shank.

The material used in this study was a commercial grade of polyamide called Nylon 6. The mechanical and physical properties of this material are shown in Table II.

The dimensions of the sheets to be welded were 13 mm thickness, 130 mm length and 65 mm width.

The number of specimens required for the experiments were at least two to four per experiment. An infrared thermometer [20] model UT302C was used to measure the temperature in the weld zone during FSW.

After welding, the weldments were visually inspected to check for any visible defects. For each welding condition, five rectangular test specimens, each of 65 mm length and 15 mm width, were cut from the weldment perpendicular to the welding direction, far enough from the edges, to eliminate possible edge effects.

Tensile test of the samples was carried out using a universal testing machine model Instron 3382 with a thermocouple at 65 °C, as shown in Fig. 3. The samples were then investigated using a Carl Zeiss Axio Lab.A1 reflected light microscope equipped with AxioVision 4 image analysis system.

### III. Results and Discussion

As described above, five test specimens were machined out from each weldment along with additional five test bars from the unwelded base material. For each test specimen the values of the ultimate tensile strength (UTS) and % elongation were determined, and the results of the five samples were averaged for each property. Table III shows the results of the tensile test and surface temperature measurements.

The UTS of the Nylon 6 base material was found to be 54 MPa. The highest tensile strength of 26 MPa (about 48% of the base material) was obtained in experiment 1, corresponding to the highest rotational speed of 1250 rpm and the lowest travel speed of 10 mm/min. On the other hand, the lowest strength of only 9 MPa (about 16% of the base material) corresponds to the lowest rotational speed of 375 rpm and the highest travel speed of 30 mm/min (experiment 9).

Figs. 4(a) and (b) show photographs of the weld joints for samples from experiments 1 and 9, respectively. It could be speculated that the improved appearance of the weld joint in experiment 1 (Fig. 4(a)), in comparison with that for experiment 9 (Fig. 4(b)), is mainly associated with the higher tool rotation rate used that generated higher friction heating. Also, lower feed rate adopted allow sufficient time for the weldment to absorb most of the heat generated.

This had resulted in more intense stirring and mixing of material which in turn leads to a significant improvement of the tensile properties of the weld joint, by a factor of 3, as indicated in Table III. Also, a typical stress-strain diagram and the two halves of a specimen from experiment 1 are shown in Figs. 5(a) and (b), respectively.

The effect of tool rotational speed and feed rate on the UTS and % elongation of welds is illustrated in Figs. 6(a) and (b), respectively. It was observed that at a rotational speed of 375 rpm and feed rate of 10 mm/min the values of UTS and % elongation were 14.3 MPa and 5, respectively. Raising the speed to 1250 rpm (at constant feed rate of 10 mm/min) increased the UTS to 25.8 MPa and % elongation to 8.7.

On the other hand, increasing the feed rate from 10 to 30 mm/min (at constant rotational speed of 375) resulted in a reduction in the UTS to 8.9 MPa and the % elongation to 2.1.

The significant increase of both the tensile strength and % elongation with increasing the rotational speed might be attributed to the increase in the temperature of the joint with rotational speed, as shown in Fig. 6(c), due to the higher frictional heat, which provided a proper flow of the polymer in the stir zone and minimized the chance of the formation of defects (See Fig. 4(a)), thus increasing the strength of the welds.
Mostafapour and Azarsa [16] who pointed out that the materials, a large amount of heat could be concentrated around the pin increased and in the nugget zone. Consequently, the amount of molten material temperature in the joint line. They suggested that due to low thermal conduction of polymeric material conditions were improved. Increase in rotational speed leads to a local increase in rotational speed and feed rate of the tool. The mechanical and physical properties of the weld joint with the rotational speed and feed rate of the tool. (a) Ultimate Tensile Strength, (b) % Elongation and (c) Weld surface temperature.

These results are in agreement with the argument of Mostafapour and Azarsa [16] who pointed out that the increase in rotational speed leads to a local increase of material temperature in the joint line. They suggested that due to low thermal conduction of polymeric materials, a large amount of heat could be concentrated in the nugget zone. Consequently, the amount of molten material around the pin increased and the stirring conditions were improved.

<table>
<thead>
<tr>
<th>Exp. No.</th>
<th>Feed rate (mm/min)</th>
<th>Rotational speed (rpm)</th>
<th>Ultimate tensile strength (MPa)</th>
<th>Welding surface temperature (°C)</th>
<th>Ductility (%)</th>
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<tr>
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<td>1250</td>
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<tr>
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<td>16.62</td>
<td>180</td>
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<tr>
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<td>8.85</td>
<td>50</td>
<td>2.1</td>
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</tbody>
</table>
Earlier studies of the FSW of different polymers also suggested that low spindle speeds usually lead to an insufficient flow of the material in the weld zone and a lack of fusion between the weld and the base material. Therefore, increasing the stirring speed of the pin could create the adequate turbulence in welding area and increase the amount of frictional heat produced.

The higher level of heat input results in welds with smaller root defect, which in turn improve the mechanical properties [15], [17], [26]. On the other hand, the tensile strength was found to decrease with increasing of the feed rate. It could be stated that the increase in feed rate reduces the heat input required to soften the base material during FSW process resulting in poor mixing of the material, and in turn a weaker weld joint. This suggestion was further confirmed via the results shown in Fig. 6(c), which depicts the reduction in temperature with the increase of feed rate. It was evident by Mostafapour and Azarsa that at lower traverse speeds, the time that stirring action takes place in the stirring zone is longer, which leads to an enhanced turbulence of welding area.

In addition, reducing the feed speed slow down the cooling rate of the weld which leads to an improved mechanical strength [27]. It could be suggested that higher travel speeds prevent the tool from heating the weld area for a longer time. The effect of travel speed on the welds appearance was obvious. Weld line deflection and deformation in samples with higher travel speed lead to poor material mixing and thus weak tensile strength (see Fig. 4(b)). Figs. 7(a) and (b) show a number of welding defects that were encountered in the FSW joints, which were mostly due to the low heat input associated with using low rotational speed and/or high feed rate. These defects included weld cavity, expelled material, pin hole, (decrease of weld surface level), and root cavity. The weld cavity might have been formed due to high feed rate and low rotational speed that resulted in an insufficient heat and poor material mixing in the weld pool [17]. The expelled material could occur either due to the sticking of the nylon to the tool shoulder, as shown in Fig. 7(c), or because of the centrifugal force (resulting from the stirring action) that might transport the molten material from the advancing side to the retreating side of the joint. In addition, the decrease of welding nugget surface was expected to be due to the scattering of expelled material. Finally, the root cavity was a common defect in most of the weld joints in the current study.

A root defect is defined as an area at the bottom of the joint that is not welded. Several causes had been held responsible for such a defect. The use of a pin that is slightly shorter than the thickness of the plates which prevented the bottom of the joint from being adequately stirred, and thus left unwelded [28]. Another possible cause might be the use of a threaded pin that caused some vertical movement of material out from the root of the weld [29]. Also, the heat distribution along the weld joint from the top to the bottom might be not homogeneous and therefore the lower part did not melt enough. In most cases, a small portion of the molten material was extruded into this gap, helping to bond the workpieces, but this extrusion weld was far weaker than the FSW region. Figs. 8(a) and (b) show optical micrographs of the surfaces of the weld joints of samples from experiments 1 and 9, respectively. More defects, such as porosity, blow holes and cavities, were detected on the joint line of a sample from experiment 9, which is suggested to be due to the relatively lower heat input in this experiment.

This caused the outer material of the weld pool to cool quickly, and the inner material shrinks away from the resulting shell during cooling [28], [30].
The quality of weld joints, evaluated in terms of tensile strength and % elongation, seems to be significantly dependent on the process parameters. Welding at high rotational speed and low travel speed resulted in a better tensile properties.

A combination of a rotational speed of 1250 rpm and a feed rate of 10 mm/min was found to result in the best joint efficiency of about 48% that of the base material.

Increasing the weld speed or decreasing the tool rpm was apparently able to generate enough heat to plasticize the polymer and to promote adequate mixing of material at the weld interface.

The joint efficiency ranged from 16% to 48% of the base material strength depending on the process parameters.

References


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