INTERNATIONAL JOURNAL OF INTEGRATED ENGINEERING
ISSN: 2229-838X e-ISSN: 2600-7916

IJIE

Vol. 16 No. 5 (2024) 126-139
https://publisher.uthm.edu.my/ojs/index.php/ijie

Comparative Analysis of Welding Processes Using Different Thermoplastics

Adelino Trindade[1], André Guimarães[1]*

[1] *Polytechnic Institute of Viseu, Department of Mechanical Engineering and Industrial Management, School of Technology and Management, Viseu, 3504-510, PORTUGAL*

*Corresponding Author: aguimaraes@estgv.ipv.pt
DOI: https://doi.org/10.30880/ijie.2024.16.05.011

Article Info

Received: 6 September 2023
Accepted: 29 May 2024
Available online: 1 August 2024

Keywords

Thermoplastics, welding, FSW, HGW, LBW.

Abstract

This study examined and contrasted three widely utilized welding techniques for modern thermoplastics: hot gas welding, laser beam welding, and friction stir welding. These techniques were employed to join various thermoplastic materials, particularly focusing on polypropylene, polyethylene, and polyvinyl chloride. The weld quality was evaluated using visual inspections and tensile strength tests. Additionally, Vickers hardness tests were performed on the welded joints to detect microstructural alterations. The research aimed to deepen the understanding of the mechanisms behind these welding processes and assess the welded joints' strength.

1. Introduction

Polymeric materials occupy a very important place in most areas of workpieces and components manufacturing. Modern thermoplastics are used in an increasing range of engineering applications because of their strength-to-density ratios, toughness, high corrosion resistance, and great processing possibilities. Thermoplastics can be used to produce machine elements using manufacturing processes, including welding.

1.1 Welding of Thermoplastics

The principle of welding thermoplastic materials is based on an energetic action that acts on the initial interface, creating a state of disorganization in the macromolecules, with or without melting. Welding occurs in the molecular reorganization that occurs with cooling, Fig. 1.

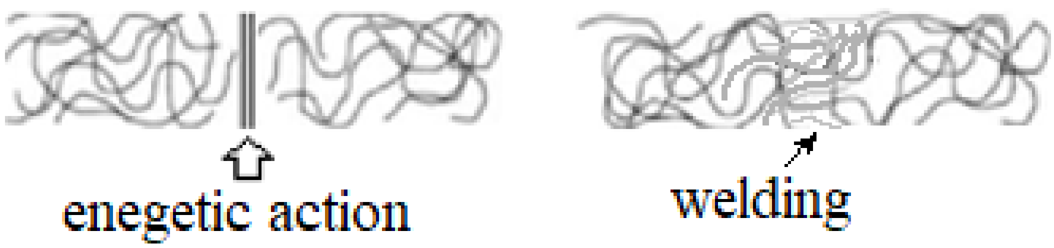


Fig. 1 *Schematic of welding thermoplastic: after an energetic action on the interface, the macromolecular reconstitution makes the weld*

Several welding processes are available to produce new parts and components of greater complexity and size that would not be possible to obtain by ordinary means of production, allowing various repairs to be made and damaged components to be reused. In all groups of welding processes, there are factors and parameters that influence the ability to produce the bond. On the one hand, human resources, and methods, and on the other hand, the materials, and the available equipment, can affect weldability. An Ishikawa diagram, Fig. 2, allows for a structured analysis, which can be adapted to the factors and variables of each process.

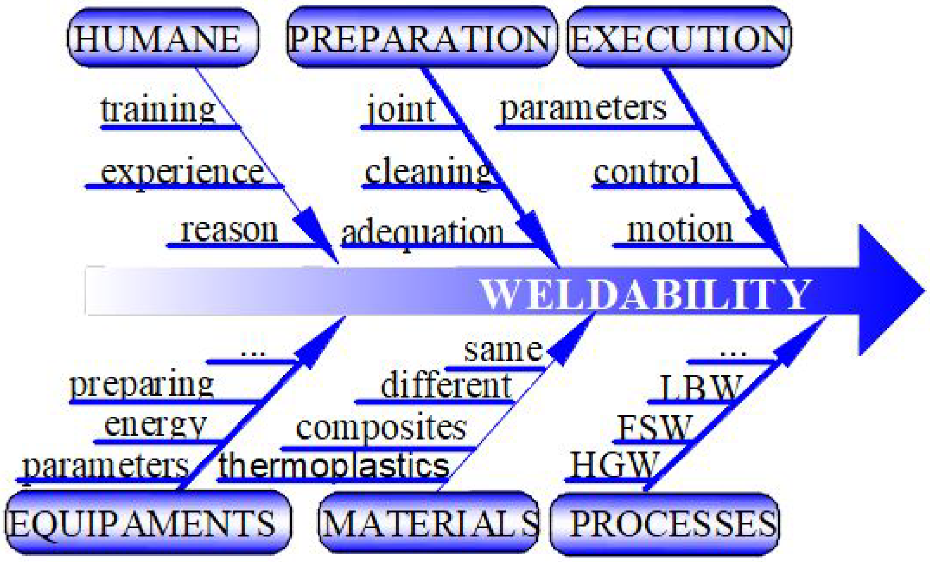


Fig. 2 *Generic Ishikawa diagram of thermoplastic welding processes*

The thickness of the parts to be welded conditions the selection of the process and the type of joint. For connections in overlapping joints of thin components, whether rigid or flexible, processes such as ultrasonic, hot plate, and transmission mode laser (TTR) are generally used. In cases of greater thickness or technical workpieces, that require more butt joints, the welds are made by processes with fusion and the use of filler material (HGW), or more energetic processes without or with filler material (LBW), or without fusion (FSW). These thicker parts are used more for machine parts, pipes and tanks, or plastic structural applications. To quantify the bond strength, f_W, called the weld strength comparison factor is used:

$$f_W = \frac{\sigma_W}{\sigma_{MB}} \tag{1}$$

Where σ_W and σ_{MB} are the strength values of the weld and the base materials, respectively. The values of f_W, in general, are still relatively low, which is typical for technology in wide development. The weldability of polymers requires strict control to prevent the formation of defects and porosity [2]. Since the HGW process is manual and without recognized nondestructive testing, welder training and certification by EN 13067 are recommended [3]. Cramer (1993) described and categorized defects in hot gas, extrusion, and hot plate welds. These defects include surface and root undercuts in weld beads, incomplete fusion, excessive melting, porosity, and excessive weld reinforcement, among others. The most common defects originating from the LBW process in thermoplastics arise in the formation of blisters or porosities, cracks, and decomposition defects such as discoloration.

The FSW process of thermoplastics can generate defects of various types: cavities, with tunneling typology, sinking or burr on the bead surface, and lack of bonding, usually at the root of the bead [5]. The generality of the defects is due to the non-optimization of the process and parameters that provide better heat generation and distribution [6, 7, 8].

1.2 Welding Processes

As previously stated, this work aimed to examine three thermoplastic welding processes that are most used and hold significant industrial importance, as well as those with the highest potential for improvement. These processes include hot gas welding (HGW), laser beam welding (LBW), and friction stir welding (FSW). Hot gas welding is a manual technique for joining thermoplastic materials. Its versatility stems from the low-cost essential equipment, as illustrated in Fig. 3, making it suitable for permanent manufacturing connections and part repair. Quality welds are achieved by controlling the temperature, speed, and pressure of the additional materials at the feed nozzle (AM) [9].

The energy input per unit length to the bead surface during hot gas welding, also known as heat input, can be utilized to estimate the overall strength of the finished joint. The heat input (Q_{HGW}) is determined using

Equation 2, where the hot gas parameters include the specific heat (c_p), the initial and final temperature (T_0 and T_f, respectively), the volumetric flow rate (q_v), density (ρ) and the welding speed (v_s) [4] and k is the thermal efficiency. Some studies performed on semicrystalline materials conclude that the higher the value of Q_{HGW} applied on the surface, the higher the resistance of the joint [4]. Controlling the temperature and maintaining high weld energy is crucial as it reduces the viscosity at the surface of the weld bead. This reduction in viscosity facilitates increased diffusion across the bond interface, leading to a stronger weld.

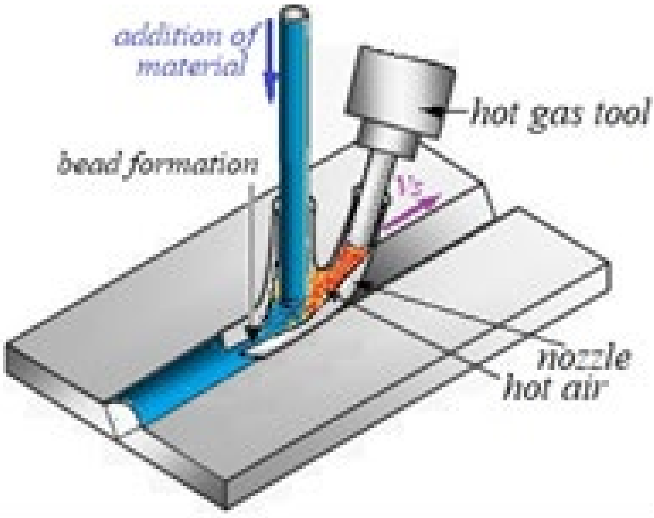


Fig. 3 *Schematic of the operation of the HGW process [10, 11]*

$$Q_{HGW} = k \, \frac{c_p(T_f - T_0)q_v\rho}{v_s} \tag{2}$$

The efficiency and effectiveness of laser beam welding depend on the system, namely on the following parameters: wavelength (λ), power (P), beam focus or incidence point, and energy distribution [4, 12]. Knowing the properties and parameters is essential to better understand the welding processing [13, 14]. The wavelength and absorption of the materials to the emitted radiation (Fig. 4), the beam focus and transmission relative to the joint type (Fig. 5), and the heat input (welding power and speed) (Fig. 6) are crucial parameters.

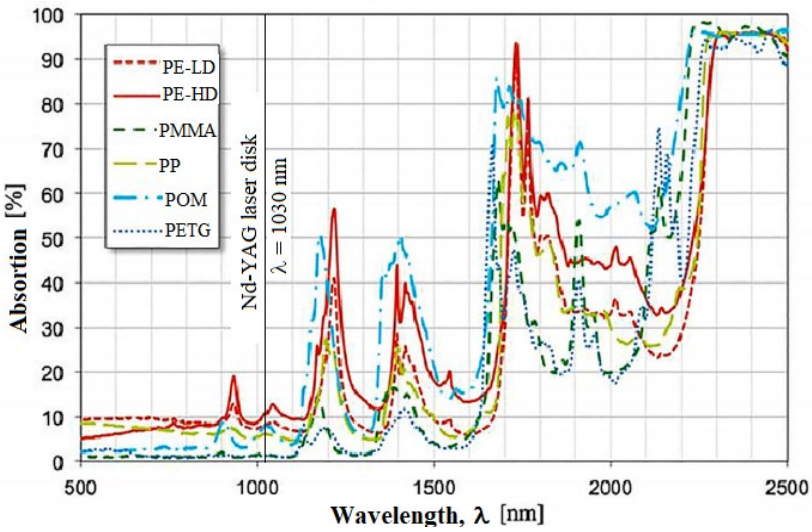


Fig. 4 *Degree of absorption of some polymers*
Source: adapted from [15]

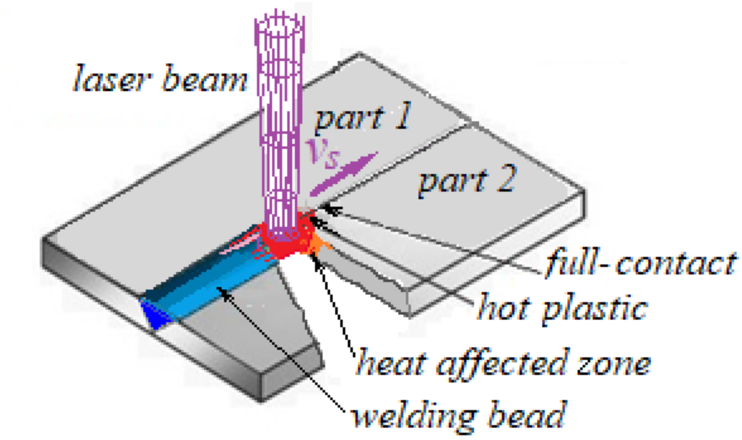


Fig. 5 *Butt joint laser welding principle*
Source: adapted from [13]

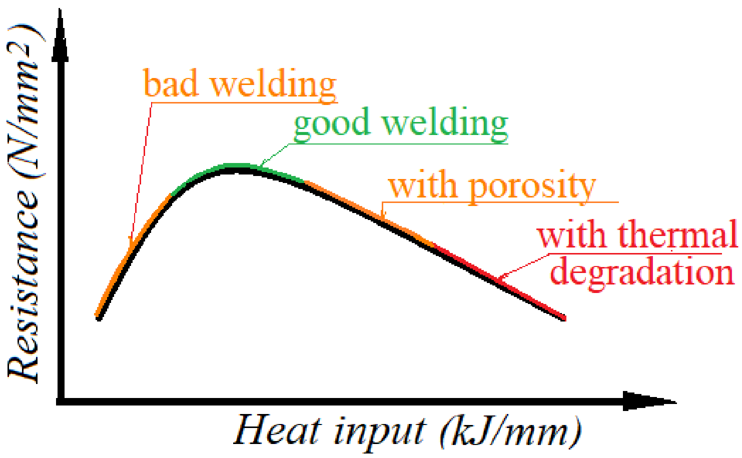


Fig. 6 *Characteristic weldability curve of the LBW process*
Source: adapted from [13]

The energy used in welding, heat input (Q_{LBW}), is very different from the energy produced in the resonance cavity and that actually reaches the workpiece, depending on the absorption capacity of the material. Thus, in determining the heat input, a thermal efficiency value (k) is used that associates the absorption of the laser beam and the weldability characteristic to the values of power (P) and welding speed (v_s), according to Equation (3):

$$Q_{LBW} = k \frac{P}{v_s} \tag{3}$$

The friction stir welding process relies on a tool that creates friction, generating heat and consequently, there is a change in the plastic behavior of the materials. This change allows them to mix and on cooling, the new molecules that define the weld are recreated. As the plastic state is a typical characteristic of thermoplastics, it would be expected that, at the outset, they would not present great welding difficulties. However, they need the optimization of several parameters, such as: the rotation speed (n) and feed speed/welding (v_s), the shapes and dimensions of the pin and the shoulder that constitute the tool, among others. In this process, due to the rotation of the tool, microstructural symmetry does not occur, since the tangential forces compress the material in the direction of the welding bead advance and in the direction of the retraction (Fig. 7) generically illustrates the distribution of the zones affected by heat and mechanical energy: a - Base Metal (BM); b - Heat Affected Zone (HAZ); c - Heat Mechanically Affected Zone (HMAZ); d - Mixing Zone (MZ).

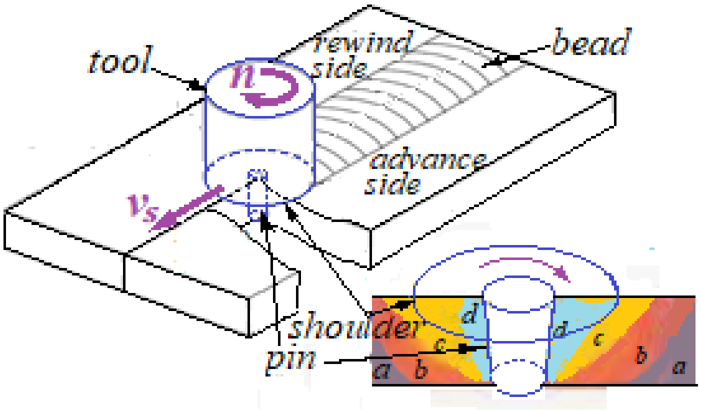


Fig. 7 *FSW welding principle and affected areas: a - BM; b - HAZ; c - HMAZ; d - MZ*

The total energy introduced in this process is determined using the Equation [16], where μ is the coefficient of friction, p_s is the pressure exerted (Pa), n is the rotation speed (rad/s) and d (mm) and D (mm), are the diameters of the pin and the shoulder, respectively. Although the FSW process has a simple operating principle and allows the formation of weld beads with good surface appearance, it is susceptible to the introduction of internal defects [18].

$$Q_{FSW} = \pi \mu p_s n \frac{D^2 + D.d + d^2}{45(D + d)} \tag{4}$$

2. Materials and Methods

Technical thermoplastic materials are the subject of several research works. In this work, three reference thermoplastics were used, specifically polyethylene (PE), polypropylene (PP), and polyvinyl chloride (PVC). The main properties of the thermoplastics used are shown in Table 1.

Table 1 *Properties of thermoplastics. Source: [17]*

	Stress (MPa)	Young Modulus (MPa)	Hardness (HV)	Thermal Conductivity (W/(m.K))
PE	37[1]	0.8	6.4	0.38
PP	32	1.4	7.6	0.22
PVC	58	3.0	14.0	0.16

2.1 Joint Preparation

Joint preparation and all the care taken prior to welding are critical to achieving a good weld. In welding that occurs with additional materials, the joint preparation must include a certain distance and chamfer depending on the thickness. In the case of the HGW process, it is advisable to obtain joints with 60° of chamfers and 0.5 mm of spacing, as indicated in Fig. 8 (a and b), where the double-V joint presents the best results [4]. In welding that occurs without additional materials, LBW and FSW processes, it is essential to have total contact between the two parts, Fig. 8 (c).

[1] High-density polyethylene (HDPE).

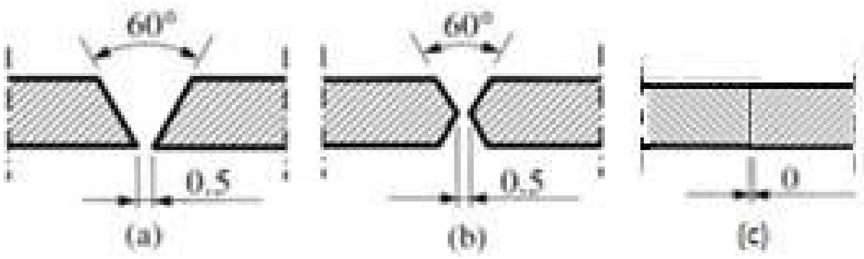


Fig. 8 *Joint preparation scheme: (a) V-shaped; (b) Double-V; (c) full-contact*

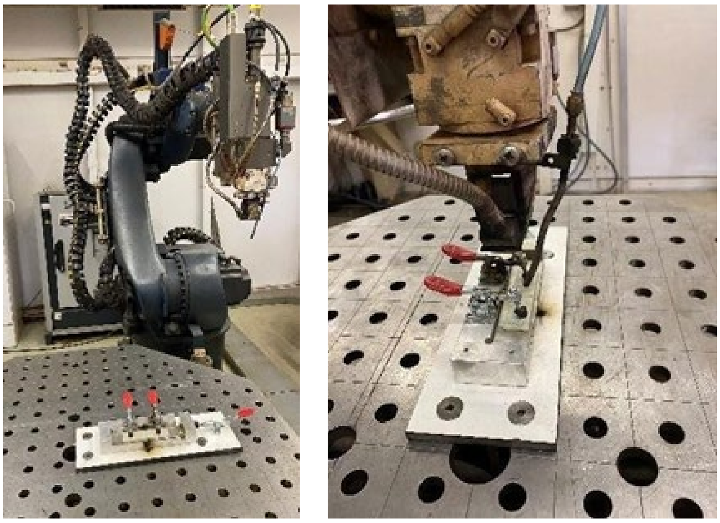
2.2 Performing The Welds

To perform the HGW welds, a Leister hot gas blower, *Triac S* model, with an adaptable nozzle for the addition of material, was used, as shown in Fig. 9. The LBW process applied is based on a Nd-YAG disk laser, whose beam is characterized by a wavelength of 1030 nm [18]. A priori, it is verified, by the analysis of Fig. 4, that this laser is not the most suitable for the welding of most thermoplastics. This laser is generated by *Trumpf* equipment, model *TruDisk 6602*, which has power regulation from 0.060 to 6.6 kW. The laser beam, with a quality of 8 mm.mrad, is conducted through an optical fiber with a diameter of 0.6 mm to the optical device, whose focus distance is 72 mm. The focus point is adjustable and can be on the workpiece surface (F = 0 mm) or set below or above the surface. Laser welding was assisted by a *Kuka KRC2* robot, Fig. 10 (a), with a range of welding speeds (v_s) that varied between 0.001 and 2 m/s [19, 20]. Due to the absence of a device for adding filler material in the equipment used, all specimens were produced using welding beads without filler material in butt joints, as depicted in Fig. 10 (b). The welding parameters used in the production of these specimens were as follows: welding power between 60 and 300 W; focus on the surface (F = 0 mm) and as well as other values below the surface; welding speed between 0.0042 and 0.0833 m/s. The FSW welds were made on a *Bulin FU 321M* 7.5 kW universal milling machine, operating in vertical axis mode. For a rigid and more practical fixation of the parts to be welded, a new support was designed and produced, to allow a good fit to the machine table, Fig. 11.

The tools were designed using 3D CAD software and fabricated with available conventional and CNC machining equipment. The tools consisted of an adjustable pin and a shoulder containing a landing, which was inserted in the shank fixed to the machine's rotating spindle. In this study, tools with simple geometries were chosen for us pin-to-shoulder diameter ratios of 1:4 and 1:5. The pin was set with length L=t - 0.2 (mm), where *t* is the plate thickness. The respective shoulders initially had diameters between 8 and 13 mm, and finally 20 mm. The pins were made of HSS steel, and the workpiece with the shoulder was made of carbon steel. After having tried some rotation values and welding speeds for the FSW process, the following were used: PP: 650 and 800 rpm and 12.5 and 20 mm/min; PE: 650 rpm and 12.5 mm/min; PVC: 800 and 1000 rpm and 12.5 and 20 mm/min, respectively.

(a) **(b)**

Fig. 9 *(a) Hot air blower; (b) HGW process execution*



(a) **(b)**

Fig. 10 *(a) Robot; (b) Detail regarding the LBWprocess*

(a) **(b)**

Fig. 11 *(a) Milling machine; (b) Detail regarding theFSW process*

2.3 Carrying Out Analysis and Tests

After the welds were made, the specimens were milled to ensure adequate accuracy. The widths, thicknesses, and initial length L_0 of each specimen were measured to allow an analysis in terms of stress σ (N/mm^2) and strain $\varepsilon = \Delta L/L_0$ (%). These were then pulled until failure in a testing machine universal *Instron*, model *4206*, where the evolution of force *versus* displacement was recorded.

After polishing, using sandpaper with increasing grain size indices, the surfaces were scanned on a Zeiss Axiotec microscope. Micrographic analysis with an optical microscope became difficult, but due to the use of differential interference contrast (DIC) and polarized light, it was possible to visualize the existence of some anomalies and defects. The hardness measurements were carried out on a *Shimadzu HMV* micro durometer with a Vickers indenter.

3. Results

The results were based essentially on visual inspection, tensile tests, and hardness measurements along the affected areas. The various butt joints made by the HGW and FSW processes are shown in Fig. 12. The FSW welds were made in plates of various thicknesses of PE and PP and PVC, with contact joints of the type of Fig. 8 (c). The thermoplastic specimens, with butt joints welded by the LBW process, presented some difficulties, which originated from the type of laser source used, the materials to be joined, and their thicknesses.

(a) **(b)**

Fig. 12 *Specimens obtained by: (a) HGW in PP; (b) FSW in PP and PVC*

3.1 Loading Curves F-ΔL and σ-ε

The results of the evolution of force versus displacement (F-ΔL) were only a means to obtain the stress-strain curves (σ-ε), which allowed comparisons to be made between the different results obtained, despite the specimens having different dimensions. The results obtained for each process are arranged in the order initially presented for the main thermoplastics under study (PP, PE and PVC). At the end, the best resistance results obtained with the tested materials, and the respective processes that were used, are compiled in a graph. The specimens obtained by the HGW process were tensile tested in the transverse direction of the weld seams. The obtained strength results are presented in Fig. 13. The joint configuration of the double-V specimens presents values of σu = 20 MPa, which corresponds to an efficiency of fW ≈ 60%, that are close to values obtained in other studies.

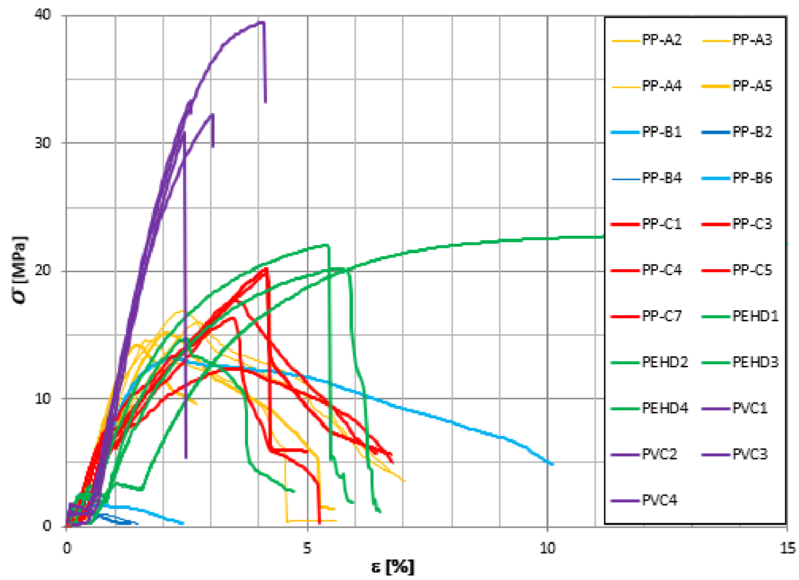


Fig. 13 *Results obtained by tensile tests on specimens welded by HGW on PP, PE and PVC*

The use of two different addition materials (comparison of PP-A and PP-C) had an influence on the values of σ_u and the brittleness behavior. In the connections made without AM (PP-B cases) the strength is varied and too low, with values of $f_W \approx 20\%$. This is the first demonstration of the importance of the welding technique on the strength of the connections. All the welds with the LBW process, with best results at P = 300 W and $v_s = 83.3$ mm/s and F = 0, were made on butt joints, as shown in Fig. 5 b). The tensile strength results of specimens obtained in the direction transverse to the connections are presented in Fig. 14. The results lead to some difficulties obtained in welds, which resulted from the low absorption of these thermoplastics by the laser used, as mentioned in Fig. 4. But it is also due to the thickness of the plates and the difficulty to optimize of according to the characteristic curve of weldability, Fig. 6. Outside the optimal region, by increasing the power or reducing the speed, when trying to obtain total penetration, there was burning of material on the surface. With more suitable values of Q_{LBW}, Equation (3), in some thermoplastics and of considerable thickness, the surface aspect of the bead was reasonable, but the mechanical resistance was low due to not having total penetration. The FSW

Int. Journal of Integrated Engineering Vol. 16 No. 5 (2024) p. 126-139

welds were made on PE, PP and PVC plates of various thicknesses. The tensile strength results of the specimens obtained in the direction transverse to the connections are shown in Fig. 15. The comparison of the best strength results obtained in welds of various thermoplastics is presented in Fig. 16.

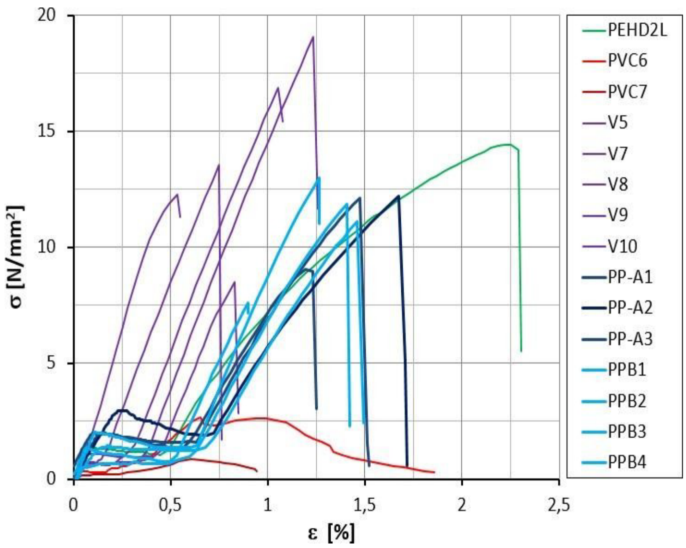


Fig. 14 *Results obtained by tensile tests on specimens welded by LBW on PP, PE and PVC*

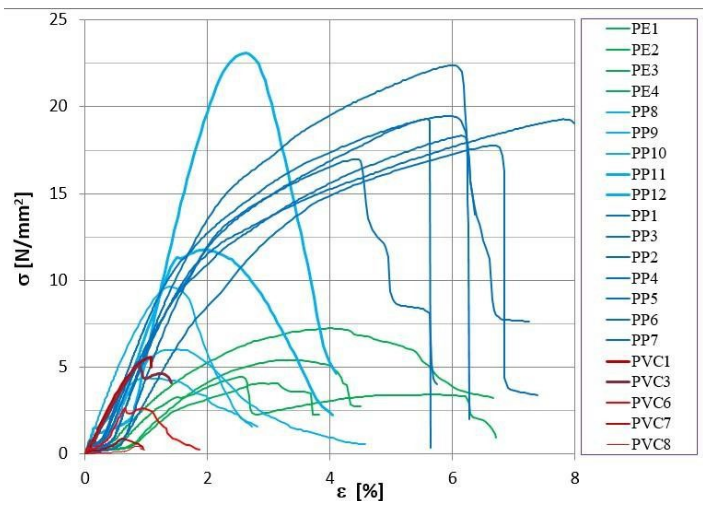


Fig. 15 *Results obtained by tensile testing on PP, PE and PVC by FSW welded specimens*

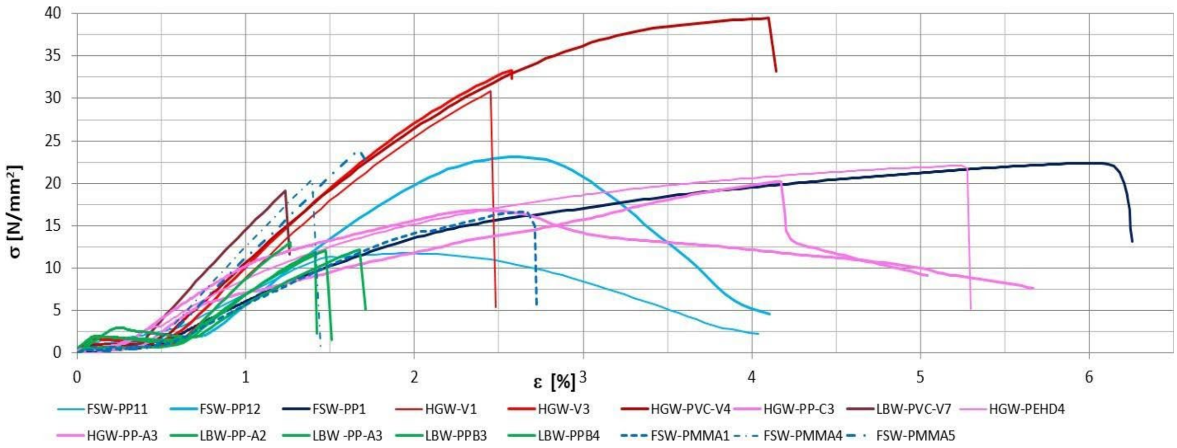


Fig. 16 *Comparison of the best results obtained by tensile tests, for the three welding processes studied, in thermoplastics:PP, PVC, PE, and PMMA*

3.2 Hardness Variation

The progression of hardness values along the heat distribution enabled the assessment of the impact of microstructural changes in the heat-affected zones (HAZs). The weld with lower hardness gradients and lower difference (or slight increase) between the bead zone and the others, has better behavior in terms of toughness and mechanical strength, respectively. The hardness variation is caused by molecular re-stabilization after heating caused by the friction of the tool with the material. The hardness decreases in thermomechanical affected (by the influence of the pin) and thermally affected (by the influence of the shoulder) zones can be significant [21]. The polypropylene allowed for visualization of the residual indentation and thus making the hardness measurement by a traditional micro durometer. Fig. 17 shows the distribution of the hardness of this thermoplastic welded by the three processes used.

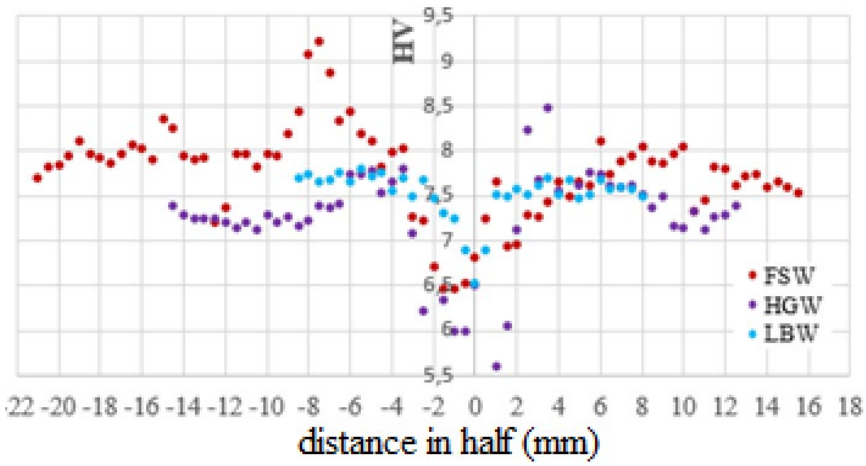
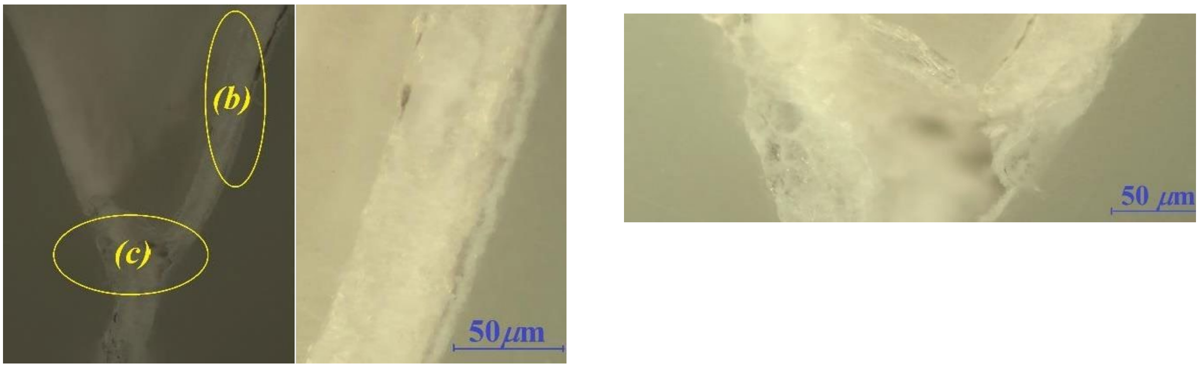


Fig. 17 *Vickers hardness results, at 1 mm depth and through the affected zones, for PP*

When comparing the Vickers hardness variation, the HGW process has a significantly larger heat-affected zone than that obtained by the LBW process. This is due to the large energy difference between these processes and the consequent influence on their microstructure. With the FSW process, the hardness variation is also extensive, which is due to the bead size and the large, affected zones caused by the tool size. It also shows some asymmetry, which was already expected, due to the rotation of the tool that compresses the material differently in the forward and in the reverse direction.

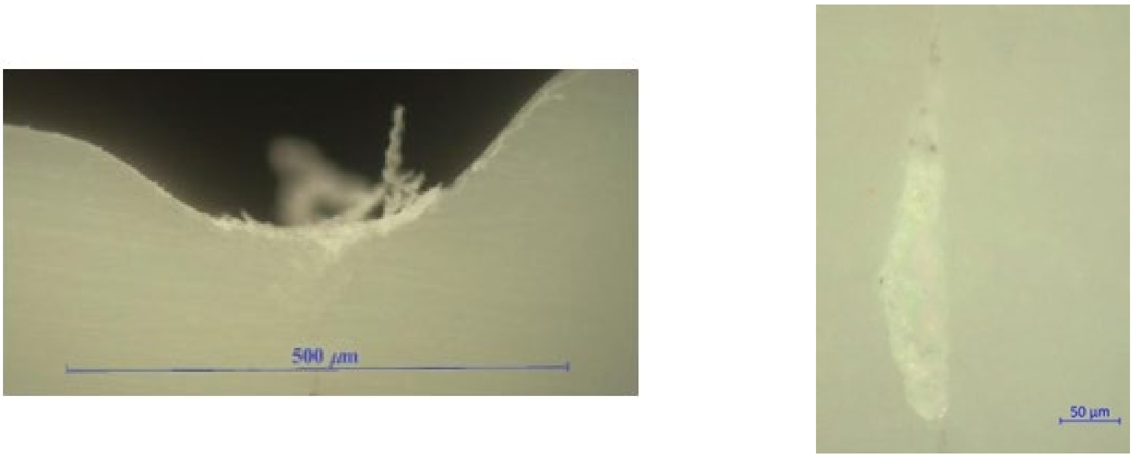
3.3 Defects

With the HGW process, some bond defects related to the lack of fusion were found, as can be seen in Fig. 18. With this process, in addition to the sunken surface on the bead, Fig. 19 a), which is a typical defect of welding without filler material, discoloration associated to different compression states and small cracks were also found, Fig.18 b). With FSW the typical defects of this process were found: the tunnel effect, Fig. 20 a), and lack of bonding from the sunken surface of the bead, Fig. 20 b). The FSW welding of the 10 mm thick PP specimen presents the following anomalies: a) tunnel-type defect, b) lack of adherence of the recessed surface of the bead. The improvement of the processes, with more adequate definition of parameters and technique, as well as the adjustment of the FSW tools, particularly the shape and dimensions of the pin and the shoulder, have allowed improvements and, going forward, will allow even better results.



(a) (b) (c)

Fig. 18 *HGW weld defects in a 10 mm thick PP specimen (a) Missing bond anomalies; (b) Detail; (c) Detail*



(a) (b)

Fig. 19 *LBW weld defects in a 3 mm thick PP sample, with anomalies of: (a) Sunken surface of the bead surface; (b) A discoloration with small pores and a crack*

(a)

(b)

Fig. 20 *FSW weld defects in a 10 mm thick PP specimen, with anomalies of the type: (a) Tunnel-like defect; (b) Lack of bonding from the sunken surface of the bead*

4. Discussion

In the case of PP, the surface quality of the weld bead obtained was not yet ideal, although the penetration was total, and it presented few internal defects. The PVC welds present better surface quality, but the bond is weak, with contour fracture of the HAZ. This fact is due to the low heat conduction of this polymer, Table 1, whose solution will be to develop a new tool or include an external heat source. Given the low absorption value of some base materials to the laser beam and the wavelength used, Fig. 4, the difficulty of some welds was already predictable. It is also fundamental to control the energy in the optimal region of the weldability characteristic curve, Fig. 6. Outside this optimal region, increasing the power or reducing the speed to obtain full penetration, Equation (3), leads to the burning of material at the surface. Thicker thermoplastics require more energy, moving outside the optimal region, with consequent surface degradation. There is then a trade-off between the thickness of the parts to be welded at full penetration and surface degradation.

In the case of HGW welds, the section of the additional materials and the shape of the deposition nozzle may not lead to the optimal weld bead shape. During the LBW welding process, too much energy was released, and this may have led to partial "burning" of the surface. In some materials, the use of a simple tool and optimization of parameters in the FSW process can provide a finish that is not yet ideal. The physicochemical characteristics of thermoplastics, the processes, the lack of complete penetration, and the presence of internal and external defects have consequences on the strengths of the bonds.

From the analysis of the connection efficiency, using the welding resistance comparison factor, Equation (1), the best results are presented in Table 2, showing that the connection with the highest efficiency was made with PVC using the HGW welding process, with f_W = 73.1%.

Table 2 *Best obtained results of f_W*

Process	PE	PP	PVC
HGW	62.1%	65.6%	73.1%
LBW	35.8%	40.6%	34.6%
FSW	31.8%	78.1%	10.3%

Table 2 shows that in the HGW process, the bond strength (f_W) values were above 60%, values that are very common. The lower strength values by LBW were a result, in part, of the high thickness that the samples used had. The lower values obtained with FSW were due in part to the amorphism and properties of PVC which has a relatively low thermal conductivity.

In the welding of all thermoplastics tested, the greatest difficulty was with PMMA, due to the almost zero absorption of the LBW process used, as mentioned in Fig. 4. However, with FSW the resistance results were reasonable, see Appendix A.

The process and method affect the hardness distribution [22]. Hardness measurement is difficult in some plastics due to elastic recovery. The standards EN ISO 868-2003 and ISO 482-2018 refer to the determination of Shore hardness in various plastics; these are methods of practical use in an industrial environment, but in this work, it is not the most suitable due to the method and dimension concerned. To perform an analysis of the variation of hardness through the zones affected by welding, such as the one performed here, it must be done with a microhardness method and preferably with a pyramidal indenter of the Vickers (HV), Knoop, or Berkovich type. HV microhardness is the most used in the investigation of microstructure behavior in affected zones [23]. The best solution is the use of nanoindentation that, by measuring the evolution of load and deformation, allows obtaining the hardness value even when the residual indentation has fully recovered and evaluates other mechanical properties [24]. There are some authors who have already worked on this subject [25].

Weld morphology, and particularly the presence of defects, is greatly influenced by the heat added in the process. Increasing the ratio of rotational speed to tool feed (n/vs) increases the temperature in the weld. The local temperature increase facilitates material flow and reduces defect formation.

5. Conclusions

The essential knowledge obtained on the welding of thermoplastics with the studied processes will remain, in the scope of their particularities and the relative importance between them. On the one hand, the HGW process is a manual process that requires the skill and training of the operator and uses the introduction of filler material with low-cost equipment. On the other hand, LBW welding, without filler material, requires more expensive equipment, which also includes a robot. Increasing efficiency in this process requires a more thermoplastic-specific laser, which would increase quality and productivity. FSW of thermoplastics also requires some improvements in tool shape and process parameter settings. This would improve the strength of the welds and minimize the appearance of defects.

The analysis of the mechanical behavior and weld strength in thermoplastics has great relevance from a scientific and industrial point of view. However, in terms of the connections made with the studied thermoplastics, many cases with comparison factor of weld strength above fw≈ 60%, reference value by many authors, were obtained.

The study performed on the weld zone, by hardness measurement, allows obtaining important information about the affected zones. Thus, some microstructural changes were revealed. In addition to the mechanical behavior of the welded joints, an analysis of the macro and microstructural quality of the produced weld seams was also performed. With the HGW process, the non-bonding anomalies can be eliminated with greater temperature control and improved welding technique on the part of the operator. However, there is the possibility of subsequent correction of the bead surface. In the FSW process, the existence of areas with pores and cavities may be a consequence of poor mixing between the materials, due to insufficient heat produced by the tool pin, as most defects are found near the nugget interface. These may originate from the fault of heat, caused by the low rotation speed and high feed rate of the tool, not being enough to promote the plasticity of the material necessary to bond. With the LBW process, the best butt welds were performed at lower thicknesses than by HGW and FSW due to the need to limit power. With the adequacy of equipment and refinement of techniques for each process, there has been a significant improvement in weld quality.

Acknowledgement

To Nuno Esteves (IPROM) for his support on the laser welds and to Eng. Nelson Santos (ESTGV) for his support in the execution of equipment and test specimens.

Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Trindade. A., Guimaraes A.;* ***data collection:*** *Trindade. A., Guimaraes A.;* ***analysis and interpretation of results:*** *Trindade. A., Guimaraes A.;* ***draft manuscript preparation:*** *Trindade. A., Guimaraes A.. All authors reviewed the results and approved the final version of the manuscript.*

References

[1] Balkan, O., Demirer, H., & Yildirim, H. (2008). Morphological and mechanical properties of hot gas welded PE, PP and PVC sheets. *Journal of achievements in materials and manufacturing engineering*, *31*(1), 60-70.
[2] Masse, S. (2010). Measuring the Sensitivity of Interfacial Gaps in Laser Transmission Welding Using

Manufactured Voids.

[3] TWI, Hot Gas Welding of Plastics: part 1 - The Basics Available: https://www.twi- global.com/technical-knowledge/job-knowledge/hot- gas-welding-of-plastics-part-1-the-basics-056.

[4] Balkan, O., Demirer, H., Ezdeşir, A., & Yıldırım, H. (2008). Effects of welding procedures on mechanical and morphological properties of hot gas butt welded PE, PP, and PVC sheets. *Polymer Engineering & Science*, *48*(4), 732-746.

[5] Mendes, N. A. M. (2014). *Robotic friction stir welding of polymers* (Doctoral dissertation, Coimbra University (Portugal)).

[6] Banjare, P. N., Sahlot, P., & Arora, A. (2017). An assisted heating tool design for FSW of thermoplastics. *Journal of Materials Processing Technology*, *239*, 83-91.

[7] Azhiri, R. B., Tekiyeh, R. M., Zeynali, E., Ahmadnia, M., & Javidpour, F. (2018). Measurement and evaluation of joint properties in friction stir welding of ABS sheets reinforced by nanosilica addition. *Measurement*, *127*, 198-204.

[8] Ahmadi, H., Arab, N. M., Ghasemi, F. A., & Farsani, R. E. (2012). Influence of pin profile on quality of friction stir lap welds in carbon fiber reinforced polypropylene composite. *International journal of mechanics and applications*, *2*(3), 24-28.

[9] Dar, S. A., Alam, M., & Dwivedi, A. (2016). An Extensive Literature Review Showing Relation Between Process Parameter And Mechanical Properties of Welded Hard PVC by Hot Air. *IRJET*, *3*, 02.

[10] Leister: Extrusion and hot-air hand welders, Plastic Fabrication (2017/2018). Available and accessed on: Feb. 8, 2021: https://www.leister.com/

[11] Laserline GmbH, Plastic Welding Plastic Welding with Diode Lasers; Germany (2005) Available and accessed on: Feb. 8, 2021: www.laserline.de.

[12] Sekou, S., Chen, S., Zou, J., & Lin, Y. (2015). Laser transmission welding of polycarbonate: geometrical and microstructure characterisation of the weld. *J Mater Sci Eng*, *4*(4), 1000179.

[13] Boglia, A. (2011). Laser welding of polymers. In *The first international workshop for project partners 'Laser welding–a versatile process for high performance production of polymeric components'. Torino: GRFI*.

[14] Asséko, A. C. A., Cosson, B., Schmidt, F., Le Maoult, Y., & Lafranche, E. (2015). Laser transmission welding of composites-Part A: Thermo-physical and optical characterization of materials. *Infrared Physics & Technology*, *72*, 293-299.

[15] Acherjee, B. (2021). State-of-art review of laser irradiation strategies applied to laser transmission welding of polymers. *Optics & Laser Technology*, *137*, 106737.

[16] Deqing, W., Shuhua, L., & Zhaoxia, C. (2004). Study of friction stir welding of aluminum. *Journal of materials science*, *39*(5), 1689-1693.

[17] Crawford, R. J. (1982). Microhardness testing of plastics. *Polymer testing*, *3*(1), 37-54.

[18] Trindade, A. (2020). A Weldability Study of AlMg0,7Si Aluminum Alloy by TIG, FSW, and LBW Processes. *International Journal of Engineering Trends and Technology*, vol. 69, no. 9, pp. 107-115.

[19] TruDisk Available: Laser-based joining Perfect quality without residues. Accessed on: Feb. 8, 2021.

[20] KUKA Robot Group [Online] Available: http://www.wtech.com.tw/public/download/manual/ kuka/ Accessed on: Feb. 8, 2021.

[21] Nath, R. K., Jha, V., Maji, P., & Barma, J. D. (2021). A novel double-side welding approach for friction stir welding of polypropylene plate. *The International Journal of Advanced Manufacturing Technology*, *113*, 691-703.

[22] Miloud, M. H., El Bahri, O. C., & Abdallah, L. (2019). Mechanical behavior analysis of a Friction Stir Welding (FSW) for welded joint applied to polymer materials. *Frattura ed Integrità Strutturale*, *13*(47), 459-467.

[23] Trindade, A. (2004). *Indentação de revestimentos finos: análise experimental e numérica* (Doctoral dissertation, Tese de Doutoramento, Universidade de Coimbra).

[24] Ovsík, M., Maňas, D., Maňas, M., Staněk, M., Krátký, P., & Šenkeřík, V. (2014). Nano-indentation test of PA12 after radiation cross-linking. *International Journal of Mechanics*.

[25] Vijendra, B., & Sharma, A. (2015). Induction heated tool assisted friction-stir welding (i-FSW): A novel hybrid process for joining of thermoplastics. *Journal of Manufacturing Processes*, *20*, 234-244.