FRICTION STIR WELDING OF FIBER REINFORCED POLYMER COMPOSITES

T. Czigány*, Z. Kiss
Department of Polymer Engineering, Faculty of Mechanical Engineering, Budapest University of Technology and Economics. Műegyetem rkp 3., H-1111 Budapest, Hungary
* Corresponding author (czigany@eik.bme.hu)

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1. Introduction

Friction stir welding (FSW) was developed in the 1990's with the cooperation of the British „The Welding Institute", the first patent was submitted by Thomas *et al*. [1]. The welding method is applied to light metals and aluminum with great success, as the process is fast, can be used in series production, thick parts can be continuously processed and the welded seam does not need any surface post-treatment. The FSW method can be used even on automatic production lines, Mazda Motor Corporation uses it to weld chassis elements [2].

FSW is used first of all to prepare butt weld joints. In this method a rotating tool is pushed in-between the sheets to be welded, leading to heat evolution, then the tool is moved along the sheets to be joined in the welding direction, thus forming the welded seam [3]. When welding metals the tool also comprises a shoulder part with the task to keep the melt in the seam area (Fig. 1.).

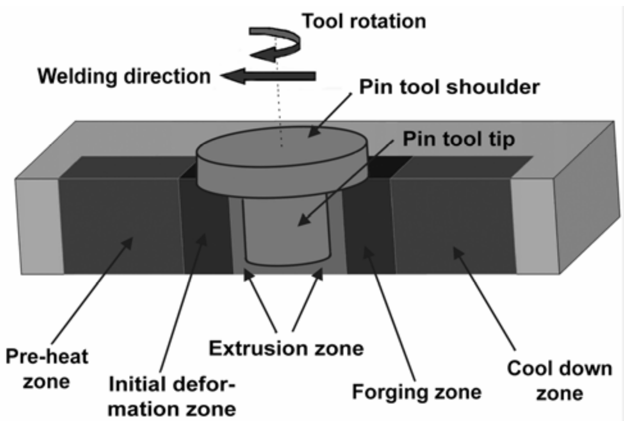

Fig.1. Scheme of the principle of friction stir welding for metals [3].

FSW has been hardly studied so far for polymeric structural materials in spite of the fact that welding of plastics is a task of high importance in the industry from the joining of plastic underground pipes to the ultrasonic welding of miniature plastic electronic parts. FSW is useful for plastics welding [4], as here advantages shown in metal welding become prominent: the sheets to be welded need minor pretreatment, complicated 3D welded seams can be produced using welding robots, it is a one-step method even in the case of large wall thickness, it can be incorporated into completely automatic production processes. The results of FSW welding with plastics obtained so far show that the welded seams exhibit a high efficiency factor (i.e. the strength of the welded seam approaches that of the bulk material) [5-9].

In the case of plastic welding the joining of composite sheets containing some kind of reinforcement has also been intensively studied [10], as such materials are the basis of more and more load bearing structures. It is a frequent problem in welded reinforced, thermoplastic matrix composites that in the welded seam the reinforcing structures of the two welded parts do not form a continuum, so the strength of the joint is provided by the matrix-matrix joint only. The rotation tool used in FSW is able to mix the reinforcement too and to homogenize its distribution in the seam, so a mutually inter-meshing structure of the two welded parts can be realized (Fig. 2.).

This paper presents the results of mechanical studies and seam micrographs obtained on chopped glass fiber reinforced polypropylene welded seams prepared on automatic FSW equipment developed by us. FSW process is demonstrated for polymeric materials together with the parameters used and with their effects on the seam properties.

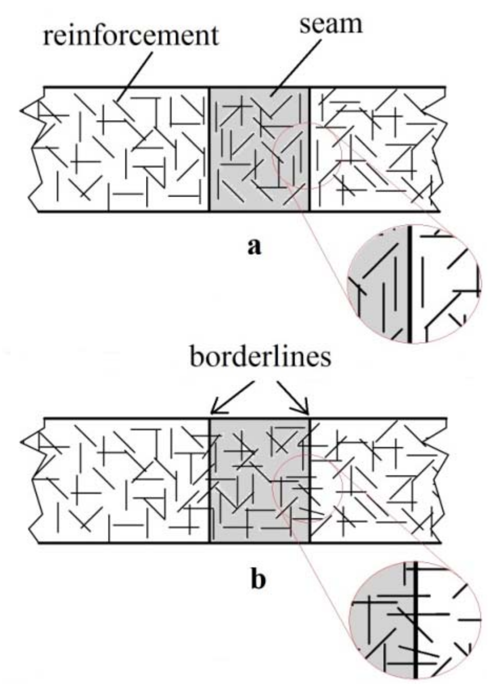

Fig.2. Welded seam in fiber reinforced composites with thermoplastic matrix. a: non-intermeshing fibers, b: intermeshing fibers at the interface.

2. Materials and methods

10 mm thick polypropylene sheets containing 30 wt% chopped glass fiber were welded in the experiments. When preparing the composite sheets 65 wt% Tipplen H483 F polypropylene homopolymer (TVK, Hungary), 30 wt% 4.5 mm long glass fibers (OCV Italia, 995-13C grade), average diameter 14 µm, average tensile strength 20 MPa) and 5 wt% Scona 8012FA (BYK Kometra GmbH, Germany) coupling agent were mixed and a compound was prepared on a Labtech Scientific twin screw extruder. 10 mm thick sheets were compression molded form the compound using Collin P200E type laboratory press. The 160x160 mm sheets were cut into two, the seams were prepared by welding the two halves along the cut line. Welded seams were investigated by tensile tests and according to a German plastics welding standard (DVS 2203-5) by three point bending. The flexural strength of the sheets without reinforcement was 46.57±4.75 MPa, while that of the reinforced composites sheets was 76.7±7.05 MPa. Under the effect of the glass fiber reinforcement the flexural strength of PP increased 1.5 times, which is mostly due to improved fiber/matrix adhesion caused by the maleic anhydride grafted coupling agent.

A JEOL JSM-6380LA scanning electron microscope (Tokyo, Japan) was used to analyze the fracture surface of the seams, the surface of the test specimens was rendered conductive by a thin gold layer. Polished samples taken from the cross section of the welded seams were investigated by an Olympus BX51 optical microscope (Tokyo, Japan).

In our preliminary experiments it has been established that the shoulder rotating together with the tool shown in Fig. 1 results in bad surface quality in the case of polymers. In our work the shoulder was replaced by a static shoe made of PTFE which allowed the production of smooth seams (Fig.3.). The effects of welding parameters (e.g. rotation speed) and of the type of welding tools have been studied in our experiments [9].

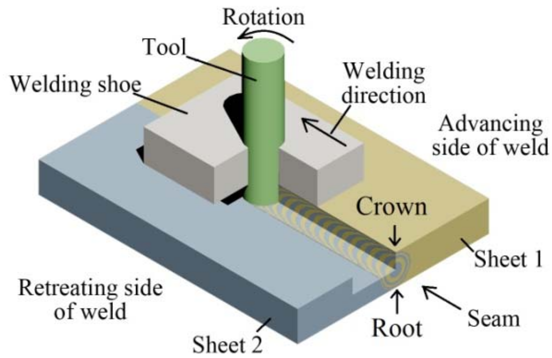

Fig.3. Scheme of the principle of friction stir welding for polymers.

3. Development of FSW equipment

Computer controlled welding equipment was developed by us for studying the FSW method, by which we could investigate all parameters important from the viewpoint of welding (feeding rate of welding, rotation speed of the rotating tool etc.). The welding tool is changeable. A milling cutter of 8 mm diameter with 8- or 4-tooth was used for welding. When studying the welded seams by three point bending, two loading geometries were distinguished, i.e. the welding was done for one side of the sheets, so that side of the seam being in contact with the smoothing shoe (crown) exhibited mechanical properties different form the lower side of the seam (root). If bending from the crown side the loading head contacted the upper (crown) side of the seam, while if bending form the root side it contacted the lower (root) side of the welded seam.

4. Results and discussion

In the experiments it could be established that the welding tool was able to melt the fiber reinforced material, therefore a welded seam could be successfully prepared. When preparing the welded joints the strength properties of the welded seams were significantly influenced by the degree of fragmentation of the reinforcing fibers located in the seam.

In the first few experiments a milling cutter with 8-tooth was used for welding as it resulted in the highest bonding strength when welding non-reinforced polypropylene sheets [9, 11]. The relative frequency of various fiber lengths in the base material and in the welded seam prepared by an end mill with 8-tooth at a rotation speed of 3000 rpm are compared in Fig. 4. Due to the shearing forces evolving during the rotation of the tool resulted in a significant reduction of the glass fiber length. The average length measured in the base material (338 µm) was roughly halved (103 µm) in the welded seam. The average fiber length was already low in the composite base sheet, which was further reduced by the rotating motion of the welding tool.

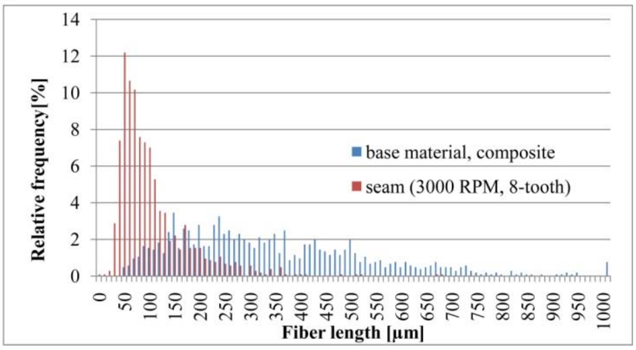

Fig.4. Fiber length distribution (frequency) of the glass fibers in the base composite sheet and in the welded seam prepared at 3000 rpm using a milling cutter of 8 mm in diameter with 8-tooth.

Meanwhile the length of a significant part (20%) of the fibers exceeds 0.5 mm, which was enough to achieve a reinforcing effect. In contrast none of the fibers in the welded seam reaches 0.4 mm length. The flexural strength of the seams prepared at 3000 rpm rotation speed with the 8-edged tool scattered in the 20-30 MPa range, which is a weak joint as compared to the flexural strength of the non-reinforced PP sheets. Increasing the length of the glass fibers in the seam is of basic importance with respect to the usefulness of the FSW method, therefore an end mill of 8 mm in diameter was used further, but not with 8, only with 4-tooth. A lower degree of fragmentation was expected with the 4-edged tool. The rotation speed of 3000 rpm proved also to be too high for welding composite sheets due to the fiber-fragmenting effect of the rotating tool. When welding glass fiber reinforced PP composites too high rotation speed is accompanied by strong fragmentation, while at too low rotation speed the material of the seam does not melt enough, also resulting in bad quality joints. The optimum welding rotation speed depends on the type of the tool used, on the initial length distribution of the fibers and on the viscosity of the matrix material. As shown in Fig. 5 at a rotation speed of 2100 rpm the flexural strength is 48.86±4.1 MPa for crown side bending and 46.67±4.6 MPa for root side bending. These values approximate with those obtained for the non-reinforced base material, which was 46.57±4.75 MPa. If no intermeshing of the reinforcing fibers is assumed, only pure matrix-matrix joining, this would practically correspond to 100% efficiency factor.

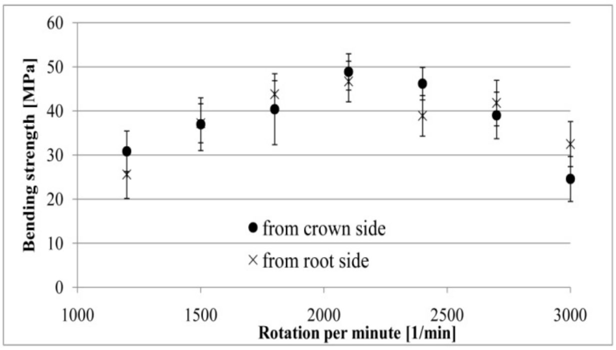

Fig.5. Three point bending strength values of glass fiber reinforced H483F PP matrix composites.

If compared to the flexural strength of the glass fiber reinforced PP sheet (76.7±7.05 MPa) the best flexural strength achieved for the welded joint would correspond to an efficiency factor of about 64% for crown-side bending. It is more spectacular, however, to take into account the welding strength of the non-reinforced H483F PP sheets. The welding of the non-reinforced H483F PP sheets was performed using a 4-edged, 8 mm diameter end mill. As the viscosity of the non-reinforced H483F polypropylene sheet is different form that of the composite, the rotation speed belonging to the best strength was also different, therefore the optimum flexural strength achievable was determined by tests performed at different rotation speeds. It has been established that the optimum flexural strength of the non-reinforced H483F PP sheets can be achieved at 1500 rpm, using crown-side loading. The difference between the strength value of 38.31±3.8 MPa achieved here and the best value obtained with composites is about 10 MPa, which can only be explained by the reinforcing effect of the fibers present in the seam.

The fiber length distribution observed after burning off the matrix of samples prepared at 2100 rpm rotation speed belonging to the best flexural strength value obtained with 4-edged tool is shown in Fig. 6. The distribution is compared to that of the base material, as in Fig. 4. It can be observed that the degree of fiber fragmentation is high also with 4-edged tool, but the average length of the fibers is 194 μm, which is almost double of that obtained with 8-edged tool.

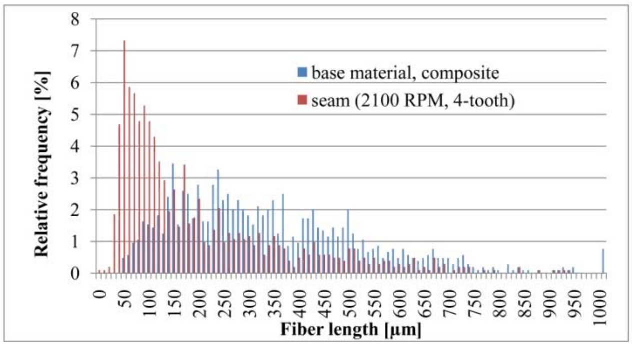

Fig.6. Fiber length distribution (frequency) of the glass fibers in the base composite sheet and in the welded seam prepared at 2100 rpm using a milling cutter of 8 mm in diameter with 4-tooth.

As shown by the frequency of fiber length occurrence the length of several of the measured fibers reaches, even exceeds 400 μm (about 15%), which, according to the flexural strength tests, already resulted in better joint strength than that of the matrix material.

Possible intermeshing of the fibers present in seams of welded glass fiber reinforced PP composite sheets with those present in the neighborhood of the seams was checked also by optical microscopy. Fig. 7 shows an optical micrograph of a polished surface prepared at the borderline of the base material and the seam, where the longer fibers of the base material exhibit intermeshing with shorter ones in the seam. The trace of the outer mantle of the tool cannot be identified, so the borderline can only be approximately found on the micrographs of the polished surfaces. As the fiber orientation in the compression molded sheets is completely random, both longer and shorter fibers can be observed on the micrograph. The absolute and the relative (mutual) orientations of the fibers appearing at the borderline of the seam and the welded sheet are also random. Several smaller voids can be found in the seam, which can be partly explained by the air admixed into the seam during welding, partly they might have formed during cooling. The average size of these voids is 0.2-0.3 mm, therefore the seam is porous, but the voids are not interconnected, so the seam exhibits sealing properties (watertight).

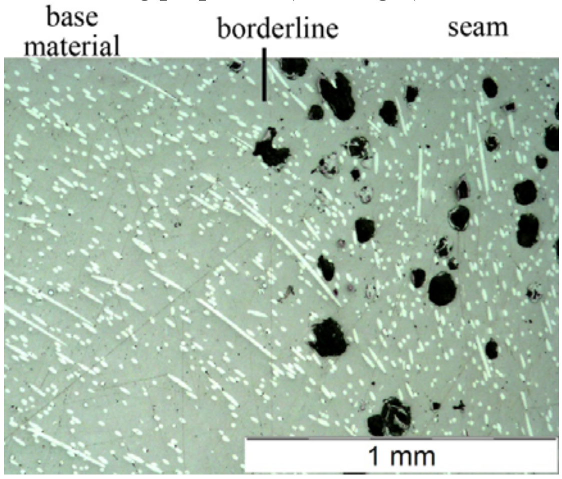

Fig.7. Optical micrograph of the polished surface prepared at the borderline of the seam and of the base material.

After the mechanical testing of the welded seams SEM micrographs revealed that the fibers (in spite of the length reduction) could fulfill their reinforcing role. Welded samples usually failed at the edge of the welded seam or within the seam but, as shown in Fig. 8 the fibers protruding from the fracture surface, the reinforcement of the two, originally separate sheets is well homogenized. As shown by Fig. 8 the glass fibers broke during failure, and fiber pull-out can also be observed. Fiber-matrix adhesion is acceptable, taking into account the fact it is not easy to create good adhesion between non-polar PP and the glass fiber, but in our case some improvement could be achieved by using a coupling agent.

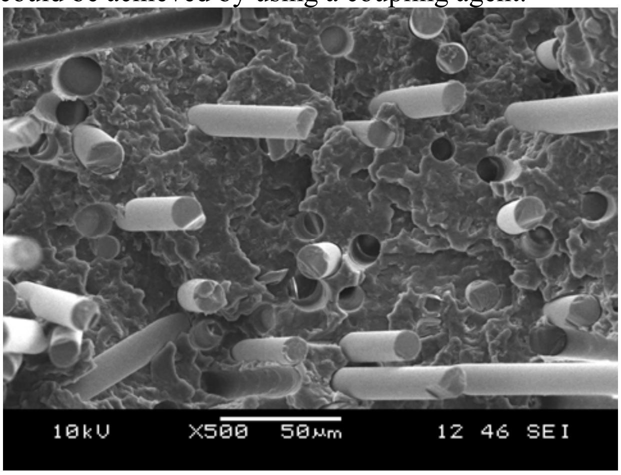

Fig.8. SEM micrograph of a fractured surface prepared by FSW on two PP sheets reinforced by 30 wt% glass fiber.

The borderline between the seam and the base material was also analyzed by SEM micrographs, similarly to the area shown in Fig. 7 studied by optical microscopy [11]. Fig. 9 shows the intermeshing of the fibers being present in the seam and in the base material at the borderline. Due to the compression molding fibers are randomly oriented in the base material, consequently the relative orientation of the fibers located on the two sides of the borderline may be parallel or may exhibit a certain angle with respect to each other. The optical and SEM micrographs show together that the tool may produce an intermeshing structure between the reinforcements of the seam and of the base material. Although the strong shearing effect caused by the rotating tool may lead to the fragmentation of the fibers in the seam, they keep their reinforcing role.

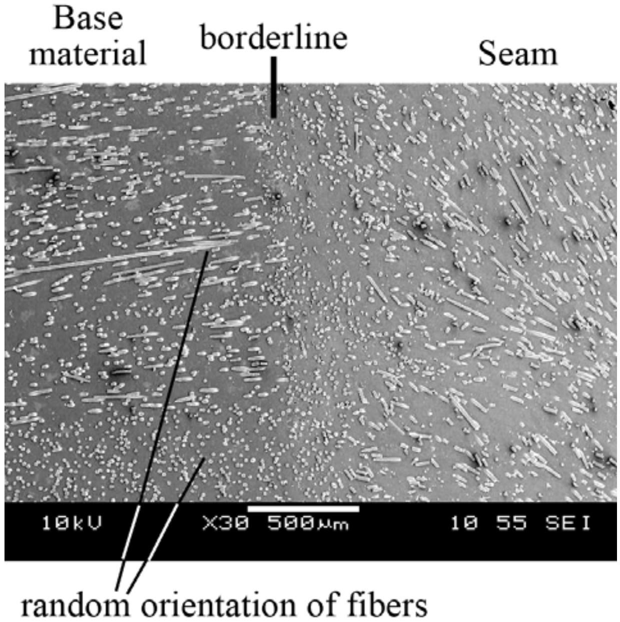

Fig.9. SEM micrograph taken at the borderline of the seam and the base material.

Figure 10 shows the interface between the seam and the base material, where the glass fibers overlap and form an intermeshing structure. Intermeshing of the reinforcing fibers was realized at the borderline of the seam, as shown schematically in Fig. 2/b.

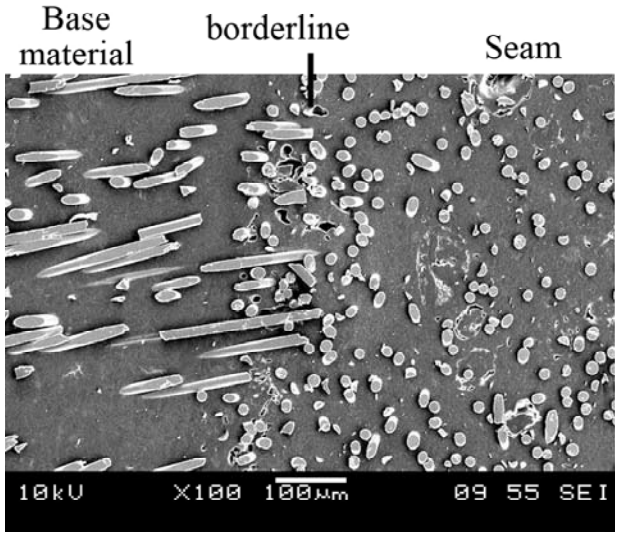

Fig.10. SEM micrograph of the intermeshing glass fiber structure formed at the borderline of the seam and the base material.

5. Summary

The aim of the paper was to present the course of the welding process, test methods of the welded seams and the results obtained by them. The applicability of FSW to fiber reinforced thermoplastic matrix composites was demonstrated by mechanical tests, optical and electron microscopic studies.

It was demonstrated that friction stir welding is an effective welding method for polypropylene matrices reinforced with 30 wt% glass fiber. In the case of 10 mm thick composite sheets, using an end mill of 8 mm in diameter with 4-tooth, the flexural strength of the seams produced exceeded those of the seams produced on non-reinforced sheets by 27%. The flexural strength increment achieved in the composite sheet proves the presence of fibers crossing the borderline of the seam and of the base material. The key element in the applicability of the FSW technology to glass fiber reinforced composites is the degree of fragmentation of the fibers. In cases when the fiber length in the composite sheets to be welded is higher, it is expected that the average fiber length in the seam will also be higher, resulting in stronger joint.

Acknowledgments

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