Acta Materialia Transylvanica 7/1. (2024) 48–53.
DOI: Hungarian: https://doi.org/10.33923/amt-2024-01-09
English: https://doi.org/10.33924/amt-2024-01-09

Investigation of Friction Stir Welded Polycarbonate Plates

Róbert Gábor STADLER,[1] Richárd HORVÁTH[2]

[1] *Doctoral School on Materials Sciences and Technologies, Óbuda University, Budapest, Hungary, stadler.robert@bgk.uni-obuda.hu*

[2] *Bánki Donát Faculty of Mechanical and Safety Engineering, Óbuda University, Budapest, Hungary horvath.richard@bgk.uni-obuda.hu*

Abstract

This study investigates how different input parameters (speed and feed rate) affect the force components during welding and weld strength. In addition, we used microscopic imaging to observe the welding defects that occurred and their effects on failure. The measurement results show that welding forces decrease with increasing tool speed. The highest weld strength (28.5 MPa) was obtained at 1000 rpm and a feed rate of 8 mm/min.

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

1. Introduction

Today, polymers are widely used in various industries. As these materials spread, we need high-quality economical joining technologies. As in the case of metals, the most commonly used bonding technology with polymers is also welding. Due to its wide industrial application, ultrasonic welding [1], laser welding [2], and friction stir welding [3] of polymers are still popular research fields.

Friction stir welding is a welding technology based on friction, patented in the early 90s [4]. During the process, a rotating tool is guided along the line where the plates are to be joined. Friction occurs between the tool and the plates, which produces the temperature required for welding and the formation of the seam. Friction stir welding can produce a high-quality bond, and is also economical, environmentally friendly and energy-efficient [5].

Although at an industrial level, it is mostly used for aluminium, the possibility of using it on polymers has been researched since the beginning of the 2000s. [6]. In addition to the advantages mentioned above, tests have proved that the technology is suitable for welding thicker polymer sheets and welding of thermoplastic polymer matrix composites [7].

Figure 1 shows the schematic diagram of friction stir welding and the force components during the process.

Polycarbonate (PC) is widely used in the automotive, construction and healthcare industries [9]. It has excellent mechanical and thermal properties, and is also one of the few polymers that can be produced in water-clear or optical quality.

Due to its wide range of applications and its water-clear property, many publications have focused on stir-friction welding tests of polycarbonate (PC) in recent years.

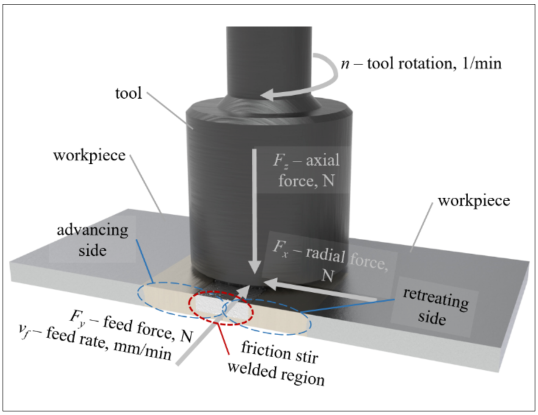

Fig. 1. *A schematic diagram of friction stir welding.* [8]

Derazkola et al. [10]] investigated the joining of polycarbonate (PC) plates by friction stir welding. The purpose of the study was to find a correlation between the welding parameters and the mechanical properties of the seam. They welded 4 mm thick PC plates. During the welding experiments, tool speed, feed rate, tool depth and tool angle were changed. After the welding tests, tensile strength, hardness and specific fracture energy were tested. The best tensile strength (55 MPa) and flexural strength (61 MPa) were achieved with 2200 1/min, a feed rate of 105 mm/min, a tool inclination angle of 2,5° and a tool depth of 1.2 mm.

Ahmed et al. [11] also investigated the friction stir welding of PC plates. They used three rotational speeds (1000, 1500 and 2000 1/min) and four feed rates (25, 50, 75 and 100 mm/min). With most parameters they managed to produce seams without defects. The best tensile strength (66 MPa) was achieved with a rotational speed of 1500 1/min and a feed rate of 50 mm/min, and a rotational speed of 1000 1/min and a feed rate of 50 mm/min.

Lambiase et al. [12] friction stir spot welded PC plates. They used three rotational speeds (2000, 4000 and 6000 1/min), and five feed rates (20, 40, 60, 80 and 100 mm/min). Their results showed that a high feed rate makes the seam thin. They achieved the highest tensile strength (32 MPa) with a feed rate of 60 mm/min.

Vidakis et al. [13] friction stir welded 4 mm thick PC sheets. They measured the force components during welding. In addition to the welding parameters, they also varied the diameter of the pin and shoulder. The morphological characteristics of the seams were examined with an optical microscope, while the porosity of the seams was examined by micro-computer tomography. Their results indicated that a low feed rate reduces the porosity of the seam and affects its dimensional accuracy. Also, a low feed rate and high rotation speed reduce the forces in the process.

Kumar et al. [14] examined the weldability of polycarbonate (PC) and acrylonitrile butadiene styrene (ABS). They welded together 6 mm thick PC and ABS plates. They used three different rotational speeds (800, 1200 and 1600 1/min), feed rates (6, 12 and 18 mm/min) and tool angles (0, 1 and 2°). The tool had a threaded geometry. They found that tensile strength increases as rotational speed and the inclination angle of the tool are increased. The best tensile strength was achieved with a feed rate of 12 mm/min (22,42 MPa).

In this study, we investigate the friction stir welding of 4 mm thick PC sheets. The force components during welding and the strength of the seams are examined as a function of the input parameters. We also examine welding defects.

2. Materials and methods

During the tests, 4 mm thick optical quality DOCANAT clear 099 (Quattroplast Kft., Budapest, Hungary) plates were welded together. The welding test specimens were cut to an overall size of 90×110 mm, so after welding, we were able to cut the standard flat tensile test specimens from the samples. Figure 2. shows the cutting and numbering of the welding test specimens.

The welding tests were performed on a MAZAK Nexus VCN 410A-II CNC milling machine. The force components 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 force meter is $F_x = F_y = -5...5$ kN and $F_z = -5...10$ kN [15].

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

$$F_e = \sqrt{F_x^2 + F_y^2 + F_z^2} \tag{1}$$

The tensile tests of the 3 tensile specimens per measurement point was performed with a Zwick Z005 tensile tester at a test speed of 10 mm/min. We recorded images of the welding seams with a Dino-lite AM3113T type microscope.

The tool used during the welding tests was chosen based on the literature [13]. The geometry of the pin was cylindrical. The diameter of the pin was 4 mm, while the diameter of the shoulder was 10 mm, and the material of the tool was C45 steel. The welding tool used is shown in Figure 3.

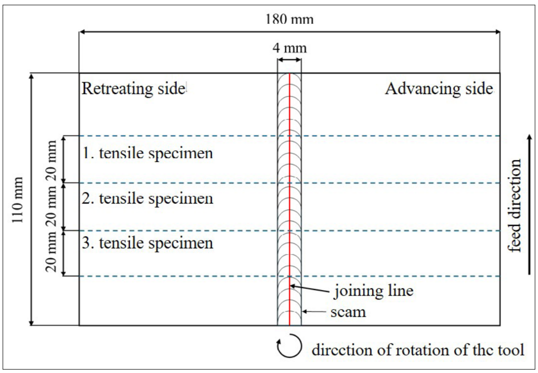

Fig. 2. *The cutting and numbering of the welding test specimens.*

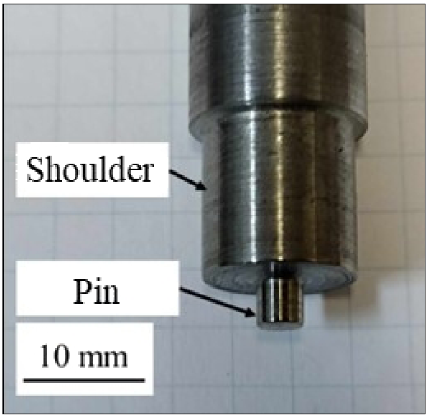

Fig. 3. *The welding tool used.*

Table. 1. *Welding parameters*

Parameters		Levels		
		–1	0	1
x_1	rotational speed – n, 1/perc	600	800	1000
x_2	feed rate – v_f, mm/perc	6	8	10

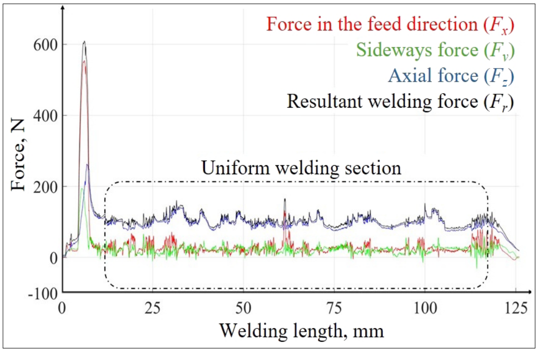

Fig. 4. *Force components during welding.*

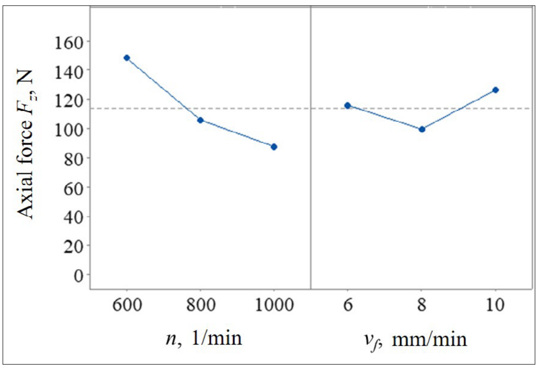

Fig. 5. *The effect of the welding parameters on axial force (F_y).*

AWe used three different rotational speeds and feed rates. The parameters were determined based on preliminary experiments and the literature (**Table 1**).

We used a full design of experiments (all parameter combinations).

3. Results

3.1 Analysis of the registered forces

Figure 4 shows the forces during welding. In addition to the three force components (F_x, F_y, and F_z) we showed the resultant force (F_r) too. There is no significant sideways (F_x) or force in the feed direction (F_y). The greatest force is axial force (F_z) so this affects the resultant force most (F_r). For all three force components, the forces can be divided into three sections during welding. An initial section, where forces increase suddenly, as the tool enters the welding zone, then welding with uniform forces and a decreasing section as the tool leaves the welding zone.

During the evaluation of forces, we always evaluated the average forces in the uniform welding section because this characterizes the welding process best

3.2. The results of the evaluation of forces

There is very little sideways force (F_x) and force in the feed direction (F_y) during welding. Therefore, we examined the axial force component (F_z) and the resultant welding force (F_r).

Figure 5 shows the effect of the axial force (F_z) depending on welding parameters. As rotational speed increases, forces decrease. This can be observed in the friction stir welding of other polymer materials as well **[8, 13, 16]**. As rotational speed is increased, the temperature in the welding zone increases, and the polymer material exerts less resistance on the welding tool. Feed rate has less influence on the axial force (F_z), than the rotational speed of the tool.

Figure 6 shows the main effects plots of F_e Fe as a function of welding parameters. Since the dominant force during welding is the axial force (F_z) the tendencies are similar here, too. As rotational speed increases, the force component decreases.

3.3. The results of strength tests

The seams were characterized with their tensile strength. We cut 3 tensile specimens from each welding sample and performed tensile tests on the specimens. The average of the three tensile tests were considered. **Figure 7** shows the average tensile strength of each measurement point and the standard deviation of the three tensile strengths.

The greatest seam strength was achieved with a tool rotational speed of 1000 1/min and a feed rate of 8 mm/min: average tensile strength was 28.5 MPa. The lowest seam tensile strength was 4.2 MPa with 1000 1/min and 6 mm/min.

The greatest seam strength was always obtained with a feed rate of 8 mm/min. Also, standard deviation was rather high, which can be attributed to welding defects in the seams.

3.4. The analysis of welding defects

Figure 8 shows a typical seam from a top view. In addition to the pin, the shoulder also plays an important role in creating the seam. The seam is not optical quality. At the border of the shoulder, burr formed at every measurement point.

To analyse welding defects and their effects, we produced microscopic images of the cross-sections of the tensile specimens before and after the tensile test. In the cross-sectional image of the measurement point of the lowest tensile strength (n = 1000 1/min and v_f = 6 mm/min) a tunnel defect was clearly visible (**Figure 9**). The tunnel defect is a part with significant material loss along the seam **[17]**. The defect occurred in the retreating side and probably greatly reduced strength. **Figure 10** shows the microscopic image of the specimen after the tensile test, where it is clearly visible that failure occurred along the tunnel defect.

At higher RPMs, the seam became thinner, which is also a typical defect in friction stir welding **[17]**. In this case, the thickness of the plate is reduced below the original thickness (**Figure 11**).

4. Conclusions

In this article, we performed a friction stir welding tests of 4 mm thick polycarbonate (PC) sheets. During the welding process, we measured the forces in 3 directions, from which we calculated the resultant welding force, and also examined the measured forces during the welding process. The quality of the seams was characterized with a tensile test. The welding defects were examined with a microscope. Based on our results, we arrived at the following conclusions:

- The force characterizing the welding process can be divided into three sections: initial section, when the force increases; a steady section with a uniform force; and a final section, when the force decreases.

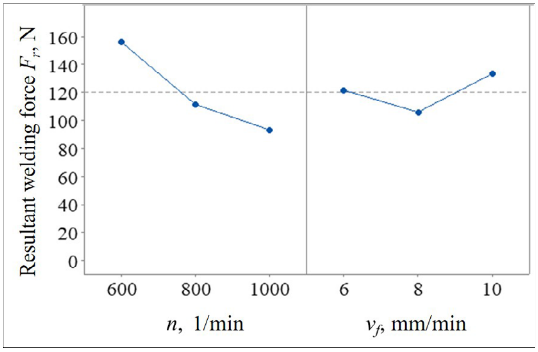

Fig. 6. *The effect of the welding parameters on resultant force (F_e).*

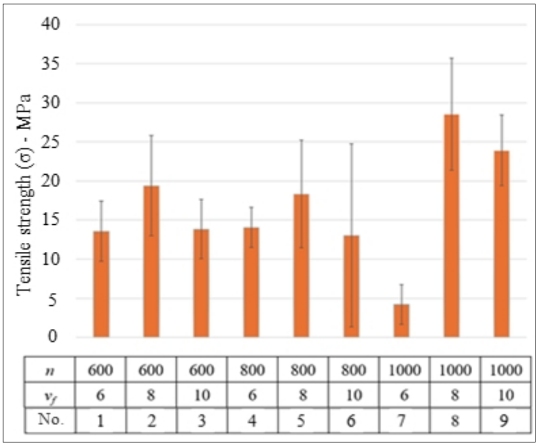

Fig. 7. *The effect of welding parameters on the strength of the seam.*

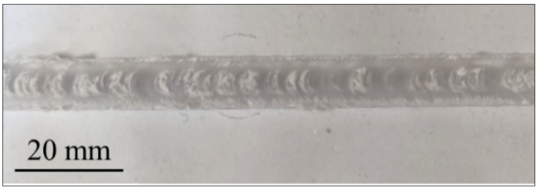

Fig. 8. *A characteristic seam from a top view.*

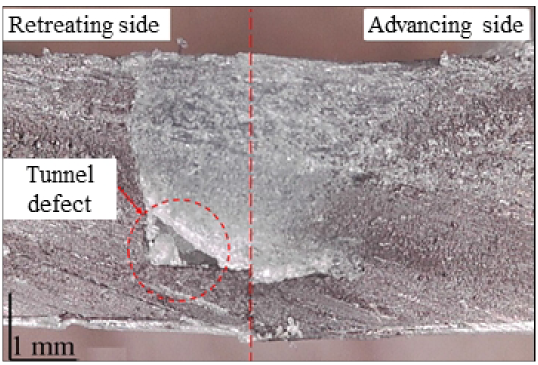

Fig. 9. *Tunnel defect at measurement point 7.*

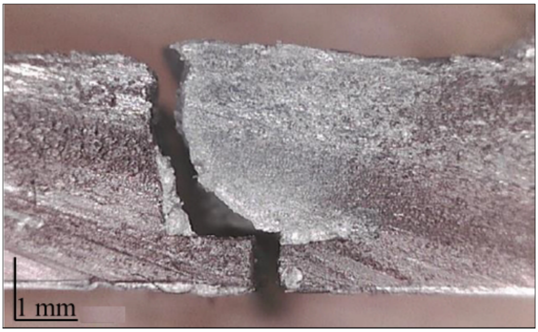

Fig. 10. *7th measurement point – specimen after the tensile test*

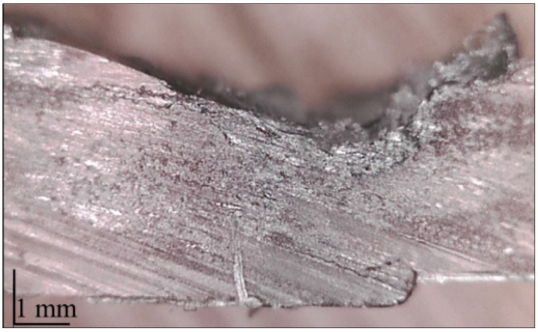

Fig. 11. *Seam thinning.*

- Among the forces during welding, the axial force (F_z) is dominant and this affects the resultant force most.
- As tool rotational speed is increased, both the axial force (F_z) and the resultant force (F_r) decrease.
- We obtained the highest tensile strength with a tool rotational speed of 1000 1/min and a feed rate of 8 mm/min (28.5 MPa), and the lowest tensile strength (4.2 MPa) with a rotational speed of 1000 1/min and a feed rate of 6 mm/min.
- The microscopic images showed tunnel defects and seam thinning in several measurement points

Acknowledgements

Supported by the ÚNKP-23-3 New National Excellence Program of The Ministry for Culture and Innovation from the Source of The National Research, Development and Innovation Fund.

References

[1] Kiss Z., Temesi T., Bitay E., Bárány T., Czigány, T.: *Ultrasonic welding of all-polypropylene composites.* Journal of Applied Polymer Science, 137/24. (2020) 48799. https://doi.org/10.1002/app.48799

[2] Temesi T., Czigany T.: *The effect of surface treatment on the shear properties of aluminium-polypropylene joints manufactured by laser beam.* Polymer Testing, 117. (2023) 107882. https://doi.org/10.1016/j.polymertesting.2022.107882

[3] Tiwari S. K., Sharma H., Rao A. U.: *A comprehensive review of the recent developments in friction stir welding of metals, alloys, and polymers: a review of process parameters and properties.* Journal of Adhesion Science and Technology, (2024) 1–24. https://doi.org/10.1080/01694243.2024.2334271

[4] Thomas W. M., Nicholas E. D., Needhan J. C., Murch M. G., Temple-Smith P., Dawes C. J.: International patent application PCT/GB92/02203 and GB patent application 9125978.8. UK Patent Office, London 6, 1991.

[5] Majeed T., Wahid M. A., Alam M. N., Mehta Y., Siddiquee A. N.: *Friction stir welding: A sustainable manufacturing process.* Materials Today: Proceedings, 46. (2021). 6558–6563. https://doi.org/10.1016/j.matpr.2021.04.025

[6] Nelson T. W., Sorenson C. D., Johns C. J.: *Friction stir welding of polymeric materials.* Brigham Young University, Provo, UT, USA, US 6, 811,632 B2, 2004.

[7] Czigány T., Kiss Z.: *Friction stir welding of fiber reinforced polymer composites.* In Proceedings of the 18th International Conference on Composite Materials. Jeju, South Korea, ICCM, 2011, August. 21–26.

[8] Stadler R. G., Horváth R.: *Investigation of Welding Forces and Weld Strength for Friction Stir Welding of Acrylonitrile-Butadiene-Styrene (ABS) Plates.* Acta Materialia Transylvanica, 6/1. (2023) 53–58. https://doi.org/10.33924/amt-2023-01-09

[9] Gohil M., Joshi, G.: *Perspective of polycarbonate composites and blends properties, applications, and future development: A review*. Green Sustainable Process for Chemical and Environmental Engineering and Science, (2022) 393–424. https://doi.org/10.1016/B978-0-323-99643-3.00012-7

[10] Derazkola Hamed Aghajani, Simchi Abdolreza, Lambiase Francesco: F*riction stir welding of polycarbonate lap joints: Relationship between processing parameters and mechanical properties*. Polymer Testing, 79, 105999, 2019, Elsevier. https://doi.org/10.1016/j.polymertesting.2019.105999

[11] Ahmed M. M. Z., Elnaml A., Shazly, M, El-Sayed Seleman M. M.: *The effect of top surface lubrication on the friction stir welding of polycarbonate sheets*. International Polymer Processing, 36/1. (2021) 94–102, , De Gruyter https://doi.org/10.1515/ipp-2020-3991

[12] Lambiase F., Grossi V., Paoletti A.: *Advanced mechanical characterization of friction stir welds*

made on polycarbonate. The International Journal of Advanced Manufacturing Technology, 104. (2019) 2089– 2102, , Springer
https://doi.org/10.1007/s00170-019-04006-4

[13] Vidakis N., Petousis M., David C., Sagris D., Mountakis N., Moutsopoulou A.: *The impact of process parameters and pin-to-shoulder ratio in FSW of polycarbonate: welding forces and critical quality indicators*. The International Journal of Advanced Manufacturing Technology, (2024) 1–21.
https://doi.org/10.1007/s00170-024-13033-9

[14] Kumar Sudhir, Roy Barnik Saha: *Novel study of joining of acrylonitrile butadiene styrene and polycarbonate plate by using friction stir welding with double-step shoulder*. Journal of Manufacturing Processes, 45. (2019) 322–330.
https://doi.org/10.1016/j.jmapro.2019.07.013

[15] KISTLER Multicomponent Dynamometer 9257b datasheet, 2009, Kistler Group

[16] Stadler G. R., Szebényi G., Horváth R.: *Investigation of weld forces and strength of friction stir welded polypropylene*. Periodica Polytechnica Mechanical Engineering, 67/3. (2023) 183–189.
https://doi.org/10.3311/PPme.21899

[17] Huang Y., Meng X., Xie Y., Wan L., Lv Z., Cao J., Feng J.: *Friction stir welding/processing of polymers and polymer matrix composites*. Composites Part A: Applied Science and Manufacturing, 105. (2018) 235–257.
https://doi.org/10.1016/j.compositesa.2017.12.005