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# The investigation of suitable welding parameters in polypropylene sheets joined with friction stir welding

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**Abstract.** Welding strength is very important in safe use of polypropylene sheets. The determination of welding parameters and design of the welding tool has an impact on the weld strength. The welding parameters can be determined experimentally. In this study, Charpy impact test is used to determine suitable welding parameters in welding of polypropylene sheets with FSW method. At the same time, the weld zone microstructure is examined and Shore hardness measurements are made. The impact tests were performed on samples cut from the welded sheets. The impact tests values and hardness values were presented graphically. According to the test results, some welded parts behaved similar to the matrix material. In some welding parameters, Charpy impact test values were obtained close to values of the main materials. The suitable welding parameters were determined for polypropylene sheets welding.

**Key words:** friction stir welding, polypropylene sheets, Charpy impact test, Shore hardness.

## 1. Introduction

Friction stir welding (FSW) is a solid-state joining process that creates extremely high-quality, high-strength joints with low distortion. A non-consumable rotating tool bit is inserted into a work piece [1]. The rotation of the tool creates friction that heats the material to a plastic state. As the tool traverses the weld joint, it extrudes the material in a distinctive flow pattern and forges the material in its wake. The resultant solid phase bond joins the two pieces into one.

The process uses no outside (filler) material, no shielding gases, and requires low energy input when compared to the other welding processes. The solid phase bond between the two pieces is made solely of the parent material. The grain structure in the weld zone is finer than that of the parent material and has similar strength, bending, and fatigue characteristics. Easily controlled process parameters – such as pin tool geometry, pin tool force, rotational speed and traversing speed – are easy to monitor, allowing easy avoidance of the errors. FSW can weld almost any shape of contoured parts, including seam welding of cylinders. The process flexibility of FSW accommodates the welding of large parts. This joining technology offers a weld with high weld strength and toughness. The weld has a fine grain structure that resists fatigue stress. Due to the low heat and small heat-affected zone, there is a minimal distortion of the joined parts, reducing the costs associated with preparing the part for subsequent use. FSW may be used to weld dissimilar alloys, even combinations that are not compatible with the other welding processes. Low energy input and lack of fumes, gases, etc., resulting from the process, make FSW friendly to environment.

Typical FSW applications are locomotive train and carriage panels (aluminum), aircraft fuselage, truck bodies, caravans and space frames, heat sinks and electronics enclosures, boat and ship panel sections, flat and cylindrical fuel tanks and bulk liquid containers, aluminum bridge sections, architectural structures and frames, pipelines and heat exchangers, electrical motor housings. The application of the classical FSW method is shown in Fig. 1.

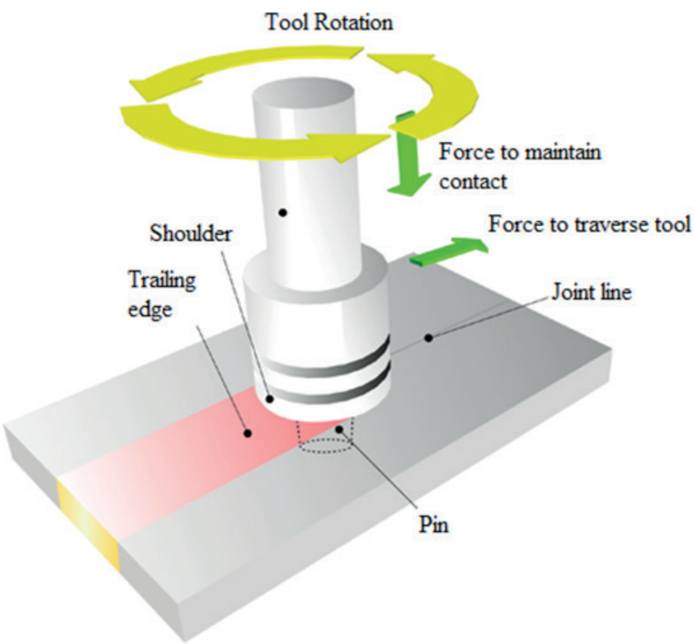


Fig. 1. Application of classical FSW method [2]

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These days, plastic materials are used in engineering applications and industry. Plastics offer freedom to many different designs. The fabrication of complex parts usually requires different joining technologies. FSW method can be used for joining plastic materials. The use of the FSW method is an important issue in plastic materials joining. The studies on the welding of plastics with FSW method are becoming more and more common over the world.

A lot of studies on the welding of plastics with FSW are in the literature. In this study, some of the studies have been examined to provide a different approach to the subject. Some of the studies have been reviewed and it is as follows.

Bagheri et al. studied on mechanical properties of ABS (acrylonitrile butadiene styrene) sheets joined with FSW. Obtained results showed a significant relationship between considered properties and processing parameters through an analysis of variance (ANOVA) study and the response surface method (RSM) [3]. Simoes and Rodrigues studied on the material flow and thermo-mechanical conditions during FSW of polymers. The study showed completely different material flow mechanisms and weld defect morphologies in polymer welding [4]. Singh et al. investigated on FSW of recycled low density polyethylene (LDPE) and high-density polyethylene (HDPE) with reinforcement of the Fe powder. The effect of FSW process parameters on mechanical and metallurgical properties has been investigated for structural engineering applications [5]. Paoletti et al. analyzed the force and torque developing during friction stir spot welding (FSSW) of thermoplastic sheets. Study showed that dwell time has a negligible effect on the developing forces. However, the dwell time was effective on the material temperature, dimension of the welded zone and mechanical behavior of the joint [6]. Lambiase et al. aimed to verify the potential advantages of plunging force control at the reduction of welding defects. The effect of the plunging force was investigated on the friction spot stir welding of polycarbonate sheets. However, excessive plunging force resulted in weaker welds due to excessive thinning of the punch-sided sheet [7]. Eslami et al. presented the parameter of optimization of FSW in dissimilar polymer. The obtained results demonstrated that stationary shoulder that was used was giving the advantages in order to achieve high-quality welds. In order to compare the effects of the welding parameters and their interactions, ANOVA method was used [8]. Bozkurt studied on FSW parameters. The quality of the joint was evaluated by examining the characteristics of the joint efficiency as a result of the ultimate tensile strength [9]. Rezgui et al. presented experimental and numerical results of FSW of the high density polyethylene. Temperatures in the joint during the welding process were measured and variances were analyzed. Variety of the models were used to determine tensile values by the finite elements [10]. Kiss and Czigany studied applicability of FSW on polypropylene sheets. The flow circumstances during welding on seams produced by proper tool geometries demonstrated that homogenization and, consequently, the joint strength, could be substantially improved [11]. Saeedy and Givi studied the effect that varying process parameters have on the weld quality of polyethylene sheets. Changes in the weld zone microstructure were investigated using the differential scanning calorimetry and scanning electron microscopy [12]. Kumar et al. investigated weldability of thermoplastic materials for FSW. They highlighted requirements of FSW and its process capability for joining similar/dissimilar polymeric materials for the future perspective [13]. Huang et al. reviewed current understanding and development of FSW of the thermoplastic polymers and polymer matrix composites, multifunctional composites fabrication as well as dissimilar FSW of metal and polymer [14]. Sahu et al. studied application of FSW process to join the thermoplastics. The effect of square pin had been proved in achieving high quality welds [15]. Eslami et al. investigated high-molecular-weight-polyethylene sheets, which were welded in the butt-joint configuration, in order to have the effect on welding parameters on the generated forces during welding. The obtained results enabled the identification of the influence of each individual welding parameter on the applied forces [16]. Eslami et al. studied two commercially used polymers used to weld in the lap-joint configuration to evaluate the fatigue life of the welded samples under shear loading conditions. The FSW joints failed due to the fatigue failure. The failure occurred from retreating side of the welds for both static and fatigue tests [17]. Yan et al. used a triflute-pin tool and a clamping plate with a circular hole for friction stir spot welding of acrylonitrile butadiene styrene sheets. They investigated the influences of the rotational speed, plunge depth and dwell time on the joint morphology, dimension and mechanical performance [18]. Paoletti et al. studied on friction spot stir welding method for joining Polycarbonate sheets of 3 mm thickness. A prototype setup was developed to monitor the evolution of main forces and tool temperature during the joining phases. At the end of the work an Artificial Neural Network has been developed in order to predict the mechanical behavior of the welded joints [19]. Hajideh et al. investigated the effects of the tool geometry on FSW of polyethylene-polypropylene. The welded joints with the best mechanical properties were obtained in the optimum rotational speed equal to 1860 rpm with the highest travel speed equal to 12.5 mm/min [20]. Barmouz et al. studied a novel method based on friction stir processing. This method was developed for fabrication of the polymer/clay nanocomposites to enhance the dispersion state of nanoclay particles and surface mechanical properties. An attempt was made to establish correlations between the significantly enhanced microhardness values and friction stir processing-induced dispersion of nanoclay [21]. Mendes et al. examined FSW of ABS plates. A robotic system was developed for this purpose. It showed the feasibility of the robotic FSW of ABS without deteriorating the mechanical properties of the welds [22]. Vijendra and Sharma studied a hybrid friction-stir welding process (i-FSW) for the joining of thermoplastics. The study presented new observations on friction-stir welding of thermoplastics through a case study on the welding of high-density polyethylene plates [23]. Hoseinlaghab et al. aimed to investigate the effects of the main FSW parameters on the quality and creep properties of polyethylene plate joints. The results showed that under special conditions creep resistance of welds is better than that of the base material [24]. Azarsa and Mostafapour determined optimal welding parameters using RSM. In this study it was found that welding at a high level of rotational speed and a lower level of the tool travel speed increases weld flexural strength by reducing size of defects [25]. Liechty and Webb investigated the plasticine for use as an analogue for modelling material flow in FSW of metals. The plasticine welds were compared to previous visualization data from welds conducted in metals. Significant vertical motion during welding was also observed in the plasticine [26]. Sadeghian and Givi studied on ABS sheets welded with friction stir method using a metallic tool. Mechanical properties of the welded sheets were investigated under varying processing parameters [27]. Oliveira et al. investigated the feasibility of friction spot welding of thermoplastics on poly (methyl methacrylate) plates. The work demonstrated feasibility of the welding of thermoplastic materials by friction spot welding [28].

The design of proper tools and the investigation of welding parameters are very important for the strength of welded joints. The main goal of this study is the investigation of suitable welding parameters for welding of polypropylene sheets with FSW method. The experimental results of the study are presented graphically. The suitable welding parameters were investigated for more welding strength. Also, the two types of tool were used in determination of welding parameters.

## 2. Experimental procedure

In this study tool rotation speed, welding speed (tool progress speed) and tool profile are used as welding parameters. These values of rotation and welding speed are shown in Table 1. FSW process of the PP sheets is shown in Fig. 2. Welding process was performed in universal milling machine as a single pass friction stir.

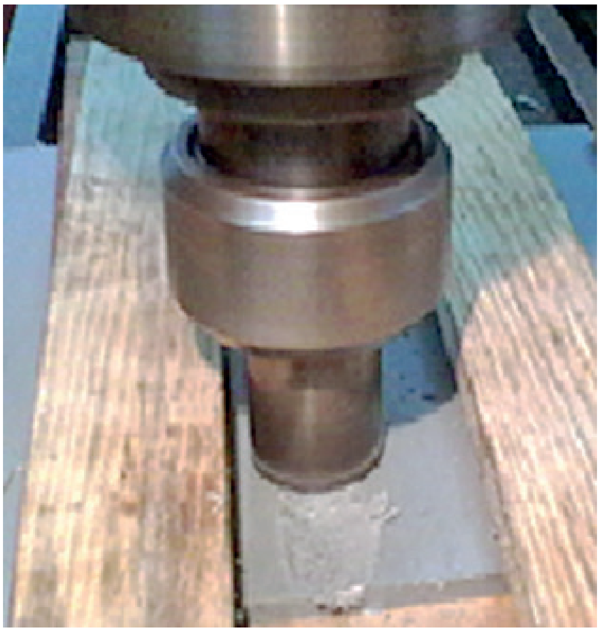

Fig. 2. FSW process of the PP sheets

The commercial 4 mm thick propylene (PP-H AlphaPlus) plates were cut into 100×300 mm size sheets for FSW. PP's mechanical properties are: density 0.91 g/cm$^3$, tensile modulus of elasticity 1700 MPa, yield stress 33 MPa and elongation at yield 8%. The values are taken from Ref. [29]. The tools used to this experiment were made of 4140 steel tool, steel material with a hardness of 44 HRC. In the conical tool, the shoulder has a diameter of 20 mm and the pin is taper-threaded with a major and minor diameter of 5 and 3 mm, respectively. The pin height is 5 mm. In the cylindrical tool, the shoulder has a diameter of 20 mm and the pin has a diameter of 5 mm and the pin height is 5 mm. The conical and cylindrical pin is right hand threaded. The design of cylindrical pin is taken from Ref. [30], and design of conical pin is developed for this topic. The conical pin has 5 threaded and cylindrical pin has 6 threaded. The tool's models are shown in Fig. 3.

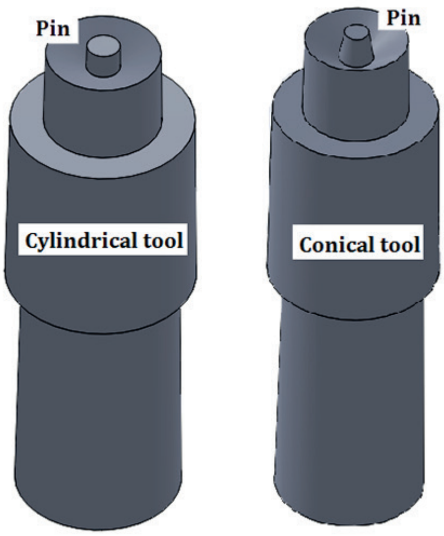


Fig. 3. Cylindrical and conical tool profile

The direction of tool rotation was anti-clockwise to promote a downward flow of the material. The pin was plunged into the PP sheets at the joint line up to the shoulder touching the surface of the PP sheets. While the rotating tool advanced, the temperature of the PP sheets below the tool shoulder increased and the strength of the PP decreased. The tool moved along the connection line and warm-up-cooling event occurred. Thus, the joining occurred between the two sheets.

The determination of the suitable welding parameters is necessary for strong seam of welding. During welding, tools heat up the material by friction and make a rotational motion for homogenization and the seam of welding occurs. The necessary shearing and mix effect can be enhanced in the molten material by changing the section and the slope of the grooves. The number and shape of the grooves on the pin must be selected appropriately to ensure that the molten material is transported to the back of the shoulder during travel between the parts to be welded.

The experimental data for cylindrical and conical tools are summarized in Table 1. In the tests, four combinations were selected for each tool and eight combinations for two tools.

Table 1
Experimental data for cylindrical and conical tools

| Rotation speed (rpm) | Welding speed (mm/min) | The number of samples |
|---|---|---|
| 560 | 11,2 | 4 |
| 560 | 22,4 | 4 |
| 900 | 11,2 | 4 |
| 900 | 22,4 | 4 |

Charpy impact is a single point test that measures the materials' resistance to the impact from a swinging pendulum. Charpy impact is defined as the kinetic energy needed to initiate fracture and continue the fracture until the sample is broken. The obtained values can be used for quality control or to differentiate general toughness. The sample is mounted horizontally and supported by clamps at both ends. The hammer is released and allowed to strike through the sample. If breakage does not occur, a heavier hammer is used until failure occurs. In the test, samples have standard dimensions. The samples can be either notched or unnotched. Impact energy is expressed in joules. Impact strength is calculated by dividing impact energy in joules by the area under the notch. A higher number indicates more material strength.

The strength of the joining was evaluated by means of Charpy impact test. ISO 179–1 standard was used in the tests. In the tests was used pendulum mass 0.101 kg and pendulum drop height 428.98 mm. The impact tester is Zwick brand. At least 4 samples were tested for the safe impact test results.

The dimensions of the sample prepared for the impact test, according to the ISO 179–1 standard, are shown in Fig. 4. A sample photograph of the non-welded material prepared according to these standard dimensions is shown in Fig. 5. This

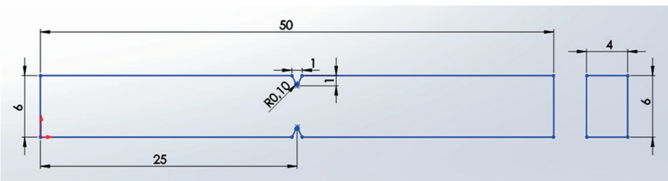


Fig. 4. The dimensions of impact test sample

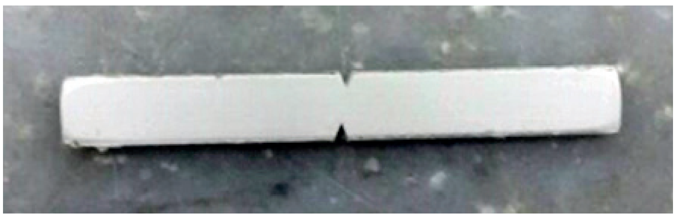

Fig. 5. Non-welded sample before impact test

sample was produced in a specially manufactured sample cutting machine. The welded samples cut to standards for the impact test are shown in Fig. 6. Figure 7 shows the photographs of the welded and non-welded samples before and after the impact test. It is seen that the samples are broken symmetrically from the notched area.

Fig. 6. Welded samples prepared before impact test


Fig. 7. Sample images of before and after impact test

ISO 7619–1 specifies a method for determining the indentation hardness (Shore hardness) of vulcanized or thermoplastic rubber using durometers with the following scales: the A scale for rubbers in the normal-hardness range; the D scale for rubbers in the high-hardness range; the AO scale for rubbers in the low-hardness range and for cellular rubbers; the AM scale for thin rubber test pieces in the normal-hardness range.

Shore hardness of the D measurement method was used to measure hardness. Hardness measurements were made from the welded zone, matrix zone of near zone of welded and the matrix material. In measurements, the depressing time of the curtailed measuring cone was set automatically at 15 s. The hardness tester is Zwick brand. Shore hardness measurements were made separately for welded samples made by the conical and cylindrical pins.

In order to inspect the welded sample, the cross-section was cut with the cutting disc. Cooling fluid was used for cutting. The welded sample was cold-formed at a room temperature for

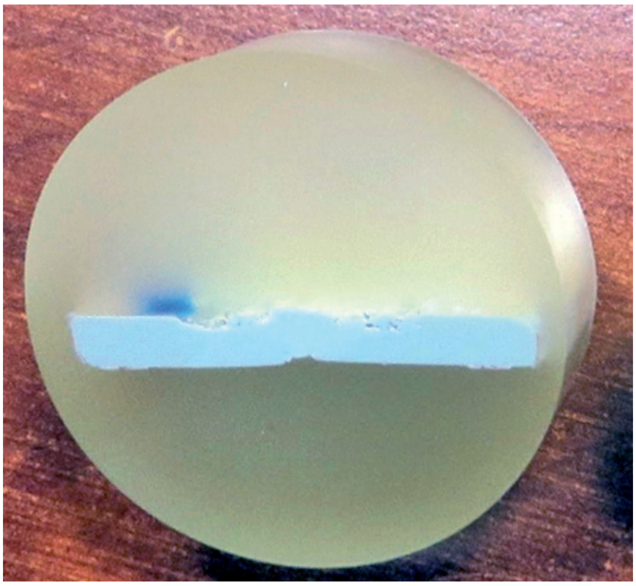

Fig. 8. Sample prepared for microstructure analysis

metallographic inspection. Pressure and temperature were not applied. In this process, the resin was mixed with the hardener in a liquid state and it was expected to harden by pouring on the sample. The surface of the sample coming out of the mold is very rough. To obtain the correct image, the surface of the molded sample was polished in aqueous environment without load applied with water sandpaper number 1200. The surface roughness value was measured between Ra = 0.50 μm and 0.60 μm. Surface roughness meter is Surtfest SJ-210 brand.

The image of the molded sample for the microstructure analyses is given in Fig. 8. The image of microstructure sample was taken from a Nikon MA 200 Eclipse Polarized Light Microscope.

## 3. Experimental results and discussion

The welded zone is seen in Fig. 9. In this figure, the welding direction and welding width can be seen with the naked eye. When we observe the welded material with the naked eye, no

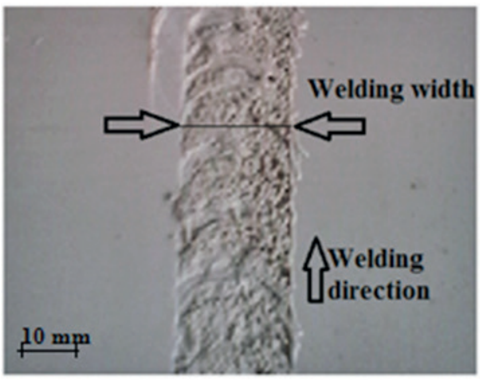


Fig. 9. Welded zone image

separation or cracking is occurring in the welded area. It can be said that welding is normal. Consequently, the welding operation is successful and there is not seen any negativity.

The microstructure photograph of matrix material is seen in Fig. 10. The matrix material is crystalline and the image was

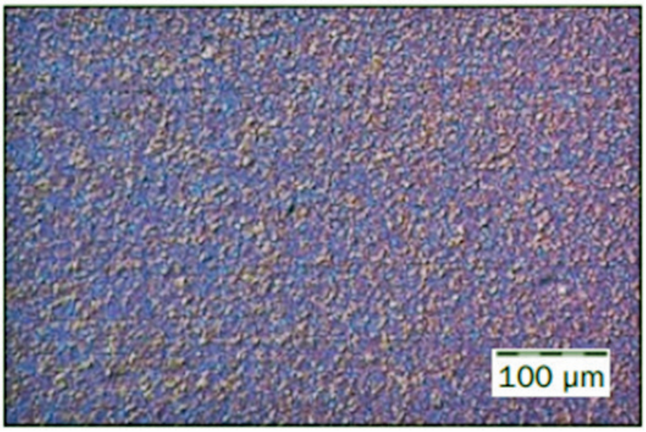


Fig. 10. Photograph of PP types taken under an optical microscope [29]

taken under an optical microscope. A PP material is fine and stable crystalline structure [29].

Figure 11 shows the structural difference between the welded zone and the matrix material. In the region where the tool passed, the grain structure of the material has changed as a result of the welding process. In the zone of passing of the tool shoulder and pin, structural difference occurred. Continuous warming and cooling down occurred in the welding zone. The material that has become dough has been pushed from the front to the back. The dough material is crushed under the shoulder. There is no volumetric reduction in the welded zone. The dough material is displaced in the zone of passing the tool. The thickness of the welded region and the thickness of the matrix material are almost the same.

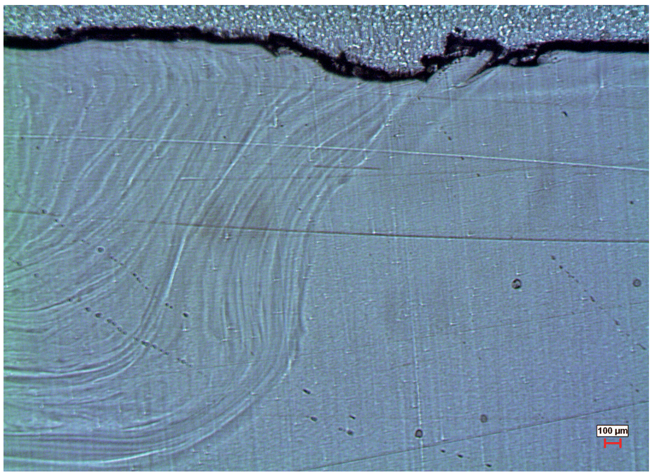

Fig. 11. Microstructure of the fracture surface of the welded seam

The microstructure image of welded zone is given in Fig. 11. There is a border line along the seam. There is a regular structure on the matrix side. There is difference in crystalline structure between matrix and seam region. The interface structure between the matrix and the seam characterizes the joint strength and the quality of the weld. In the seam region, a large grained structure with no homogeneity is observed. On the side of the matrix, the crystalline structure is seen to be more uniform. The lack of contact along the boundary line can be mentioned. The seam region showed fast warming and slow cooling. During welding, the tool quickly moves away from the molten zone. In the remaining region slow cooling occurred. At this time the grain structure is different. If the welding parameters are selected properly, contact defects at the boundary line can be reduced and welding quality can be improved. The crystalline structure of the near boundary line differs from the matrix and seam. It is observed that grain grows in the weld seam region. Also, the appearance of the boundary line does not indicate that the seam is bad. It indicates that the microstructure is different on both sides of the boundary. Welding strength values are verified by tests.

The results of impact strength carried out by cylindrical and conical tools, on samples cut from the welded sheets, are shown in Fig. 12 and 13, respectively. Figures show the test results for different rotational speeds. In Fig. 12 and 13 are also shown the results of the original sample impact strength. Fig. 14 shows results of Shore hardness of welded joints prepared by cylindrical pin. Figure 15 shows the results of Shore hardness of the welded joints prepared by the conical pin. The results of the hardness on the near of the welded zone are given in Fig. 16 and 17. In hardness graphs the hardness value of the matrix material was given in order to make the comparison with the Shore hardness values of welded samples. In Fig. 12–17 were used bar graphs including error bar. Graphs are for average values of four samples.

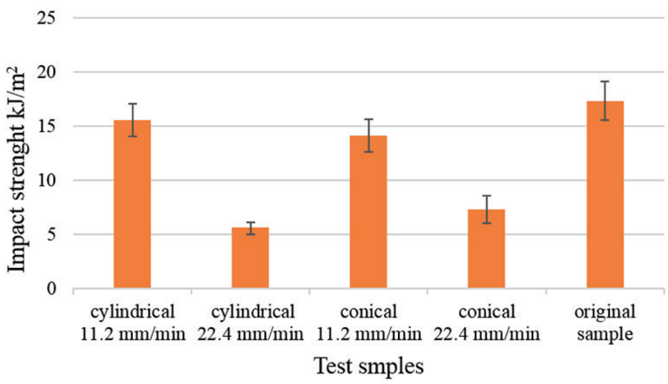


Fig. 12. The results of impact strength of welded joints prepared in 560 rpm

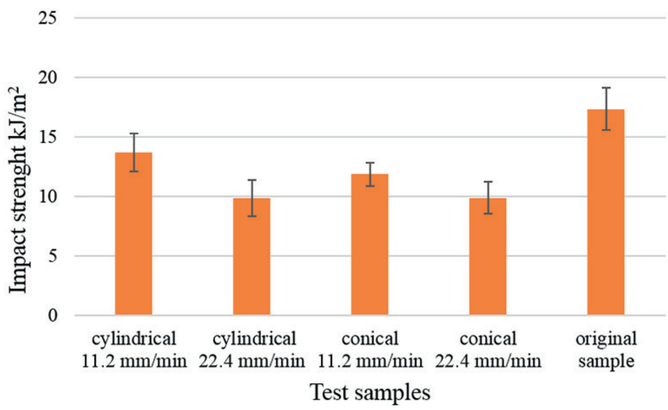


Fig. 13. The results of impact strength of welded joints prepared in 900 rpm

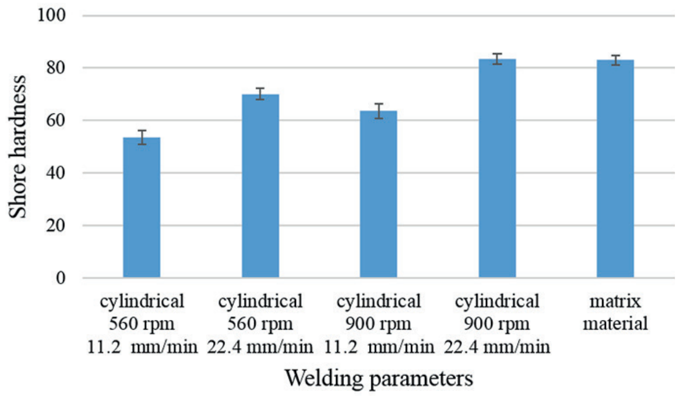


Fig. 14. The results of Shore hardness of welded joints prepared by cylindrical pin

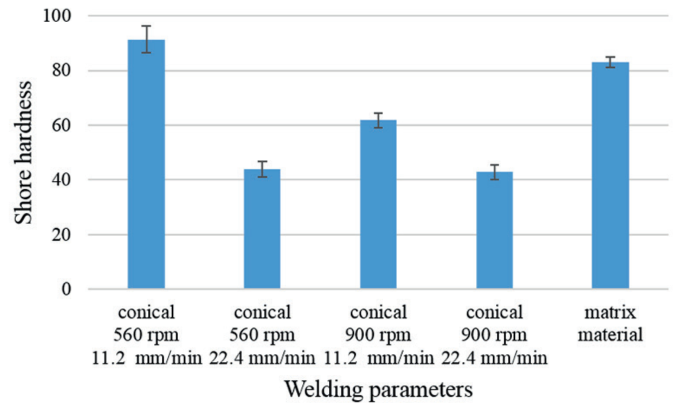


Fig. 15. The results of Shore hardness of welded joints prepared by conical pin

As can be seen in Fig. 12, the impact test minimum values of the samples prepared with cylindrical and conical pin at 560 rpm rotation speed are obtained at the 22.4 mm/min welding speed. It can be said that both pin type impact test results at the 11.2 mm/min welding speed approach the results of the original sample impact test. Test results of 22.4 mm/min welding speed at 560 rpm rotation speed seem to be weak for both pin types.

Figure 13 shows higher impact test results at 11.2 mm/min welding speeds for both pin types in tests made on samples prepared at 900 rpm. The test values of cylindrical pin type at 11.2 mm/min welding speed showed slightly higher values according to the test values of the conical pin type.

In Fig. 14, Shore hardness values of the welded zone at the rotation speed of 560 and 900 rpm and at the welding speed 11.2 mm/min are lower in samples prepared with cylindrical pin. It is seen that the results of parameters of 900 rpm and 22.4 mm/min are closer to the matrix material hardness values.

In Fig. 15, Shore hardness results of the welded zone at parameters of 560 rpm and 11.2 mm/min are the highest values in samples prepared with the conical pin. In the parameters of 900 rpm and 11.2 mm/min, Shore hardness values are the second high values. The hardness value of parameter of 560 rpm and 11.2 mm/min is close to hardness value of the matrix material.

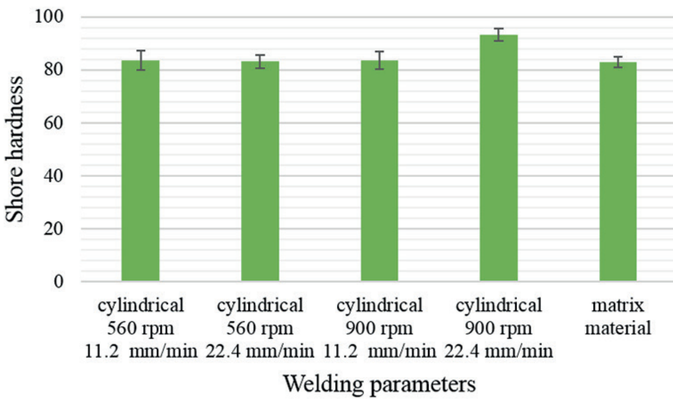


Fig. 16. The results of Shore hardness of near zone of welded by cylindrical pin

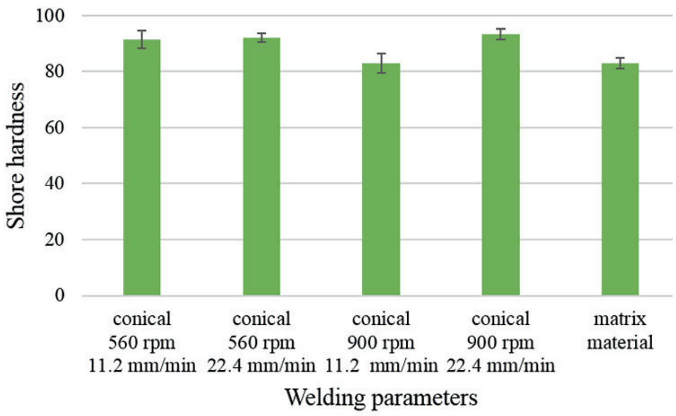


Fig. 17. The results of Shore hardness of the near zone of the welded by conical pin

In Fig. 16, cylindrical pin was used in welding process. Fig. 16 shows Shore hardness results of the near of the welded zone. The hardness results of the near of the welded zone with cylindrical pin are seen close to hardness values of matrix material. It can be said that this zone behaves like a matrix zone in terms of hardness.

In Fig. 17, conical pin was used in welding process. Figure 17 shows Shore hardness results of the near of the welded zone. In this figure, the hardness values of the near of the welded zone with the conical pin are seen higher from the matrix material value. In this zone, the hardening occurred and fragility can be mentioned.

## 4. Conclusions

Based on the impact tests performed on samples cut from the welded sheets it has been concluded that some welded parts behaved in a manner of the matrix material. In some samples, Charpy impact test values were measured close to values of matrix materials. The results showed that the method can be applied for polymer materials. It can be seen from the impact test graphics that the welding speed of 11.2 mm/min can be applied at 560 and 900 rpm rotation speed for two pin types. At the same time, it is seen that the cylindrical pin gives higher impact test values when the pin types are compared. It can be seen from the hardness values graphs that the hardness values of the zone welded with the cylindrical pin are close to the original sample values. The results of Shore hardness of the near welded zone of the samples for two pin types are close to hardness values of the matrix material. Especially, the welded samples made with a cylindrical pin at the 11.2 mm/min welding speed exhibited similar mechanical properties to the original sample. Different pin and tool geometries can be designed to improve welding strength. At the same time different tool rotation speeds and welding speeds can be tested to improve this process. The selection of suitable tool geometry and welding parameters is an important process in weld strength. In addition, appropriate collection of the material under and behind the tool is required during the passage of the tool for the successful welding operation. More welding strength can be obtained by testing different welding parameters.

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