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EVOLUTION OF TEMPERATURE AND MICROHARDNESS IN POLYMER PLATES WELDED BY FRICTION STIR SPOT WELDING (FSSW) USING A WELDING TOOL WITHOUT PIN

RAZVOJ TEMPERATURE I MIKROTVRDOĆE U POLIMERNIM PLOČAMA ZAVARENIM TAČKASTO TRENJEM SA MEŠANJEM (FSSW) SA ALATOM ZA ZAVARIVANJE BEZ TRNA

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- Vickers hardness test
- temperature
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- assembly
- welding parameters

Abstract

The research paper focuses on the study of high-density polyethylene (HDPE) polymer material weldability using the friction stir spot welding (FSSW) technique. The study is a contribution, using microhardness, to a parametric analysis in order to optimise the welding temperature to evaluate its influence on the behaviour of the material. Experimental analysis helps to understand the welding temperature effect on weld quality during friction stir spot welding (FSSW). The results obtained allowed us to better understand certain phenomena resulting for example the heat flow effect on the mechanical property of weld spot during FSSW welding. Experimental tests have been carried out under various operational parameters such as the tool rotation speed and dwell time. The latter has been carried out to highlight the effect of the heat flow and operational parameters of the welding on the mechanical property of the friction stir spot welding of thermoplastic polymers. Microhardness tests at room temperature show that tool rotation speed and dwell time play a very important part. From this study we can say that welding by FSSW with operational parameters - rotational speed 720 rpm and dwell time 40 s gives the best welding quality for the studied polymers.

Ključne reči
- tačkasto zavarivanje trenjem sa mešanjem (FSSW)
- Vikersova metoda ispitivanja tvrdoće
- temperatura
- polietilen visoke gustine (HDPE)
- sklop
- parametri zavarivanja

Izvod

Ovaj istraživački rad se fokusira na proučavanje zavarljivosti polimernog materijala polietilena visoke gustine (HDPE) primenom tehnike tačkastog zavarivanja trenjem sa mešanjem (FSSW). Koristeći mikrotvrdoću, rad doprinosi parametarskoj analizi u cilju optimizacije temperature zavarivanja kako bi se odredio njen uticaj na ponašanje materijala. Eksperimentalna analiza pomaže u razumevanju uticaja temperature zavarivanja na kvalitet šava tokom tačkastog zavarivanja trenjem sa mešanjem (FSSW). Dobijeni rezultati omogućavaju bolje razumevanje određenih pojava koje su rezultat, na pr., uticaja prostiranja toplote na mehanička svojstva šava pri FSSW zavarivanju. Eksperimentalna ispitivanja su izvedena sa različitim radnim parametrima kao što su brzina rotacije alata i vreme dejstva. Ovo drugo je urađeno kako bi se istakli uticaji prostiranja toplote i radnih parametara zavarivanja na mehanička svojstva termoplastičnih polimera tačkasto zavarenih trenjem sa mešanjem. Ispitivanja mikrotvrdoće na sobnoj temperaturi pokazuju da brzina rotacije alata i vreme dejstva igraju veoma važnu ulogu. Iz ovog istraživanja možemo reći da zavarivanje FSSW sa radnim parametrima, brzina rotacije 720 min^{-1} i vreme dejstva 40 s, daju najbolji kvalitet zavarivanja.

INTRODUCTION

There are many methods for joining metals, welding is one of the most convenient and rapid methods available. Welding is a fabrication process used to join materials, metals, or thermoplastics. During welding, the pieces to be joined are melted at the joining interface and usually a filler material is added to form a pool of molten material that solidifies to become a strong joint. Welding is an industrial process, it may be performed in many different environments, including in open air, under water, and in outer space. Many different energy sources can be used for welding, a gas flame, an electric arc, a laser, an electron beam, friction, and ultrasound. The evaluation of the weld joint mechanical strength is mainly based on the knowledge of the microstructure and the residual stresses. Generally, three microstructural zones can be distinguished in a welded joint: the heat affected zone (HAZ), the fusion metal, and the base metal. These areas show different mechanical behaviours such as mechanical properties, resilience, and hardness. Among these mechanical properties, the stress intensity factor, the J-integral, and CTOD (Crack Tip Opening Displacement). Various experimental and numerical techniques were developed to measure these parameters to depict the breaking strength of materials /1-8/.

A new variation of the more common friction welding technique called friction stir welding (FSW) was invented in 1991 and later patented by the Welding Institute (TWI) in the United Kingdom. In 2001, a new procedure derived from friction stir welding (FSW) appeared, called friction stir spot welding (FSSW). This technology was used in the Mazda RX-8 automotive industry which replaced spot welding with the strength of aluminium sheets. This new welding technology (FSSW) claims a 40 % reduction in equipment

/9, 10/, reduced energy consumption by 99 % of that used by the conventional welding process. Thus, welding by FSSW offers the designer new opportunities for innovative products. Unlike traditional welding processes, this technique makes it possible to weld materials that are difficult or impossible to weld with other techniques, it enables solid assembly, which eliminates solidification-related defects and leads to lower internal stresses than conventional welding processes /11, 12/. It is a weld in the pasty state of the material recommended for applications where it is important to keep the original characteristics of the materials.

FSW can be used to join sheets without filler wire or shielding gas. Several types of metallic materials and recently polymer materials have been welded by the FSW technique. The welding parameters differ from polymer material to another. In various industrial applications, pipe manufacturing, polymer materials are becoming the most widely used materials because of their resistance to wear and corrosion, good durability, and low cost. The behaviour of this type of material is related to the loading conditions as well as the shape and position of the existing crack. Generally, during the forming process of solid materials, the phenomena of plastic instability often control the appearance and performance of the finished product according to authors /13-18/. These authors have studied different behaviours characterizing polymeric materials such as the stresses triaxiality effect on several cases of polymers, such as polyvinyl chloride, polybutylene terephthalate, and thermoplastic copolyetherester under high plastic stress. They concluded that the evolution of polyvinyl chloride and polybutylene terephthalate damage in service is influenced by the level of stress triaxiality. The creep properties of FSW welded HDPE plate joints were investigated. It has been found that creep resistance of welds under controlled conditions can be better than that of the base material /19, 20/. This relatively new welding method involves a solid state assembly process; its principle is based on the phenomenon of softening following melting caused by heating the assembled material with a special non-consumable rotary tool. This welding technique may have a longer weld life compared to other welding processes /21, 22/. This process, which performs the assembly at a temperature below the melting temperature of the material to be assembled, consists of providing heat to the material to be assembled by friction using the tool rotational movement,. This technique uses a non-consumable tool to generate friction heating and produces a plasticized region at the weld area. A layer of material in plastic and pasty form forms under the shoulder.

The FSSW process has three stages: plunging, stirring and solidification, once the solidification operation is complete, the tool is retreated, Fig. 1. Tool rotates and plunges into the attached workpieces with a force to a certain depth providing heat to basic material by friction between the tool and the plates to be welded and by plastic dissipation. In the stirring phase, the tool does not plunge. This operation generates friction heat. Then, the heated and softened material near the tool deforms plastically and a solid state bond is created between the surfaces of the upper and lower sheets /9, 10/.

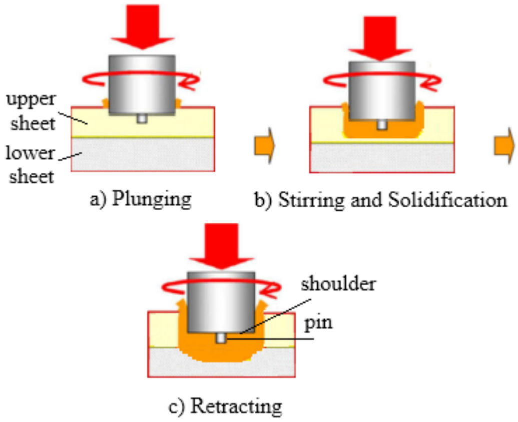


Figure 1. Friction stir spot welding (FSSW) process.

From a metallurgical point of view, the friction stir spot welding (FSSW) process is very different from a fusion weld, because it is a thermomechanical process. The heat comes from two sources, by friction between the shoulder and the sheets, and by plastic deformation. The high local shear rate combined with the high temperature of the process produces an active competition between recrystallization and dynamic recovery. The total heat input the base materials receive is lower than in any traditional fusion welding technique, where base materials are melted. Furthermore, the size of HAZ is smaller and so are the residual stresses and distortions of the welded sheets. Moreover, the microstructural changes related to the welding thermal cycle are reduced, /25/.

FSSW has important advantages over traditional welding. Provided are many functional advantages: lightness, no need for additional materials, very good reproducibility, automation possibilities. The operation can be applied to materials, thermoplastics, dissimilar materials can be assembled such as aluminium alloys, lead, polymers, magnesium, zinc, and copper for thicknesses ranging from 0.8 to 65 mm that have been reported for successful welded joints at full penetration and without porosity or internal voids, /26/, no welding fumes or radiation, and temperatures do not reach the melting point of base materials. This avoids problems encountered during fusion welding (porosities, blisters, and cracks) which leads to lower internal stresses and moreover, the mechanical characteristics of the welded materials remain close to the initial values of base materials, /27/.

EXPERIMENTAL PROCEDURE AND MATERIAL

This study is a contribution to a parametric analysis in order to optimise the welding temperature and microhardness in order to evaluate its influence on the mechanical property and quality of the weld using a new tool shape for FSSW. The polymer that is used is polyethylene with high density (HDPE), used in the manufacture of pipes reserved for the supply and distribution of water in accordance with Algerian standards NA7700-2, manufactured by CHIALIi group. The temperatures of vitreous transition and fusion are respectively of -125 °C and 35 °C, molar mass is about 500 kg/mol, and the density is 0.97 g/cm^3 /28/. It is a semi-crystalline thermoplastic comprising a crystalline phase and an amorphous phase. For the investigation, HDPE sheets having 4 mm thickness, 6 mm width, and 300 mm length are cut from commercial plates and are used to study the FSSW welding. Figure 2 shows the tool position and specimen dimensions during the FSSW welding process.

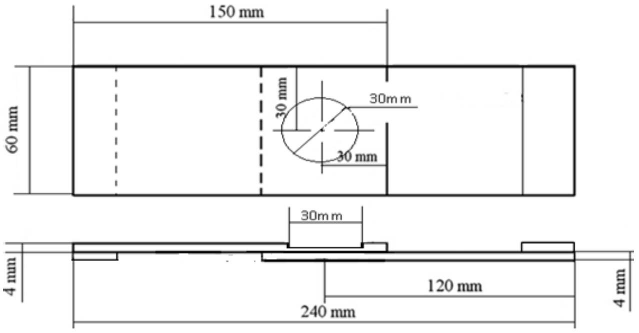


Figure 2. Tool position and specimen geometry for the FSSW process, /29/.

The tool has a shoulder diameter of 30 mm and a length of 5 mm, without pin and is made from a GS235 structural steel (formerly E36 standard) to ensure good mixing and good softening of the material entrained. This tool is suitable for FSSW of HDPE plates. It is able to provide the main welding functions (heating the parts by friction and by plastic deformation, mixing the materials to form the joint and contain the flow of material under the shoulder). The welding parameters and their ranges are summarized in Table 1.

Table 1. Welding parameters and their ranges.

Parameters	Units	Ranges
Tool rotation speed	(min^{-1})	475, 580, 720, 875
Tool plunge rate	(mm/s)	3.3 /30/
Tool plunge depth	(mm)	1.7
Dwell time	(s)	10-50
Tool retracting delay	(s)	30 /31/
Tool concavity angle	(°)	4

Specimens were welded on a semi-automatic milling machine using a steel tool with a new shape for friction stir spot welding, Fig. 3. This machine has the necessary characteristics to perform the experimental campaign for welding by FSSW an HDPE lap shear joint. The fixing of the plates on the machine table is ensured by plane metal holds which maintain by fastening the plates one on the other in order to ensure a uniform pressure distribution on the specimen. At the end of each welding operation, we leave the tool to be cooled until room temperature before starting a second operation of welding. The tool is maintained plunged in the part

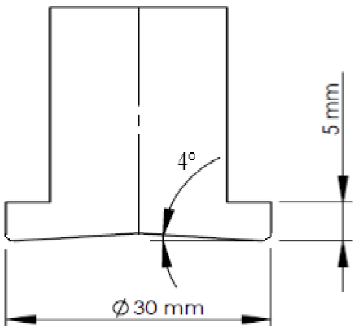


Figure 3. Cross-section of the novel FSSW tool used for welding HDPE sheets.

during 30 s after the end of the solidification phase, and then we retract it immediately, Fig. 1 /31/. The tool sizes used in this study are summarized in Table 2 and Fig. 3.

Table 2. Dimension of tools.

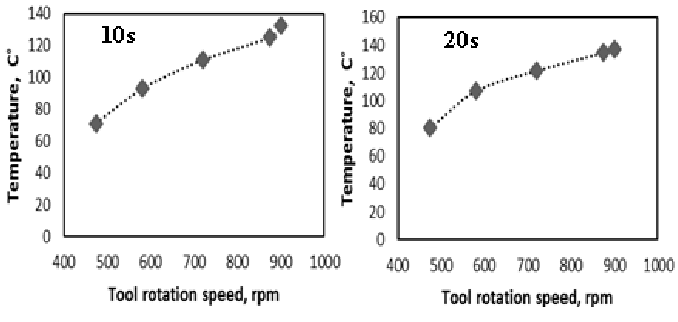
Parameters	Units	Ranges
Tool concavity angle	(°)	4
Tool edge shape: rounded edge	(mm)	R = 1

This study deals with the effect of temperature and the microhardness affecting the weld strength of HDPE plates on the quality of the weld using a new tool shape for the FSSW welding technique. Shear tensile test campaign was conducted on the tensile testing machine Zwick/Roell Z100 with a traverse speed of 5 mm/s. The fracture load was evaluated from load-displacement data during lap shear tests. This load is the average of tensile shear loads of three tests carried out on specimens welded and tested under the same conditions.

EXPERIMENTAL RESULTS AND DISCUSSION

Effect of dwell time on temperature distribution

Studies have been carried out on the temperature distribution during FSSW welding using the thermocouple implanted in the plates. On the other hand, it is difficult to obtain information on temperatures reached in the welded plates at the level of the mixed material and near the tool. The distribution of the temperature field plays an important role in the quality of the welded joint formation and in the understanding and control of material flow in the welded area to improve the mechanical properties of the welded joint. After the successful application of friction stir spot welding, Adeel et al. have found that depending on the physical and rheological properties of the material, the welding parameters differ from one polymer to another. Polymers with high melting temperature and viscosity require a higher rotational speed and achieve sufficient heat and possibly good weld strength, /32/. Here, we varied the tool rotation speed between 720 and 875 min^{-1} and the dwell time of the tool between 10 and 50 s. Figure 4 illustrates the rotational speed effect on temperature distribution in the welded joint and Fig. 5 illustrates the dwell time effect on the temperature distribution in the welded joints for four rotation speeds: 475, 580, 720 and 875 min^{-1}. The upper sheet is heated by tool/plate friction and plastic deformation. Heat is transferred to the lower sheet. After a predetermined time of rotation of the tool, the area under the tool will be in a pasty state, and thus, the material of the two sheets is mixed by diffusing the material of the upper sheet into the lower sheet.



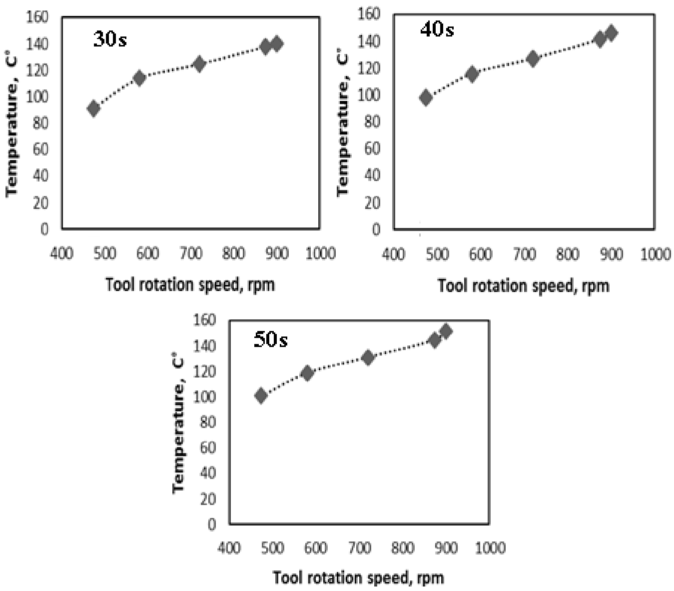


Figure 4. Effect of rotational speeds on temperature distribution in the welded joint.

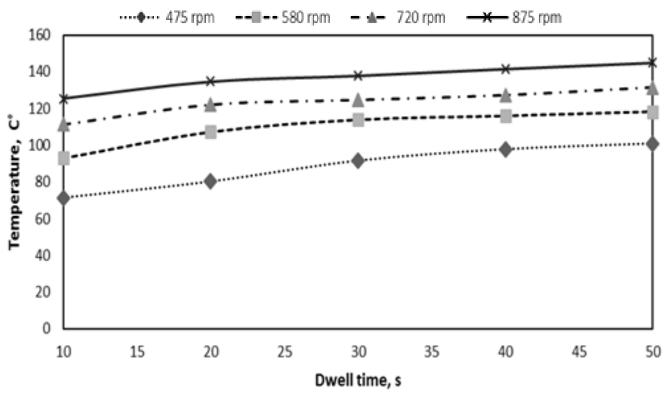


Figure 5. Effect of dwell time on temperature distribution in the welded joint for rotational speeds of 475, 580, 720 and 875 min^{-1}.

For tool rotation speeds equal to 475 and 580 min^{-1}, the temperature generated by friction between the rotating tool and the material increases without reaching the melting temperature of HDPE. The insufficient heat from the low mixing friction between the two sheets is linked to the low speed of rotation of the tool despite the increase in the dwell time up to 50 s. Therefore, the low amount of friction induced heat and consequently the low mixing of the material of the upper sheet with that of the lower sheet during the range of dwell times from 10 to 50 s greatly affects the weld strength. For tool rotation speed of 720 min^{-1} the temperature generated by friction between rotating tool and the material increases with increasing dwell time for the same range (10 to 50 s). But considering the two factors, the melting temperature of HDPE (125 °C) is obtained with a tool dwell time of 40 s. Then it remains increased slightly until reaching a threshold value of 141 °C at 50 s. For tool rotation speed of 875 min^{-1}, the temperature generated by friction between the rotating tool and material increases with increasing dwell time for in range of 10 to 50 s. Melting temperature of HDPE (125 °C) is obtained with a tool dwell time between 20 and 30 s. Then it remains increased slightly until reaching a threshold value of 149 °C at 50 s. Short dwell times cause thin nugget thicknesses; there is less time for heat to be conducted around the tool. When dwell time is greater than 30 s, the temperature generated by friction between the rotating tool and the material increases the melting temperature of HDPE by reaching a threshold value of 149 °C. The temperature increases with the increase in dwell time, it reaches its maximal level 142 °C at 34 s, and after the 34th second the temperature does not change with increase in dwell time, Figs. 4 and 5. The melting temperature of HDPE is about 132 °C. The most important temperatures are concentrated under the shoulder. Then, as we move away from the tool, the temperatures gradually decrease until they drop to room temperature. From these measurements, it can be concluded that the maximal temperatures during the FSSW welding process reach 90 to 96 % of the melting temperature, depending on the welding conditions. Significant microstructural changes will therefore take place.

Microhardness test

For Vickers microhardness measurement, we used a very sophisticated FT-ARS 9000 automatic tester with a load of 500 gf for 10 seconds at room temperature, /33/. This tester is equipped with an optical camera and advanced data processing software with various formats of data output and statistical processing (graphs, diagrams, etc.) /34/. Figure 6 illustrates the footprint of the Vickers pyramid.

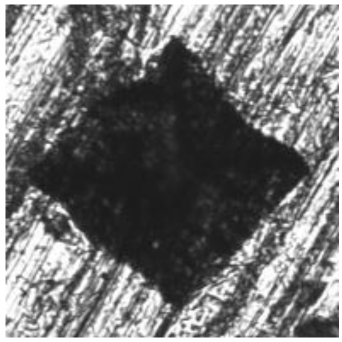


Figure 6. Vickers pyramid footprint.

Vickers microhardness testing is carried out on a prepared sample removed from 4 mm thick FSSW welded plates with a pitch between points of 0.5 mm spacing, the measurements are made symmetrically with respect to the main welding axis, Fig. 7.

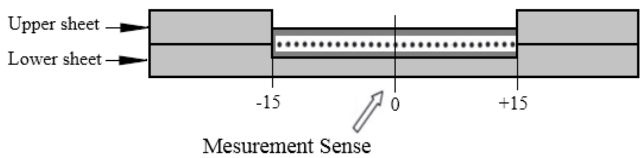


Figure 7. Profile of welded joint at half thickness.

Microhardness was measured from the weld points to compare the results to those of the unwelded material. The results of Vickers microhardness (HV) are shown in Fig. 8. Generally, friction stir welding is very different from fusion welding because it is a thermomechanical process without reaching the melting temperature of the welded material. The variation in hardness applies for the four main welding zones. The base material's (BM) mechanical and metallurgical characteristics remain invariable in this zone after welding. The core zone (NZ) undergoes the largest plastic deformation and the temperature reaches maximal values. The thermomechanical affected zone (TMAZ) is subjected to both the temperature and plastic deformations generated by the movement of the tool. The heat affected zone (HAZ) is affected by heat induced by FSSW welding and the material undergoes a microstructural change due to the rise in temperature. The typical distribution of microhardness values in the zones is almost symmetrical about the weld midline (0) because the plastic flow field at both sides of the weld centre is uniform.

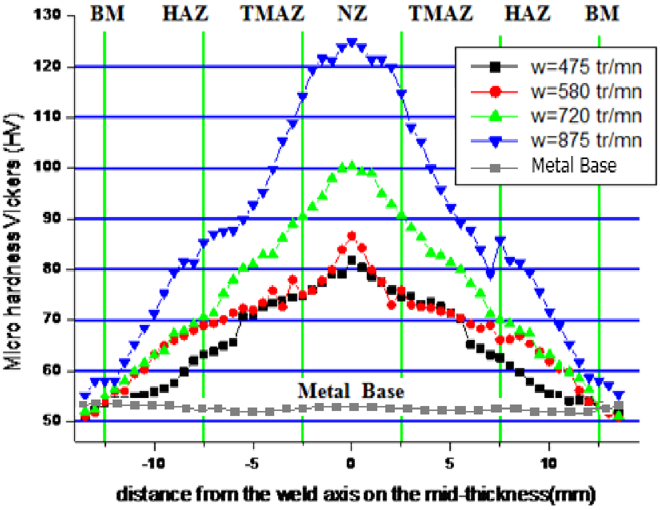


Figure 8. Variation of Vickers HV microhardness.

The microhardness profile shows an increase in all cases reaching a maximal value in the central zone (NZ) which is harder than the in other zones. The microhardness decreases towards the softer zone, the latter represents the normal state of the unwelded material, and this area is located outside the plastic deformation, but receives heat from the welding process. So, mechanical properties vary between different zones induced by the welding. Several research have been carried out in recent years to prove that typical distribution of microhardness in areas being almost symmetrical to the central weld line, because the plastic flow field on both sides of the weld centreline is uniform, and the value hardness in the NZ zone should be greater than in the other zones due to its structure, which confirms our result /35, 36/.

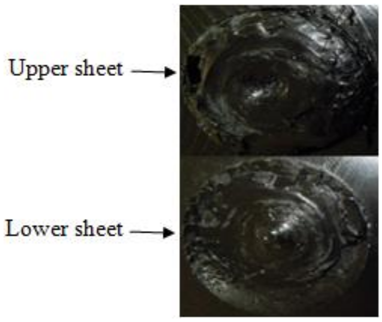


Figure 9. Weld nugget surface after lap shear tensile test: rotation speed 720 min^{-1}; plunge rate 3.3 mm/s; dwell time 40 s; plunge 1.7 mm, /29/.

The typical force-displacement curve of lap shear tensile test of the HDPE sheets welded by FSSW using the new tool for welding is given in Figs. 9 and 10. The work carried out in this part shows that there is a relationship between the tool rotational speed and the dwell time that influences the resistance of the welding nugget. The best resistance is obtained for tool rotation speed of 720 min^{-1} and dwell time of 40 s.

A typical force-displacement curve of lap-shear tensile test of HDPE sheets welded by FSSW using the conventional tool geometries with pin is shown in Fig. 11, /31/.

The results of the tensile tests performed on specimens prepared from sheets welded by a tool without a pin compared to the conventional FSSW tool with pin are shown in Figs. 10 and 11, respectively. Using a tool without a pin, the applied force is kept constant during the welding operation; the same behaviour cannot be found with the conventional FSSW tool with pin. It can also be observed that the tensile strength for nuggets welded with a tool without a pin is much higher than that observed for the tool with a pin. It can be concluded that the tool without a pin is advantageous for a better weld quality.

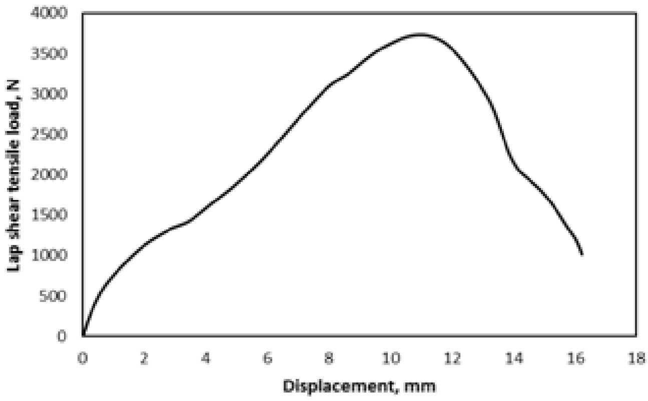


Figure 10. Lap shear tensile load vs. displacement of HDPE sheets welded by FSSW (rotation speed 720 min^{-1}; plunging rate 3.3 mm/s; dwell time 40 s; and plunge 1.7 mm).

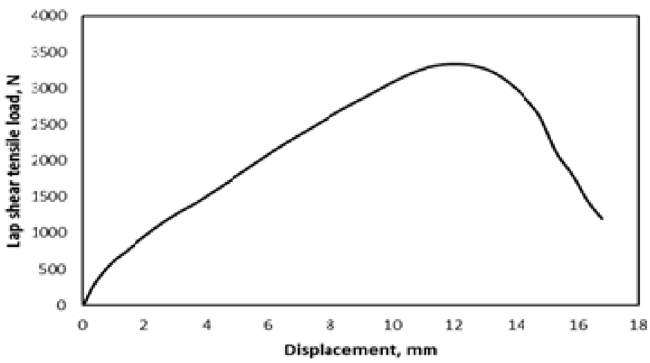


Figure 11. Lap shear tensile load vs. displacement (rotation speed 710 min^{-1}; plunge rate 3.3 mm/s; dwell time 45 s; plunge 5.7 mm.

CONCLUSIONS

A new geometry of the tool for the technique of friction stir spot welding (FSSW) of HDPE sheets was developed and presented. Based on the determined temperature and hardness value of weld seams for comparing the results to those of the non-welded material, the following conclusions are drawn:

- The results of temperature and Vickers microhardness (HV) show that the mechanical behaviour of materials strongly depends on the temperature and the hardness values of the weld.
- It should be noted that the analysis of results made it possible to understand the influence of tool geometry and the effect of parameters used in FSSW, and especially in the case of thermoplastic polymers.
- Results obtained for characterizing the mechanical behaviour of materials through various tests carried out show the complicated relationship between material-tool which contributes to the evolution of physicochemical properties affected by several welding parameters, such as the dwell time and rotation speed.
- The good results observed are suitable for obtaining good welding quality of thermoplastic materials such are HDPE.

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