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Research paper

Thermoplastics Polymers Friction Stir Welding: Review

Randa Kamel Hussain[1]*, Assel Mustafa Abdul Majeed[2]

[1, 2] College of science, Mustansiriyah University, Iraq
**Corresponding author E-mail: dr.randa.kamel@uomustansiriyah.edu.iq*

Abstract

Friction stir welding (FSW) is a relatively new technique has great potential it is an eco-friendly, low cost, used a wide range of materials and an excellent success to materials that un-fused. FSW technique recently developed for joining of thermoplastic polymeric materials and their composites. This review pointed to polymers welded by FSW method, focusing on previous articles that study the weld generation mechanisms. Displaying the explanations to reach a well understanding of polymer welding is presented in this review. The relationships and the effects of friction stir welding parameters on yield microstructure, phases, and mechanical properties were also re-discussed.

Keywords: *crystallinity degree, friction stir welding, microstructure, thermoplastic polymer, welding parameters.*

1. Polymers

Regarding their behavior to heat, polymers could categories into two type thermoplastics, and thermosetting polymers. The heat effect on thermosetting is irreversible; polymer chain is possess a significant cross-linking to offer an in-fusible of polymers, causing the degeneration it. The common examples to thermosetting polymers are the epoxy resin and polyester resin; these resins could mold in proper shape at once only.

Thermoplastics polymers are softening when heating and at a certain temperature behave like a fluid, cooling thermoplastics will return it to a solid form. Thermoplastics feature about the reversible response to heat, make it recycling to re-mold. The popular examples of thermoplastics are polyethylene, polypropylene, polystyrene, and poly (vinyl chloride). These materials may either amorphous or semicrystalline. Thermoplastics flow in manner of a fluid state if it heated up the glass transition for amorphous thermoplastics, and flow will occur by heating above the melting temperature in semicrystalline thermoplastics polymers [1].

2. Welding of stir friction

Welding by stirring friction invented in 1990s, for joining metals and alloys that prevent fusion as aluminum alloys [2] by TWI.
The friction stir welding machine consists of main parts; rotating tool pin to implement into the joint, tool probe connects with the part to generate heat, shoulder responsible of connecting for improving the implementation while expanding the hot zone, and surface stir at the bottom of the tool which responsible about formation a friction-stir-weld nugget. Figure 1 showed the typically machine of a friction stir welding [3].

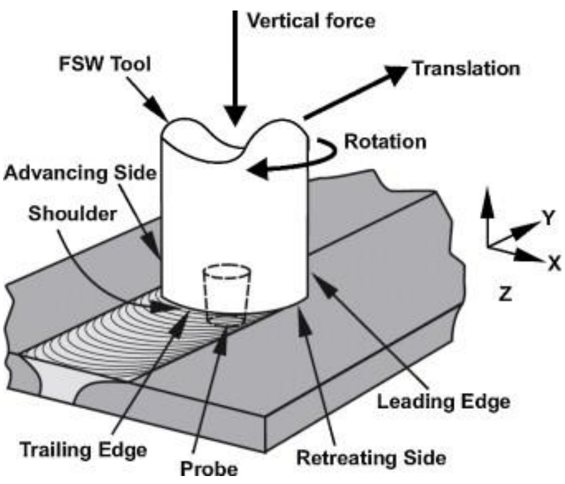

Fig. 1: The schematic of FSW method [3]

The similar or dissimilar materials could join together by creating a molecular bonding via a welding process. For any a welding process there are three basic stages; started with the pressing of materials workprices, then heating them at , could pass and transport from side to side. The final arrangement of the transported molecules is dependent on the cooling; cooling stage is allowing the new material to re-build in its own last microstructure by solidification. The applied pressure through clamps over heating and cooling is necessary in order to fix the workpieces as well as to help the molecular diffusion through the interface. Consequently a new solid microstructure, the weld strength is strongly depending on cooling conditions, it is necessary to control the cooling. The slow cooling provides, the fused traveling material, enough time to re-crystallization in less distortion and defects in the microstructure.

Many advantages could achieve with the FSW comparing with other welding methods, but this method remains has some obstacles about weld strength; mostly the welding efficiency is just nearly approaches to 80% of base materials [4]. The degradation and weakness creating in a transition region are due to fatigue generated in the interface region. The non-homogeneity of microstructure created by the transformation from molting to nugget solid materials that lie in the transition region caused distortions and defects in microstructure building, thus crack diffusion become easier in interface region. The locations where the failure happened specified by the tensile test, in the region of TMAZ the tensile failure is 56.67% while it is 36.67% in the HAZ region, and in nugget region has 6.7% [5]. The higher temperature at TMAZ region deforms the material without re-crystallization, reducing the material strain deformation that is necessary to resist fracture. In the HAZ region the material subjected to thermal cycling which avoiding the plastic deformation.

3. Polymer Joining

Within few years after aluminum welding for the first time by FSW, efforts focused on used friction stir welding method to join similar or dissimilar polymers. Friction Stir Welding (FSW) being first used successfully on metals and alloys especially aluminum alloys, then spread to composites, many articles discussed the FSW for composites consist of metals, ceramics, and polymers [6-8].

Actually, the concern of used the polymer materials in FSW is due to that the high speed rotational of pin tool, pushing the polymer to flow in the nugget zone that could destroyed the macromolecular chains and change the structure building of polymer. Thus, the polymers are not much as metals joined by FSW. A wide range of polymers have been successfully welded by FSW, the common polymers welded are polyethylene (PE) [9], polypropylene (PP) [10], polycarbonate (PC) [11], polyamide (PA) [12], and polymethylmethacrylate (PMMA) [13]. Nanocomposites are also welded by FSW, spot friction used to join thermoplastic sheets of nanocomposite for PMMA with PMMA/silica and PMMA/silica-g-PMMA nanocomposites [14]. Friction stir machine could be used to improve the material by their surface treatment; in fact, FSW is a candidate to be attractive strategy in composite modification. It is applied to produce high-density polyethylene polymer – copper powder metal composite via friction stir processing to improve the composite properties, the heat source is applied within the shoulder. The composite displayed good mechanical properties of tensile strength and elasticity. Moreover the surface properties and good uniformity of microstructure are exhibited [15]. Plastic welding methods can classify into mechanical, electro-magnetical, and thermal. Heating method related to heat source whether it is internal or external heating. Thus many techniques may introduce to polymer welding, such as spin, hot plate, laser or infrared, radio frequency. The joining methods of thermoplastics polymers are exhibiting in Figure 2 [16].

FSW is dominating on other joining methods in many advantages; short time process, do not need to further surface treatments, joining without foreign parts or materials (such as glue, adhesives, clamps, or screws), and ability to enhancement the joint quality by reprocessing it [17]. Unlike the chemical reactions which produce a permanent bond to join materials together, the welding melts small zone of pieces materials by heat to parts that be joined together without chemical reaction bonds.

The shear strength generated in friction welding is higher than other means of the microwave, thermal heating, and ultrasonic welding. This feature provides the friction welding feasibility [18].

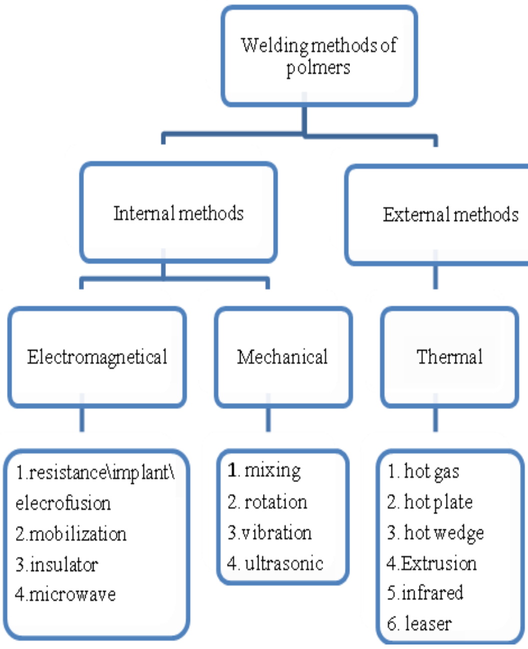

Fig. 2: Welding methods for thermoplastics [16]

4. FSW Parameters

A significant relationship between the quality and strength of welding with the process parameters of FSW, such process parameters are pin geometry, a temperature of shoe, the speed of spindle, feed rate, and distance between top of the anvil and the bottom of the pin. The feed rate affected by speed rotational that moves-away more molecules to travel to the other side of the join. Figure 3 exhibits the effect of rotational rate and welding speed on common polymers, most polymers required welding speed around 20 (mm/min), rotational rate is more related to material microstructure, that explained the high variance appears in rotational rate values. There is some balancing between rotational speeds and welding speed with the polymer physical properties. Thus, a higher rotational speed combined low welding speed are required for polymers with high melting temperature and viscosity, for generating heat that sufficient to flow the fused materials to ensure producing a high strength of welding.

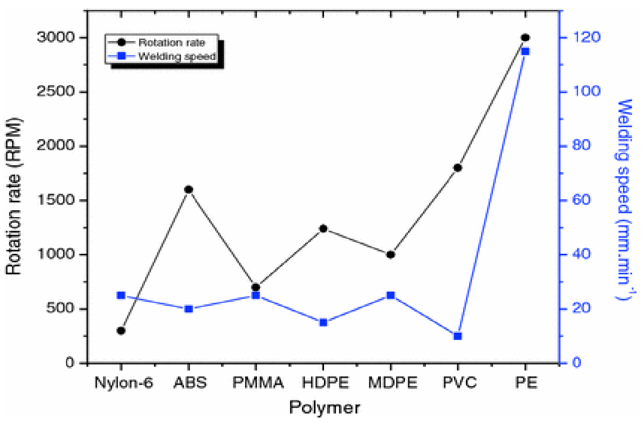

Fig. 3: Some FSW parameters for different polymers [19]

The higher rotational speed of pin led to a higher tensile and flexural strength, for example the maximum stress could the material welded withstand is reached up 95% in contrast with the un-welded material for polyethylene sheets when increased the rotational speed. The high - velocity of rotational nail elevates the topical temperature near of pin position in material because the thermal conductivity of polyethylene polymer is too low, that allows the heat transferring to narrow zone. Thus a concentrated in heat energy is generated at this zone and melts it. It observed that high level of rotational speed combining with minimal temperature of shoe leads to degrading polymeric material; the best value of transverse speed is 25 mm/min [20]. By adjusted the rotational speed of the pin and the temperature of the shoe to high levels at welding of acrylonitrile butadiene styrene (ABS) sheets showed an improvement in weld quality, the shoe heat is kept a fixed while a rotating pin through this shoe stirs melted material [21].

Remember that the rotational pin speed needs not too high, for example used the tool rotational speed in range (1000 and 1500 (rpm)), transverse speed (50 and 200 (mm/min)), and the axial force (0.75 to 4 (kN)) for acrylonitrile butadiene styrene (ABS) plate welds gives good quality. The tensile strength of the resultant weld is below the base material and is at higher efficiencies of above 60 (%) for higher rotational speed and axial force providing the weld a good quality. But increasing the rotational speed more than certain speed created cavities and porosity which draw back the strength weld and smoothing of weld zone [22].

The welding quality related to the tensile strength of joined work-spaces that are strongly accompanied with the correct choice of polymers, the best results obtained by polypropylene regarding it is crystalline microstructure and the high mechanical properties comparing with other polymers. A very high welding quality was obtained sustainably with some conditions of welding process; polypropylene welded with very high tensile strength approached to value of base materials [23] with the assistance of some conditions as heat plates. With optimization of the weld parameters, the experimental weld strength reach up to 97% and 101% for cylindrical and conical pinned tools respectively, to a tensile strength of the base Acrylonitrile Butadiene Styrene sheets [24]. Table 1 presented the tensile strengths of friction stir welding polymers contrast with base materials [25].

Table 1 : Ultimate Tensile Stress of base material and FSW polymers [25]

Material	Base Material Ultimate Tensile Stress (MPa)	Friction Stir Welding Results	
		Ultimate Tensile Stress (psi)	% base material Ultimate Tensile Stress
ABS	34.1	32.7	96
HDPE	22.5	21.5	95
PA	72.4	28.4	39
PC	68.3	57.1	83
PMMA	42.0	21.5	51
PP	31.3	30.6	98
UHMWPE	28.8	20.0	69

5. Microstructure

The process of heating polymer until melting it followed by cooling that permitted polymer to solidification consists of four phases [26-27]:

I) Initial heating: in this phase, the friction generated a heat that warmed material to high temperature. When the temperature of interface reached to the melting temperature or glass transition temperature dependent to polymer crystallinity, the polymer will melt.

II) Un-steady melting: the molten zone is heating by shear dissipation. Related to extremely height of the shear stress and the heat creation which fast increasing the temperature. In this phase, the molten film is very thin and material could flow. At increment of the molting film thickness, somewhat of the melted material will squeezed abroad of the shear stress region.

III) Steady-state flow: At equilibrium of heat generation with heat dissipated at the connecting region the steady–state flow will tack place. In this case, both temperature and thickness of the molten zone are constant. This phase acquires the weld zone the strength and quality.

IV) Solidification: The stopping of the rotating machine with continues of the clamps pressure benefits the diffusion through an interface. The temperature will lower down that permits to solidification of the polymer. Figure 4 illustrates the phases of the polymer during heating–cooling process [19].

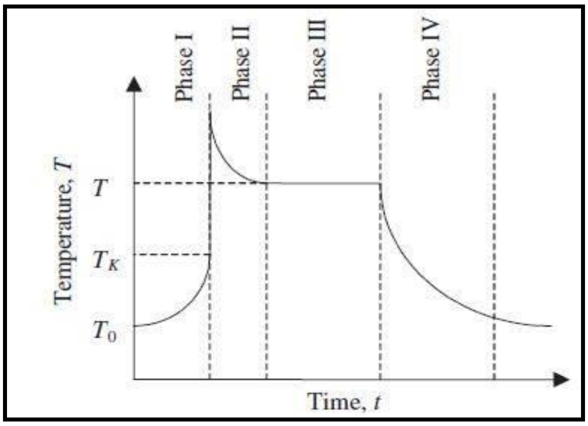

Fig. 4: Phases formation profile [19]

Accordingly the fusion-solidification mechanisms, the welded material regions characterized into four splits regions: base material (BM), heat affected zone (HAZ), thermo-mechanical affected zone (TMAZ), and weld nugget (WN) that are shown in Figure 5.

Fig. 5: Regions formed by SFW [28]

At some circumstances a root defect appears in the zone under of the joint, this area lies bottom the rotating pin that forbidden it to stir causing a lack of molting the material especially at a single passing of weld machine. This root defect is the accountable of the weakness for all tensile and bending failure causing the weld is weak.

Unfortunately, It is seems there a limitation in numbers of studies about the FSW, as our survey. A coating of shoulder used to improve the remains stress accumulated in weld region came from the imputation of fused material to the tool and thus, better joining performance could obtained. Furthermore, a high quality of welding material surface is result by coated the tool. These results obtained by optimization the FSW parameters to enhance the microstructural and mechanical results. From mechanical tests results and microscopic observations, the best passing speed for polyethylene of 25 mm/min with using heat assistance of friction stir welding [20].

Sometimes the technology used to modify the structure of materials, rather than welding, in this case, it is known as (friction stir process FSP). The re-orientation of material particles is an example to the structural modification, a composite of SiC/Al [29] composite is displayed a change in orientation of silicon carbide particles after a single pass of stir friction. The SiC particles acquired the anisotropic shape of aspect ratio in range (1.6 -1.8). From SEM investigation it is found that the particles oriented in a preferred orientation for the non-equiaxed SiC particles after extrusion processing, and the alignment is parallel to the extrusion direction. Figure 6 exhibits the SEM images that showed the microstructure modification for SiC/Al composite obtained by using FSP technology.

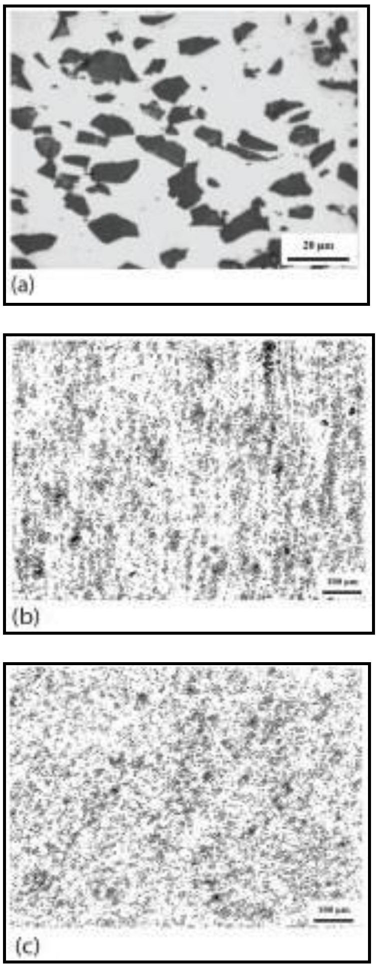

Fig. 6: SEM for SiC/Al microstructure: a)anisotropic SiC particles, b)SiC/Al composite, and c)The composite structure after FSP [29]

The SEM investigation at the center of the seam polypropylene displayed that the polypropylene kept its spherulitic structure with a smaller diameter to half size. Several large molecular of cylindritic structures appeared in the transition zone, the spherulitic particles were aligned at the melted polypropylene and then crystallized in super-molecules. In HAZ, the shears stress activate the polymer to soft and exhibited a distorted spherulites structure [30]. At these parts the melt was exposed to strong shearing during welding, so the polymer crystallized in a layered form, along certain lines, corresponding to the streamlines. The interface area for 2000 rpm showed an absence of semicrystalline structure, the flow pushes the spherulitic structure towards base material, see Figure 7.

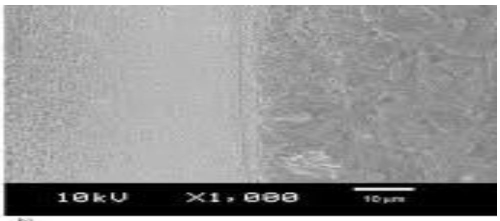

Fig. 5: Spherulitics formation in PP at 2000 rpm [30]

6. Crystallinity

Crystallinity is the content of structure alignment in solids materials. In crystalline material, their atoms or molecules arranged in regular, periodic order and their order is long with respect the atomic distance [31]. The crystalline degree is a fractional amount to the total mass (or total volume). Thermoplastics polymers included some polymers with a semi-crystalline structure like PP and PE or amorphous polymers as PS and PV. In polymers, the crystallinity is the important physical properties since it specifies the microstructure that has a strong effect on properties such as: hardness, tensile, stiffness, yield point, impact, density, transparency and diffusion. Crystallinity measured by x-ray diffraction or DSC technique. In most polymers, their crystallinity specified as a percentage of crystalline volume, since there some volume is still amorphous. The degree of crystallinity for thermoplastic polymers is the percentage ratio for the enthalpy of molten and its normalization to the enthalpy of molten of fully crystalline polymer. DSC curves are commonly used to determine the crystalline degree as in the formula [32]:

$$\text{Degree of crystallinity} = ((\text{Delta } H_f - \text{Delta } H_c)/\text{Delta } H_{f,100\%}) \times 100\% \quad (1)$$

Where: Delta H_f , Delta H_c ,and Delta $H_{f,100\%}$ are the enthalpy of fused polymer, the enthalpy of crystalline polymer, and is the enthalpy of fused for a totally crystalline polymer respectively. The enthalpy measured from the area below peaks of DSC curves. The crystallinity degree is variable with the position; this is observed at investigate the crystallinity degree of HDPE at different conditions [28]. The weld nugget possesses the lower crystallinity degree this is due to the fine grain formation at the center area. As directed from a center area of weld nugget toward the base material, an increasing in crystalline degree occurred. The explained in term of cool rate and shear stress; as far distance from the rotational pin tool the cooling rate becomes slower and the shear stress is less. The same results were obtained for polypropylene [33]; the crystallinity is at the minimum value in weld nugget (WN) and increased gradually as far away from weld nugget (WN) to the base material (BS), passing through thermo-mechanical affected zone (TMAZ) in polypropylene workpiece. It is suggested that using a fit size and a proper distance of rotating tool about to weld nugget size will help to prevent the rapid cooling which controlled the crystallinity. The high temperature and shear stress will push the soft center materials to flow away from center, besides the rapid cooling rate induces the crystal to grow in fine grains as become closer to nugget zone.

7. Conclusions

Good welding properties achieved to join thermoplastic polymers by friction stir welding; FSW technique is suitable for many polymers about their thermal, mechanical and physical properties. The welding parameters variant depending on polymer itself, furthermore, to improve the welding strength, the heating tool and proper select of pin profile may be helpful conditions. The point must keep in mind is the flow of fused material is sufficiently followed by proper cooling rate to achieve good weld quality. The welding quality is significantly dependent on microstructure and hence the degree crystallinity in the center region.

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