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Investigation of Welding Forces and Weld Strength for Friction Stir Welding of Acrylonitrile-Butadiene-Styrene (ABS) Plates

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Abstract

The purpose of this study is to investigate the applicability of the friction stir welding technology to acrylonitrile butadiene styrene (ABS) type polymer and the effect of welding parameters on the force values and weld strength during he-welding. The tests were carried out on 4 mm thick ABS sheets using a conventional mould design. The input parameters (speed – n, feed rate – v_f) were varied in 3-3 steps and a complete set of experiments was performed. From the force measurements, it was concluded that the force values in the feed direction (F_y) and axial direction (F_z) are the dominant force values during welding. The force components decrease with increasing speed and n/v_f ratio, while they increase with increasing feed rate. The tensile strength of the weld improves with increasing speed and n/v_f ratio, while they deteriorate with increasing feed rate. The best weld strength (10.69 MPa) was measured at 1000 rpm and 50 mm/min feed rate.

Keywords: *friction Stir Welding, ABS, welding force, joint efficiency.*

1. Introduction

Friction stir welding (FSW) is a welding process based on the principle of mechanical friction, patented in the early 1990s [1]. The process has become particularly successful and popular, for example in the case of aluminium. It is used in industries such as the aerospace industry [2, 3, 4]. For the time being, it is only used with aluminium at an industrial level, but there are already publications on welding experiments of magnesium [5], titanium [6] and copper [7]. Friction stir welding is not only investigated for welding metallic materials. There are several studies on the friction stir welding of various polymers and fibre-reinforced thermoplastics [8] One of the greatest advantages of the technology is that it is also suitable for welding fibre-reinforced thermoplastics [9]. In addition, friction stir welding is energy-efficient and environmentally friendly, because neither auxiliary materials nor shielding gas is needed [10].

In friction stir welding, a rotating tool with a special shoulder and pin geometry moves between the workpieces which are in contact and to be welded together. Friction between the workpiece and the rotating tool produces the temperature required for welding. Also, the tool mixes and circulates the melted material in the welding zone, thus ensuring an even and uniform seam. The tool used during welding is sunk into the materials to be welded to a depth approaching the thickness of the workpieces to be welded. After the tool reaches the end of the welding path, it is lifted out of the welding zone. Figure 1 shows a schematic diagram of friction stir welding, as well as the force components during welding.

ABS is one of the most common thermoplastics, which can be found in large quantities in vehicles or very often in various household appliances. This is because it can be easily processed, is stiff and is scratch resistant and durable [11].

In recent years, many publications have focused on the friction stir welding of ABS.

Arvin et al. [12] studied the friction stir welding of ABS sheets using a special tool with a heated shoulder. The diameter of the tool was 10 mm and

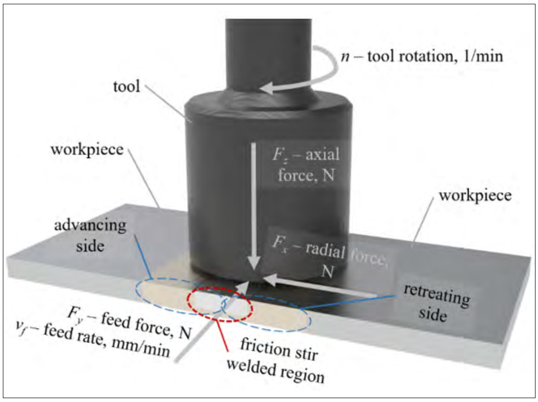

Figure 1. *Schematic diagram of friction stir welding.*

the pin was threaded. The shoulder was equipped with an electric heater, which was used to control the temperature of the shoulder. During their tests, they varied 3 parameters (tool rotational speed, feed and the initial temperature of the tool) at 3 levels. They used a complete design of experiments, therefore they carried out experiments at 27 measurement points. The output parameters were the tensile strength of the seam and bonding efficiency (the ratio of the tensile strength of the seam and the bulk material). They analysed their measurement results by analysis of variance (ANOVA) and the response surface method (RSM). The authors concluded that the tensile strength of the seam increases with increasing rotational speed and tool temperature, while with increasing feed, it decreases. The best welding efficiency (88% of that of the raw material) was achieved with a rotational speed of 1600 1/min, a feed of 20 mm/min and a tool temperature of 100 °C.

Sadeghian and Givi [13] studied the friction stir welding of 8 mm thick ABS sheets, using tools with cylindrical and conical pin geometries. The shoulder had a standing design, but was not heated. Among the input parameters, rotational speed, feed, as well as the inclination angle of the tool, the diameter of the shoulder and the pin, and the ratio of these diameters were changed at 3 levels. Here again, the output parameters were the tensile strength of the seam and bonding efficiency. From their measurement results, the authors concluded that the conical pin geometry, larger tool inclination angle and diameter ratio, as well as a low feed improve tensile strength.

Mendes et al. [14] studied the friction stir welding of ABS using a robotic system. In their study, they used a heated, standing shoulder tool design. The welding parameters examined were rotational speed, feed and the axial forces. After welding, they examined the strength and hardness of the seam. The authors concluded that high-quality seams can be achieved with robot-assisted friction stir welding; the high axial force promotes the compression of the polymer in the molten state, and rotational speed is responsible for heat production, which increases the strength of the seam.

Examining the welding of different polymer materials to each other is also an increasingly researched topic these days [15].

Gao et al. [16] investigated the weldability of ABS and high-density polyethylene (HDPE) sheets by stir friction welding. In addition to these two materials, the authors introduced carbon nanotubes into the joint to strengthen the seam. The tool had a pin with a tapered thread. In the study, the thickness of the welded plates was 4 mm, during welding, the two materials were placed overlapping each other, where the lower material was always ABS. The tool had a tapered thread pin geometry. The input parameters were rotational speed, feed and tool (welding) depth. These parameters were varied at 3 levels. They analysed the effect of changes in process parameters on the strength and microstructure of the seam. They achieved the best seam tensile strength (14.7 MPa) with a feed of 30 mm/min, a rotational speed of 2500 1/min and an immersion depth of 0.2 mm. They also point out that a lower feed rate increases mixing time, which ensures better mixing in the welding zone, while increasing the speed results in more heat.

Hajideh et al. [17] also investigated the friction stir welding of ABS and polypropylene (PP). At some measurement points, they introduced copper powder into the welding zone to investigate its effect on the strength and hardness of the weld. The tool was a heated, standing shoulder design, and the pin was threaded. The input parameters (rotational speed, feed and tool temperature) were varied at 3 levels. A complete experimental plan was used. The output parameters were the strength and hardness of the seam. The results indicated that copper powder significantly increases the strength and hardness of the weld.

In this study, we investigate the friction stir welding of 4 mm thick ABS plates. We examine the force components occurring during the welding process and the strength of the seams as a function of the input parameters.

2. Materials and methods

During the experiments, 4 mm thick DOCA-ABS R (Quattroplast Kft., Budapest, Hungary) plates were welded together. The welded specimens were 90 mm x 85 mm so that we could cut three 3 standard tensile test specimens from them. **Figure 2** shows the cutting and numbering of the test specimens.

The welding experiments were performed on a MAZAK Nexus VCN 410A-II type CNC milling machine. The force components occurring during welding (F_x, F_y, F_z – **Figure 1**) were measured with a Kistler9257B piezoelectric force meter clamped under the machine vice. The range of the dynamometer was $F_x = F_y = -5...+5$ kN and $F_z = 5...10$ kN **[18]**.

Using the three measured force components, we calculated the resulting force during welding as follows:

$$F_e = \sqrt{F_x^2 + F_y^2 + F_z^2} \quad (1)$$

The tensile testing of the 3 tensile specimens per measurement point was performed on a Zwick Z005 universal testing machine at a cross-head speed of 10 mm/min. In addition to the strength of the seam, the tensile strength of the bulk material was also determined based on 3 tests (29 MPa). We used this value when determining welding efficiency as follows:

$$JE = \frac{\sigma_{\max,welded\_specimen}}{\sigma_{base\_material}} \quad (2)$$

The pin geometry of the tool used during the welding tests was a cylinder. The diameter of the pin is 12 mm, the diameter of the shoulder is 29 mm, and the material of the tool is C45 steel. The welding tool used is shown in **Figure 3**.

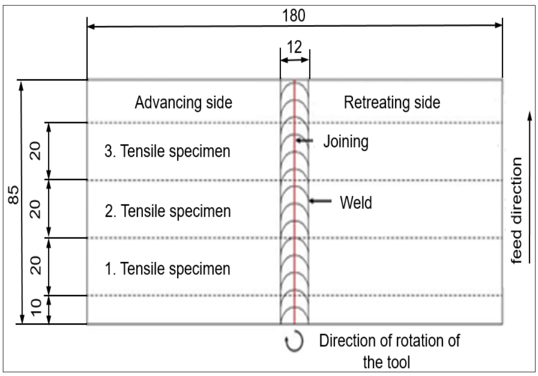

Figure 2. *Numbering of the tensile test specimens on the welded specimens (dimensions in mm).*

Two of the welding parameters, tool rotational speed and feed, were changed at 3 levels. We determined the parameters used based on preliminary experiments (**Table 1**).

We used a complete experimental design. **Table 2** shows the measurement points and their welding parameters. The table also shows the value of the n/vf ratio for each measurement point. During the evaluation of the results, we also examined the results as a function of this parameter.

Table 1. *The welding parameters*

Parameters		Levels		
		–1	0	1
x_1	rotational speed – n, 1/min	500	750	1000
x_2	feed – v_f, mm/min	50	75	100

Table 2. *The measurement points and their welding parameters*

Measurement point	n [1/min]	v_f [mm/min]	n/v_f
1	500	50	10
2	500	75	6.67
3	500	100	5
4	750	50	15
5	750	75	10
6	750	100	7.5
7	1000	50	20
8	1000	75	13.3
9	1000	100	10

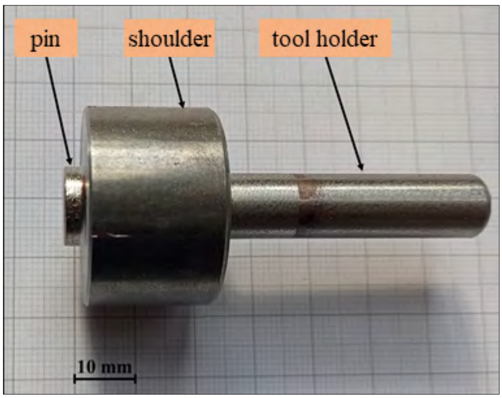

Figure 3. *The tool used in the experiments.*

3. Results

3.1. Analysis of forces

Figure 4 shows the force components during welding (F_x, F_y, F_z). No significant lateral force occurs during welding (F_y) the dominant forces are the force in the feed direction (F_z) For the latter force component, the force diagram can be divided into two significant sections. An increasing section, where the force suddenly jumps as a result of the tool entering the welding zone, and the subsequent, almost constant section. The force in the feed direction (F_y) remains nearly constant throughout the welding process.

During the evaluation of the forces, we always evaluated the average force measured in the constant section.

3.2. Results of the examination of forces

During the analysis of forces, we examined the force in the feed direction (F_y), the force components in the axial direction (F_z), and the resulting welding force (F_r). Figure 5 shows the effect of the force in the F_y direction as a function of the welding parameters. The force values decrease as rotational speed increases, while they increase as feed increases. In addition, increasing the n/v_f ratio decreases the force.

Figure 6. shows the main effect plots for the force in the F_z direction as a function of the welding parameters. Similar trends can be observed in this case as well. The value of the force component decreases with increasing speed and n/v_f ratio, while it increases with increasing feed.

Finally Figure 7 shows the main effect plots of the resultant force (F_r) Since this force comes from the two forces presented above and the lateral force component, the trends here are also similar. As the speed and the n/vf ratio increase, the resultant welding force decreases, while it increases as feed increases.

The dominant forces and the resulting welding force indicate that the temperature in the welding zone increases with increasing rotational speed, as a result of which the polymer can melt, thus the forces during welding are lower. Feed has a similar effect to welding time: the higher it is, the less time the tool stays in the welding zone, therefore it has less time to properly melt the material, and so the forces during welding increase.

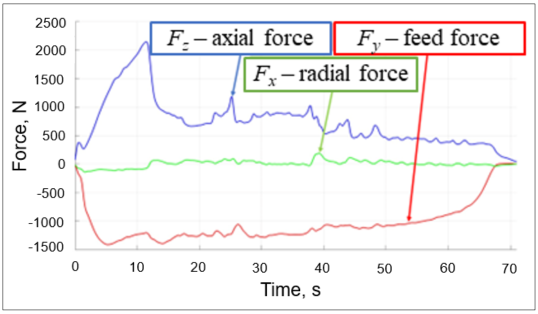

Figure 4. *The force components during welding.*

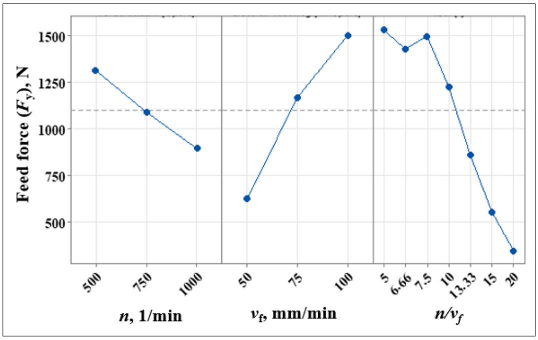

Figure 5. *The effect of welding parameters on the force in the feed direction (F_y).*

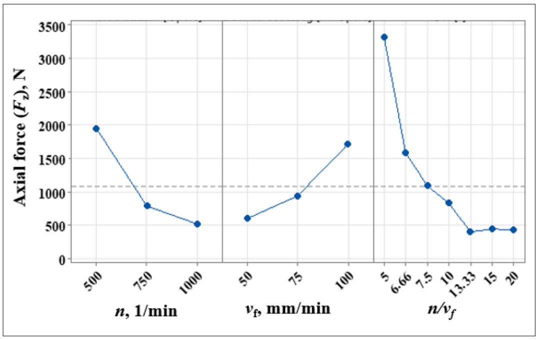

Figure 6. *The effect of welding parameters on axial force (F_z).*

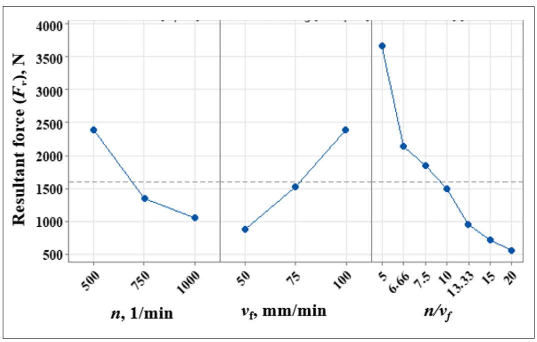

Figure 7. *The effect of welding parameters on the resulting welding force (F_r).*

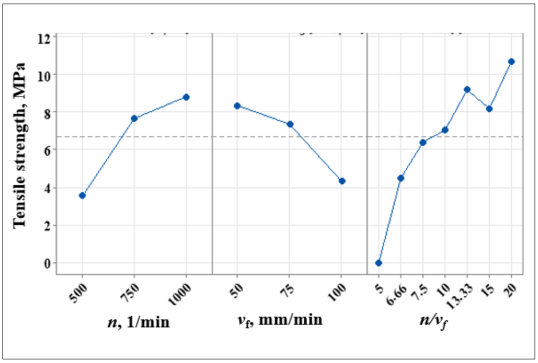

Figure 8. *The effect of welding parameters on the tensile strength of the seams.*

3.3. Tensile test results

The other output is the tensile strength of the seams. We performed 3 tests at each measurement point and calculated the average of the 3 test results. **Figure 8** shows the main effect plots of the tensile strength of the seams.

The strength of the seam tends to improve as the speed and the n/v_f ratio increase. In the case of a too small n/v_f ratio (measurement point 3, $n/v_f = 5$) no detectable bond was created between the two plates. Increasing the feed rate results in worsening seam stiffness. The best seam strength (10.69 MPa) was obtained at measurement point 7, with a rotational speed of 1000 1/min and a feed of 50 mm/min.

4. Conclusions

In this paper, we performed the friction stir welding testing of 4 mm thick ABS plates with a conventionally designed tool. During the tests, we changed the rotational speed of the tool and feed at 3 levels. When evaluating the experiments, we analysed the effect of the welding parameters on the forces during the process and the strength of the seam. Based on the results, the following conclusions can be drawn:

- Among the forces during welding, the dominant forces are the force in the feed direction (F_y) and the axial force (F_z).
- As rotational speed (n) and the n/v_f ratio are increased during welding, the force in the feed direction (F_y), the axial force (F_z) and the resultant welding force (F_r) decrease, while the strength of the weld increases.
- As feed (v_f) is increased, the force in the feed direction (F_y), the axial force (F_z) and the resultant welding force (F_r) increase, while the strength of the seam decreases.
- The best seam strength (10.69 MPa) was achieved with a rotational speed of 1000 1/min and a feed of 50 mm/min. This is 37% of the tensile strength of the bulk material.

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