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Measurement and evaluation of joint properties in friction stir welding of ABS sheets reinforced by nanosilica addition

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ABSTRACT

In the present study, experimental investigation has been carried out to find effect of nanosilica addition in joining of acrylonitrile butadiene styrene (ABS) fabricated by friction stir welding (FSW). Experiments were carried out under different values of tool rotations and travel speeds under presence and absence of nanosilica addition. After finding optimum welding condition, effect of pass number on distribution of nanosilica in ABS matrix has been studied through X-ray diffraction (XRD) analysis and scanning electron microscopy (SEM). Results revealed that sound joints with desired characteristics and efficiency are fabricated at welding speed of 20mm/min and rotation speed of 1600 RPM. Also, it is found from tensile testing results that addition of nanosilica reinforcement causes 26% enhancement in joint strength. Furthermore, from XRD and SEM analyses it is found that welding with two pass number results in uniform distribution of nanosilica in friction stir processed (FSP) zone which causes formation of composite like structure that adds to joint efficiency up to 100%.

Keywords: Friction Stir Welding; ABS; nanosilica; XRD, SEM; Joint Strength

INTORUDCTION

Using light weight structure made of thermoplastic, fiber reinforced polymers and light weight metals are increasing progressively in industries such as transportation, building, automobile and aeronautics during recent past. The plastic materials have large degrees of freedom in manufacturing due to their good formability, desired machinability, great molding properties and low cost. However, the strength of this type of material compared to metallic component is one of main disadvantage.

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Although plastic materials have good manufacturability; in order to fabricate complex parts with specified dimensions, joining technologies should be utilized [1]. The welding mechanisms of thermoplastic materials can be classified into three main groups: (i) joined by heat conduction (such as hot gas welding), (ii) joined by heat radiation (such as laser welding) and (iii) joined by mechanical friction (such as friction welding, ultrasonic welding etc.). The first two groups cause emission of toxic gas that is harmful for averment and operator due to excessive heat input and evaporation of polymeric material during welding [2]. But, mechanism of welding in the third joining family is out of evaporation of polymeric material and emission of toxic gases. Here, the joint is accomplished by surface friction that results in intense motion in molecular structure of parent material [2].

Friction stir welding (FSW) is an emerging joining technique that belongs to the last joining family. The method was successful in welding of similar and dissimilar materials including metals and polymers in different configurations. Various researchers reported feasibility of welding polymeric materials by FSW. Seth et al. [3] developed a hot shoe tool to join polypropylene sheets in butt configuration. In order to attain sound joint with desired strength they found that low feed rate, hot shoe temperature, long dwell time and large shoulder diameter should be utilized. Arici and Sinmaz [4] developed a new FSW method to eliminate root defect from weld line. They reported that double side welding process is a practical method to eliminate the defect and improve the joint strength. Bjorkman et al [5] used a new FSW tool which can process both sides of a butt joint in a single pass. They called the method as self-reacting FSW. The method eliminates the need of high forging force and severe plunging action. Pirzadeh et al. [6] developed a newly designed tool for touching both sides of polymeric sheets made of ABS. They found that the tool has outstanding effect in eliminating root defects. Bagheri et al. [7] analyzed effect of hot shoe friction stir welding parameter on joint strength of ABS sheets. They reported that setting process parameters to 1600 rpm tool rotation, 20mm/min feed rate and 100°C shoe temperature will result in attaining maximum strength. Sadeghian et al. [8] used design of experiment (DOE) to find optimum setting of FSW parameters regarding desired joint strength. The obtained results showed that conical tool pin profile along with 900 rpm rotational speed, 25 mm/min linear speed, shoulder to pin ratio of 20/6 and tilt angle of 2° lead to obtaining 101% joint efficiency. Mendes et al. [9] used stationary shoulder along with external heating system to study the effect of FSW plunge force on ABS joint strength. The results revealed that higher axial force provided by design improved tool causes significant enhancements in joint strength and elongation. In another attempt, Mendes et al. [10] showed that when FSW is carried out without external heating and the same stationary shoulder tool, tool rotational speed and axial force should be above threshold value that is sued in presence of heating. Azarsara and Mostafapour [11] applied FSW to analyze the flexural behavior of the polyethylene joints. They used response surface methodology along with analysis of variances to find which factor has great impact on joint strength. The results showed that travel speed followed by tool rotational speed have great impact on flexural strength of the joint.

Recently, association of Nano-ceramic powder for enhancement of metallic joint properties made by FSW has been reported by different researchers [12-15]. However, a limited number of works used the Nano-addition powders for fabrication of polymeric joints. Carbon Nano tubes (CNT) were used to reinforce dissimilar thermoplastic joints made of high density polyethylene sheet and ABS [16]. On the basis of authors' knowledge, association of nanosilica particles for improvement of the joint properties of ABS sheets has hardly been reported in the literature. In the present study, it is attempted to use Nano-ceramic material such as nanosilica to reinforce the ABS joints fabricated by FSW. The reason for selection of nanosilica is its high modulus of elasticity and good strength as well as desired combination with ABS material [17]. In this study, at first single pass FSW is carried out to find optimal welding parameters in conventional FSW process in which nanosilica is added. After finding optimum condition, effect of pass number on the joint strength and dispersion of Nanosilica particles on friction stir processed zone is analyzed.

MATERIALS AND METHODS

The material used in this study was acrylonitrile butadiene styrene (ABS) sheets with thickness of 4mm which were prepared in dimension of 100 mm×150 mm. Table 1 presents the properties of as received ABS sheet. A groove with depth of 2.5 mm and width of 0.5 mm was machined along the length of the specimens in order to prepare a proper location in butt configuration and fill it with nanoceramic material. The machined grooves are filled with nanosilica powders of average diameter of 50 nm. The amount of nanosilica particles for all fabricated samples was about 0.1g. After nano powders addition, a pinless tool was designed and swept the filled groove to compress the powders in the groove and restrict outpouring during FSP. In other words, sweeping with pinless tool causes closing of upper surface of grooves and prevents expelling out. A similar work has been carried out by Barmouz et al. [18] during fabrication of ABS-Clay composite by FSP.

The friction stir welding experiments were carried out on a milling machine with maximum power of 20 hp. The FSW tool used in experiments was a cylindrical shape AISI H13 with threaded pin profile. The tool shoulder diameter was 20 mm, the pin diameter was 6 mm and its length was 3.7 mm. During all experiments, the plunge depth and tilt angle were kept constant to 0.15 mm and 2°, respectively. Fig. 1 illustrates experimental setup.

The fabricated joints were machined to prepare tensile testing samples according to ASTM-D638 standard. The samples were then subjected to tensile testing by SANTAM universal testing machine with a 100 kN load frame. The ram speed during tensile test was about 2 mm/min. In the next step, scanning electron microscopy (SEM) was utilized here to estimate dispersion of Nano-particles in the ABS matrix by means of TESCAN SEM machine. X-ray diffraction analysis was also used to study uniformity in dispersion of nanosilica in the polymeric phase. To do so, PHILIPS XRD machine was used with angular position of $2\theta=0.5°\text{-}30°$. The machine scanned the FSP region with increment of 0.4°. XRD analysis was carried out using Cu-Kα radiation scanned by 30 kV and 25 mA.

In addition, micro-hardness analysis was carried out on the joint cross section by use of Vickers microhardness tester. The indenter load was 50 g and 15 s dwell time. The profile of micro-hardness was obtained every 1.5 mm along the joint.

In the present study, the experiments can be classified into two main stages. In the first stage, series of experiment were carried out under different tool rotation (800, 1200 and 1600 rpm) and travel speeds (20, 50 and 80 mm/min). In this stage, based on full factorial design numbers of 9 single-pass experiments were carried out without nanosilica addition; also, 9 experiments were conducted by addition of nanosilica. The main purpose of this stage is to discover how FSW parameters and silica addition influence the tensile strength of the joint. After finding optimal tool rotation and travel speeds, a series of experiments under optimumparameters aiming to find effect of pass number (1, 2 and 3 pass) on dispersion of nanosilica on ABS matrix. In this stage, microstructure study based on SEM and XRD is carried out; also, the strength and ductility of fabricated samples are analyzed based on results of tensile testing.

RESULTS AND DISCUSSION

In this section, effect of tool rotational speed and travel speed on tensile strength of the fabricated joints in presence and absence of nanosilica powder in the process are evaluated. The main purpose of this section is finding the optimal combination of tool rotation and travel speed which results in obtaining maximum tensile strength.

Finding optimum FSW parameter

Fig. 2 represents effect of tool rotational speed and travel speed on the tensile strength of the joints fabricated in presence and absence of nanosilica particles. It is clear from the figure 2a that irrespective of addition of nanosilica, the tensile strength of the joints increases as the tool rotational speed increases . During friction stir welding process, the tool rotational speed plays the role of heat generation and stirring of material. For thermoplastic materials, since the ability of heat transfer is very low, high amount of heat input is required to soft the material make them stirred [19]. In such conditions, the material flow during the process is enhanced and defects such as pin hole and tunnel which are due to low heat input is eliminated [19]. Therefore, the tensile strength of the joint is significantly enhanced.

Figure 2b illustrates effect of welding speed on the joint strength of the samples. It is obvious that irrespective of addition of nanosilica particles, the tensile strength of the joints decreases as travel speed increases . When the travel speed increases, the cooling rate during stirring action also increases. Hence, for a low heat transferrable material such as ABS; the local heat input is significantly reduced which material flow. In such conditions, long defect is formed in the weld line which eventually causes reduction of tensile strength. Fig. 3 shows weld micrograph at different welding conditions (800 RPM rotational speed with 80 mm/min travel speed and 1600 RPM rotational speed with 20 mm/min travel speed). It is obvious that in the first situation, due to low heat input, a defect like tunnel is formed in the root of weld nugget that significantly reduces the joint strength while in the second, the heat input is enough and subsequently the defect is eliminated because of better material flow and therefore, higher strengths are accomplished.

Another point that can be interpreted from figure 2 is the reduction of tensile strength in higher travel speeds when silica is added to FSP zone. When FSW is performed without addition of silica, the slope of reduction of tensile strength is moderate and in the range analyzed, it experienced a decrease of about 22%. However, when the process is carried out in presence of silica, the slope of reduction of joint strength got severe and reached 41%. This trend is attributed to the effect of travel speed on dispersion of nanosilica. The dispersion of nanosilica powders in ABS matrix is significantly influenced by travel speed. When the travel speed is low, nanosilica particles are uniformly dispersed in the FSP zone because in low welding feed forces, more uniform mixing of soft material with silica particles occurs. However, when the travel speeds increase, due to high feed forces and very high cooling rates, silica particles is expelled out of FSP region and agglomeration in matrix happens. In such cases, the tensile strength drastically reduces.

The main point that can be inferred from figure 2 is strengthening of the joints in presence of silica addition. The increase in the tensile strength of the joints by addition of nano-particles can be attributed to the large specific surface area of nanosilica that results in enhancement of the mechanical properties of the ABS joints. Elimination of porosities and cracked surfaces is another reason for improving the tensile strength of the joint. When the nanosilica particles are added to the FSP region, it can produce a composite like structure that significantly enhances the joint properties. When silica is associated with a thermoplastic material such as ABS, it produces a layered structure and microfibers that boosts the endurance limit of the composite against tensile forces [19]. Therefore, by formation of this structure, the tensile strength of the fabricated joint is significantly improved. Fig. 4 represents the SEM image of the weld cross section fabricated in presence and absence Nano-additive in the same processing condition. It is seen that the joint line has a simple flat surface when no silica particle is added to FSP region. However, when the process is carried out with silica addition, a layered like structure is formed in weld cross section that includes nanoparticles between each layer. Association of polymeric structure and nano-particles acts as an adhesive bond between each layer and influence the composite strength against tensile loads..

According to the results, it is obvious thatirrespective of silica addition, the tensile strength of the joints attains maximum value when processed by 1600 rpm tool rotation and 20 mm/min travel speed. In addition, addition of nano-silica to FSP region causes an improvement about 25.2 % in mean values of tensile strength.

Effect of pass number

Based on previous analysis, it is found that the tensile strengths of the samples processed by tool rotation of 1600 rpm and travel speed of 20 mm/min in presence of silica addition show maximum values. Therefore, in order to analyze the effect of pass number, another set of specimens are fabricated under the mentioned process parameters and subjected to multi-pass FSW process from 1 pass to 3 passes. Discussions on how pass number influences microstructure and properties of the weld are presented in the following sections.

XRD analysis

Fig. 5 illustrates XRD spectrum of pure nanosilica particles and FSP regions of specimens subjected to 1 to 3 pass FSW process. As it is seen from XRD pattern, pure nanosilica particles have a peak in 4.1° in which the distance between its layers is approximately 23.5 A°. This is totallly in consistent with what reported by the manufacturer. When FSW is carried out by addition of nanosilica and 1 pass number, the distance between nanosilica layers increases and causes elimination of peaks from XRD spectrum. It is also observed that for the joint fabricated by 2 pass FSW, the aforementioned peaks are completely eliminated implying a uniform dispersion of nano-particles in the ABS matrix. When the pass number increases from 1 to 2, the agglomerated micro structures created in 1 pass FSW is broken and more uniformed dispersion of Nano-particles is obtained. However, when the pass number reaches to 3, new peak is formed in 3.2° which implies a decrease in the distance between nanosilica layers. It means that the 3 pass FSW causes agglomeration of composite phase. This occurs because of degradation of ABS at further pass numbers which damages uniformity of composite structure. Therefore, it is concluded that 2 pass number is an optimum value resulting in uniform dispersion of nanosilica particles in matrix phase.

SEM analysis

Fig. 6 reveals SEM images of cross section of the joints fabricated in presence of nanosilica particles under different pass numbers. When the process is carried out by 1 pass number FSW, the silica particles are dispersed in weld cross section and cause formation of layered structure and microfibers that was discussed in previous section. Applying 2 pass FSW process results in breaking the large layers to smaller ones of uniform size. This phenomenon improves mechanical properties due to formation of regular, fine and uniform structure. However, when the process is carried out by 3 pass number FSW, the uniform structure of the composite is deteriorated. As can be seen, the structure of the weld nugget processed by 2 pass FSW is very different from the matrix. The materials in weld nugget became clumpy, but the matrix materials maintained chain structure. Kiss et al. studied the morphology of FSW seams of the polypropylene, who indicated that the average size of the original spherulites was 24 to 30μm. However, the average size of the spherulites in weld seam was only 10 to 20μm [20]. Strand et al. studied the microstructure of polypropylene FSW sheets, and they pointed out that the microstructure was disrupted when the inappropriate processing parameters was adopted [21]. Compared to the metal, the unique macromolecular structure of polymer materials made the FSW processing different from the metal. In FSW metal, the materials suffered intense plastic deformation, which caused in fine and equiaxed recrystallized grains [22]. The metal materials were affected by heating and then stirring due to their good thermal conductivity. However, the polymer materials were affected via FSW by stirring and then heating due to their poor thermal conductivity. That is, the macromolecular structure was broken before fully preheat in FSW processing. Squeo et al. used FSW to join polyethylene sheets and they came to the conclusion that preheating or heating the plastic sheets was a feasible approach to make the FSW of polymer materials more robust [23]. Compared to the microstructure of the weld nugget illustrated in Fig. 6, it found that the microstructure was fairly completed by increase of pass number from 1 to 2, and that, the fracture wan not smooth but rugged. It is generally known that the nanosilica possessed of unique thermal properties and similar chain structure to polymer materials. It may improve the thermal properties of the weld nugget by adding the nanosilica. The groove used for filling the nanosilcia also had the effect of heat dissipation. At further pass numbers, the layered structure is destructed due to excessive mechanical and thermal load and hence, uniform dispersion of nanosilica particles is interrupted. Moreover, at further pass numbers, the nanosilica particles are again agglomerated in ABS layer and consequently, reduction of adhesive strength emerges. This structure is the weakest against external tensile loading.

Tensile strength and frctography analysis

Figure 7 represents stress-strain curves of the samples fabricated by using different pass numbers. According to this figure, the joint fabricated by two pass number results in an enhancement in joint strength close to the value of as received ABS. It is also clear that the tensile strength of the joint fabricated by 1 pass FSW is about 88% of as received material. When the pass number increases to 2, the joint efficiency enhances to 98% of base material. However, at further pass numbers, the tensile strength of the joint is drastically descends to 75% of as received material. As shown in figures 4 and 5, when the process is carried out by 1 and 2 pass numbers, the structure of FSP region changes to layered type with uniform distribution of silica in each layer. This altered structure significantly influences the adhesion strength between each layer of FSP region and improves the joint strength. In other words, by addition of nanosilica to FSP region, a composite like structure is formed that causes strengthening of fabricated joint. However, when FSW process is carried out with 3 pass number, excessive mechanical and thermal loadings leads to destruction of layered structure and disruption of the uniformity of nanosilica dispersion. Therefore, the tensile strength is reduced. It is also seen from the results that the lowest strength belongs to the sample processed without silica addition. The joint efficiency of this type material is relatively about 71% of as received material. The joint strength of this sample is even lower than that of the sample fabricated by three pass FSW in presence of nanosilica. This difference shows the importance of formation of composite like structure in FSP region that helps improve the strength properties of the joint. The silica shows a good combinability with ABS and formation of composite structure. As reported by different researchers, silica has desired tendency to be composed with polymeric chain. It promotes the endurance limit and elasticity modulus of the polymer [19]. Therefore, this characteristic of nanosilica causes significant enhancement of ABS joint strength.

Figure 8 displays the fracture surface of the samples fabricated by different pass numbers. Adorning to this, for specimens with no silica addition, the fracture surface is relatively smooth and without dimples. However, for the joints fabricated by nanosilica, the fracture surface is rough including micro-layers that eventually result in enhancement of joint strength.

Hardness analysis

Micro-hardness profile of weld cross section fabricated by different pass numbers and silica addition is illustrated in figure 9. Based on this picture, the value of weld nugget hardness has significantly enhanced by addition of nanosilica. This enhancement is due to existence of ceramic phase such as nanosilica that decreases the porosity of weld nugget. Also, when pass number rises from 1 to 2, because of formation of uniform micro-fibers and layered structures, the values of hardness increases. However, when FSW process is carried out with three passes, due to high amount of heat input and mechanical loading, ABSmaterial experiences degradation [7]. In such conditions, the porosity level increases and causes reduction of hardness. In addition, it is inferred from figure 9 that for the samples fabricated without addition of nanosilica, the hardness value is significantly lower than base material. During FSW of ABS, since thermo-machincal loading is induced to the polymeric material, degradation and increased porosity occurs. In such conditions, the hardness is significantly reduced.

CONCLUSION

In the present investigation, experimental study was carried out to analyze the effect of addition of nanosilica particles on the reinforcement of crylonitrile butadiene styrene joints fabricated by FSW. Here, first a series of experiments were carried out to find optimum setting of tool rotation and travel speed regarding maximum joint strength. Then, the samples were fabricated under optimum condition and finally, influence of pass number on dispersion of nanosilica, micro-structure, tensile strength and hardness were studied. The obtained results can be summarized as follows:

- Irrespective of addition of nanosilica, the joint strength reaches to the maximum value when tool rotation speed is 1600 rpm and travel speed is 20 mm/min. Also, in the similar condition, addition of nanosilica causes 25.2% improvement in mean values of tensile strength.
- The XRD analysis of the samples showed that for samples reinforced by nanosilica particles, at 1 and 2 pass numbers, the peaks in XRD spectrum are eliminated. This implies desired dispersion of nanosilica in matrix phase. Moreovre, when FSW is carried out at 3 pass number, due to excessive mechanical and thermal loading, the porosity occurred in ABS matrix and destructed the uniformity of silica dispersion.
- SEM micrograph of the cross section shows that by addition of silica to the FSP region, micro-fibers and composite structures with layered patterns are formed. This structure causes enhancement of joint strength against tensile loading and increases the strength. At two pass number, the layered structure is uniformly distributed in FSP region and causes further enhancement in mechanical properties.
- Comparing stress-strain curves of fabricated samples shows that the joint efficiency of samples without nanosilica addition is about 71% of base material. However, by addition of nanosilica to FSP region and performing two pass FSW process, the joint strength is significantly enhanced and reaches 98% of base material.
- The micro-hardness profiles obtained at different conditions show that addition of nanosilica causes significant improvement in hardness of the weld nugget compared to base metal. This is due to the formation of composite like structure (polymers with nanoceramic particles) that lowers the porosity level and improves the hardness.

REFRENCES

1. Oliveira, P. H. F., Amancio-Filho, S. T., Dos Santos, J. F., & Hage, E. (2010). Preliminary study on the feasibility of friction spot welding in PMMA. *Materials Letters*, *64*(19), 2098-2101.
2. Kiss, Z., & Czigány, T. (2007). Applicability of friction stir welding in polymeric materials. *Periodica Polytechnica. Engineering. Mechanical Engineering*, *51*(1), 15.
3. Strand, S. R., Sorensen, C. D., & Nelson, T. W. (2003). Effects of friction stir welding on polymer microstructure. In *ANTEC 2003 Conference Proceedings* (pp. 1078-1082).
4. Arici, A., & Sinmazçelýk, T. (2005). Effects of double passes of the tool on friction stir welding of polyethylene. *Journal of materials science*, *40*(12), 3313-3316.
5. Bjorkman, G., Cantrell, M., & Carter, R. (2003). Self-reacting friction stir welding for aluminum alloy circumferential weld applications.
6. Pirizadeh, M., Azdast, T., Ahmadi, S. R., Shishavan, S. M., & Bagheri, A. (2014). Friction stir welding of thermoplastics using a newly designed tool. *Materials & Design*, *54*, 342-347.
7. Bagheri, A., Azdast, T., & Doniavi, A. (2013). An experimental study on mechanical properties of friction stir welded ABS sheets. *Materials & Design*, *43*, 402-409.
8. Sadeghian, N., & Givi, M. K. B. (2015). Experimental optimization of the mechanical properties of friction stir welded Acrylonitrile Butadiene Styrene sheets. *Materials & Design*, *67*, 145-153.
9. Mendes, N., Loureiro, A., Martins, C., Neto, P., & Pires, J. N. (2014). Morphology and strength of acrylonitrile butadiene styrene welds performed by robotic friction stir welding. *Materials & Design*, *64*, 81-90.
10. Mendes, N., Loureiro, A., Martins, C., Neto, P., & Pires, J. N. (2014). Effect of friction stir welding parameters on morphology and strength of acrylonitrile butadiene styrene plate welds. *Materials & Design*, *58*, 457-464.
11. Azarsa, E., & Mostafapour, A. (2014). Experimental investigation on flexural behavior of friction stir welded high density polyethylene sheets. *Journal of Manufacturing Processes*, *16*(1), 149-155.
12. Saeidi, M., Barmouz, M., & Givi, M. K. B. (2015). Investigation on AA5083/AA7075+ Al2O3 joint fabricated by friction stir welding: characterizing microstructure, corrosion and toughness behavior. *Materials Research*, *18*(6), 1156-1162.
13. Sun, Y. F., & Fujii, H. (2011). The effect of SiC particles on the microstructure and mechanical properties of friction stir welded pure copper joints. *Materials Science and Engineering: A*, *528*(16), 5470-5475.
14. Kartsonakis, I. A., Dragatogiannis, D. A., Koumoulos, E. P., Karantonis, A., & Charitidis, C. A. (2016). Corrosion behaviour of dissimilar friction stir welded aluminium alloys reinforced with nanoadditives. *Materials & Design*, *102*, 56-67.

15. Bodaghi, M., & Dehghani, K. (2017). Friction stir welding of AA5052: the effects of SiC nano-particles addition. *The International Journal of Advanced Manufacturing Technology*, *88*(9-12), 2651-2660.
16. Gao, J., Li, C., Shilpakar, U., & Shen, Y. (2015). Improvements of mechanical properties in dissimilar joints of HDPE and ABS via carbon nanotubes during friction stir welding process. *Materials & Design*, *86*, 289-296.
17. Kim, I. J., Kwon, O. S., Park, J. B., & Joo, H. (2006). Synthesis and characterization of ABS/silica hybrid nanocomposites. *Current Applied Physics*, *6*, e43-e47.
18. Barmouz M, Seyfi J, Givi MK, Hejazi I, Davachi SM. A novel approach for producing polymer nanocomposites by in-situ dispersion of clay particles via friction stir processing. Materials Science and Engineering: A. 2011 Mar 15;528(6):3003-6.
19. Teimouri, R., & Baseri, H. (2015). Forward and backward predictions of the friction stir welding parameters using fuzzy-artificial bee colony-imperialist competitive algorithm systems. *Journal of Intelligent Manufacturing*, *26*(2), 307-319.
20. Kiss Z, Czigany T. Microscopic analysis of the morphology of seams in friction stir welded polypropylene. Express Polymer Letters. 2012 Jan 1;6(1).
21. Bagheri A, Azdast T, Doniavi A. An experimental study on mechanical properties of friction stir welded ABS sheets. Materials & Design. 2013 Jan 1;43:402-9.
22. Panneerselvam K, Lenin K. Effects and defects of the polypropylene plate for different parameters in friction stir welding process. Taper. 2013;40:1500.
23. Squeo EA, Bruno G, Guglielmotti A, Quadrini F. Friction stir welding of polyethylene sheets. The Annals of Dunarea de Jos University of Galati, Technologies in Machine Building. 2009;5:241-6.

Figures

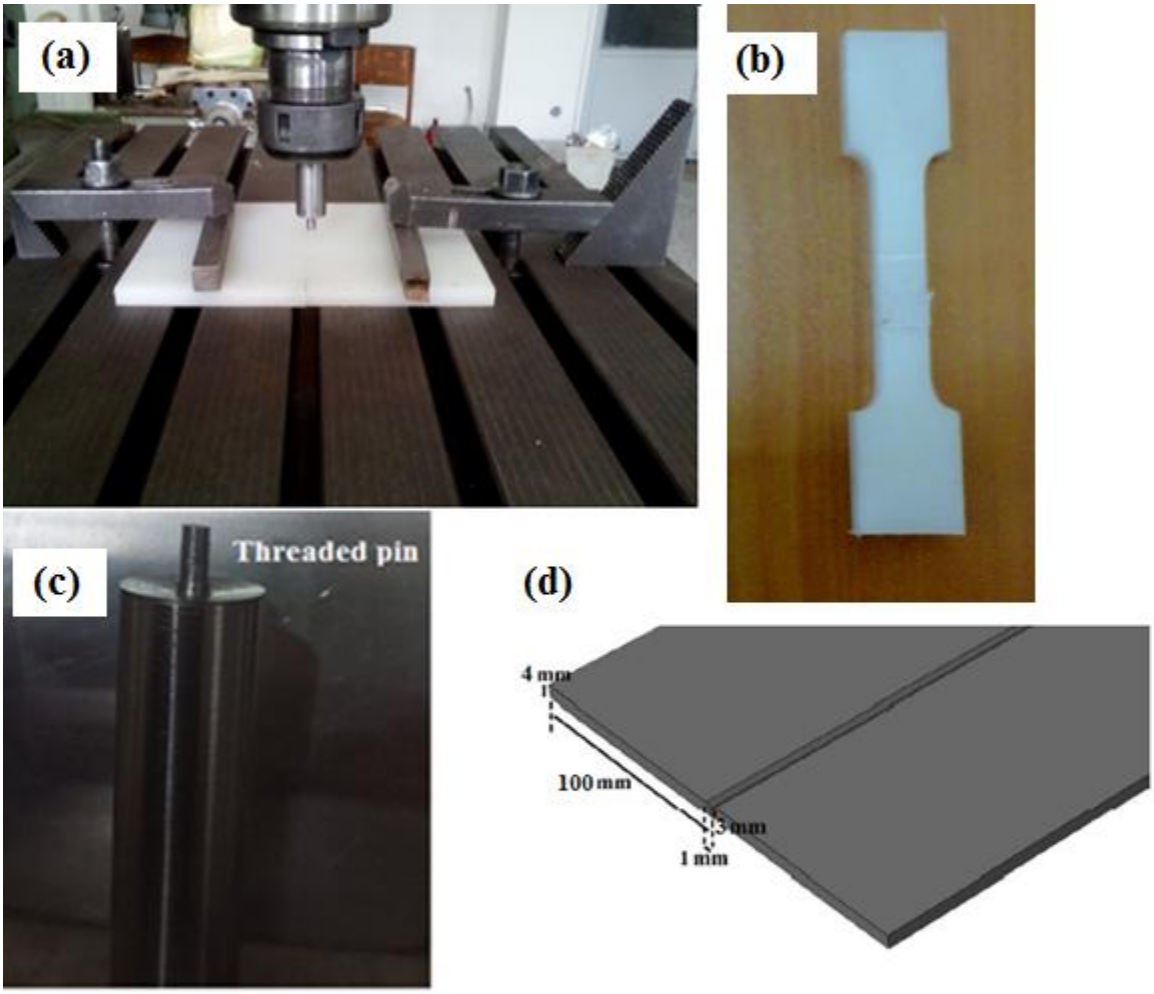

Fig. 1 (a) Experimental setup including FSW attachment on milling machine, clamping system, (b) sample cut from the joint for tensile test (c) threaded pin tool (d) schematic illustration of grooved sheets for filling by nanosilica addition

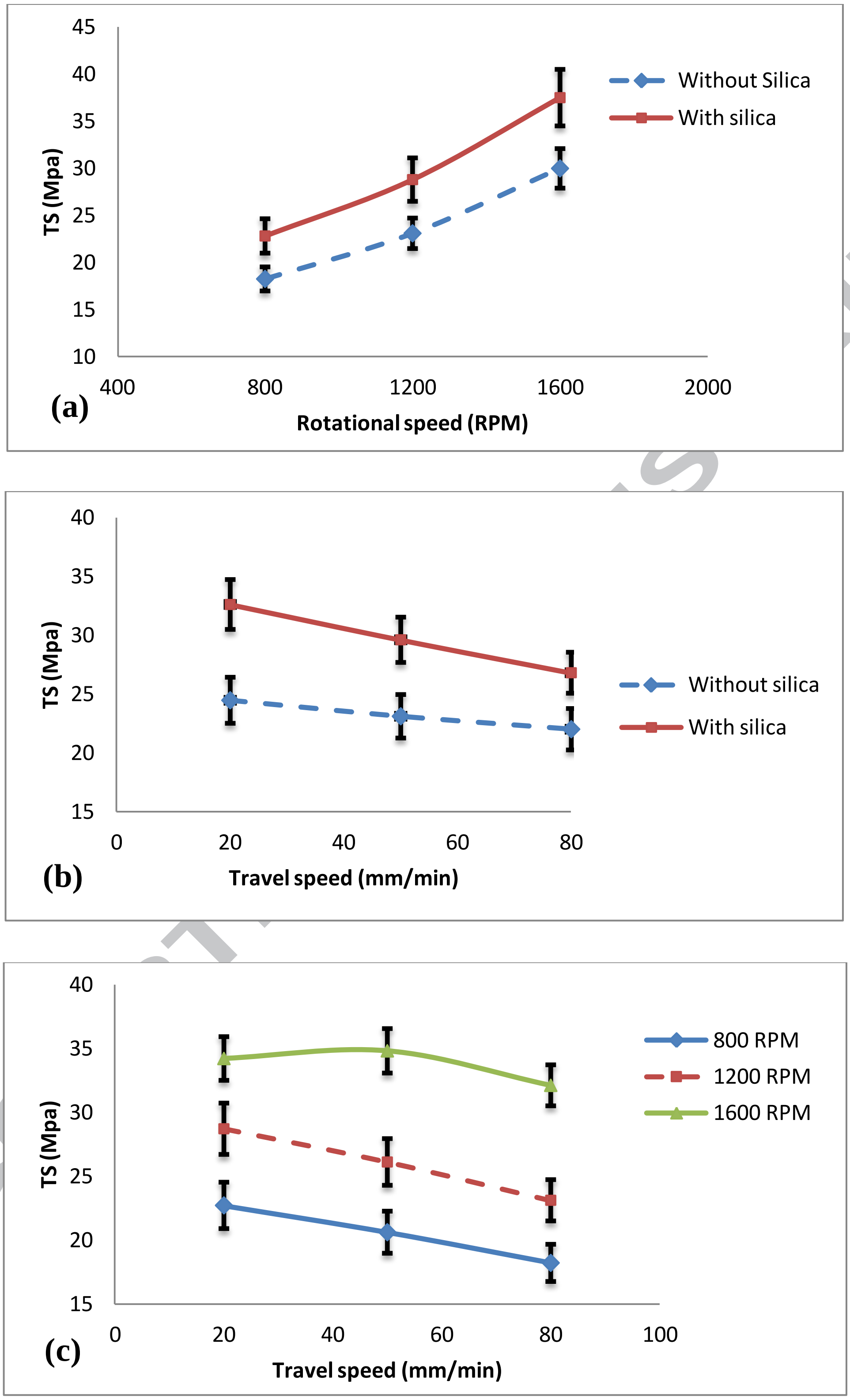

Fig. 2 Effect of process factors on tensile strength (a) interaction of silica addition and tool rotation (b) interaction of silica addition and travel speed (c) interaction tool rotation and travel speed

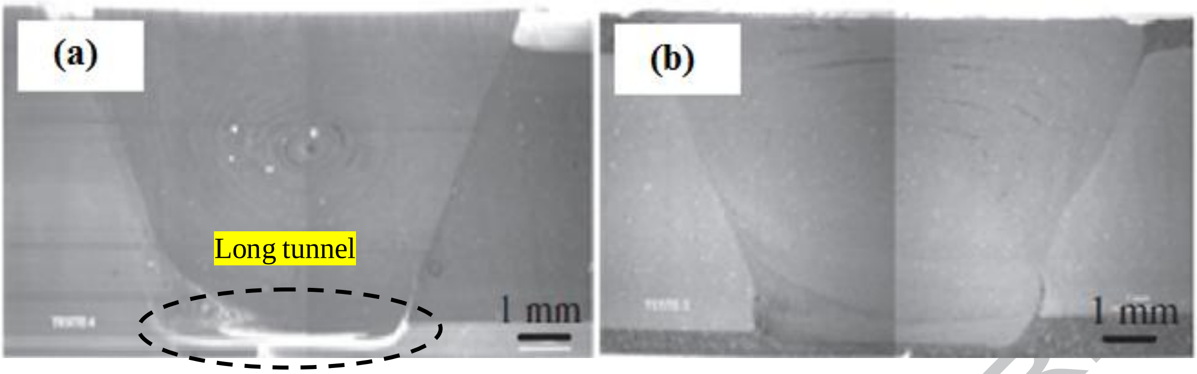

Fig. 3 Micrograph of weld cross section at (a) 800 RPM rotational speed and 80 mm/min travel speed (b) 1600 RPM rotational speed and 20 mm/min travel speed

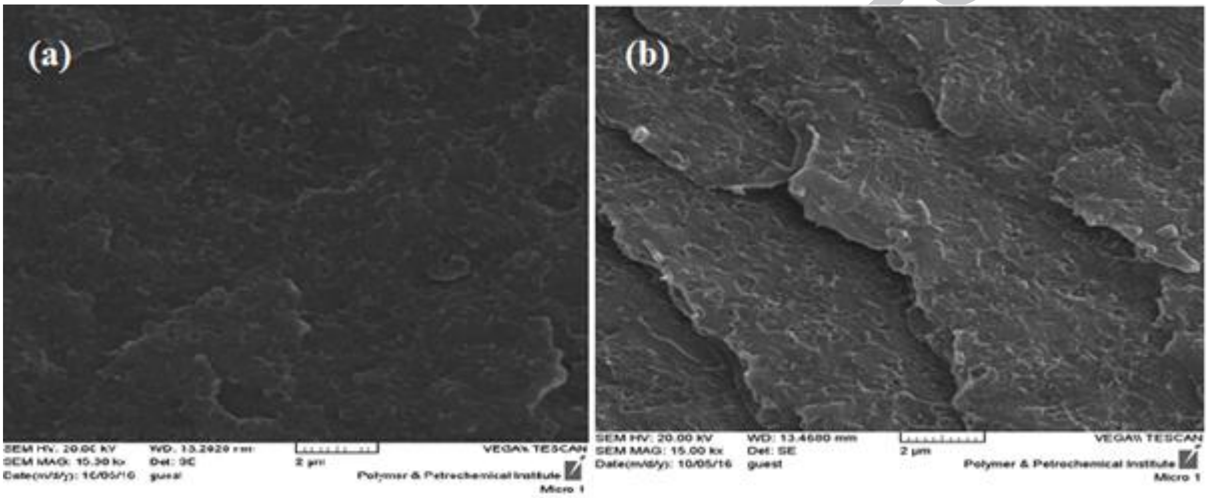

Fig. 4 SEM image of FSP region cross section fabricated (a) without addition of nanosilica particles (b) with addition of nanosilica particles

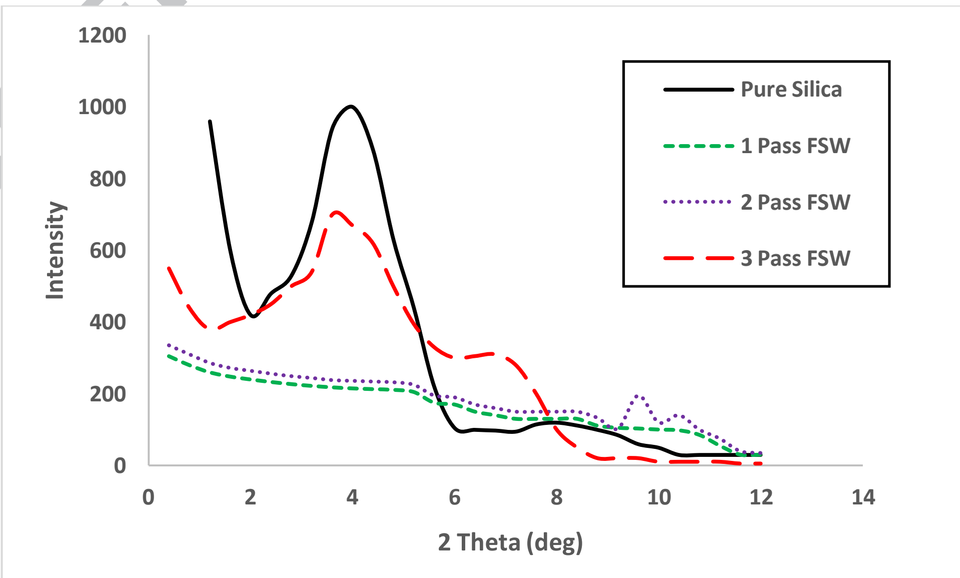

Fig. 5 XRD spectrum of pure nano-silica material and joints fabricated by FSW of 1 to 3 pass.

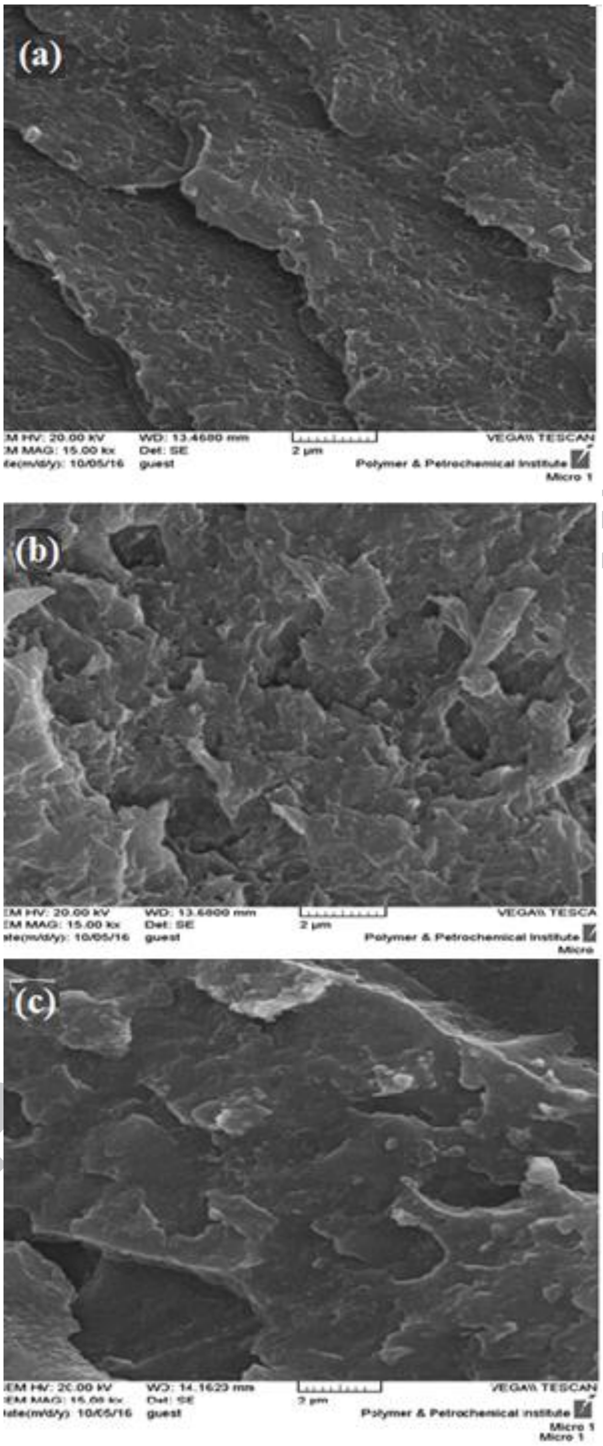

Fig. 6 Micro-structure of weld cross section including nanosilica particles fabricated by FSW with different pass numbers: (a) 1 pass (b) 2 pass (c) 3 pass.

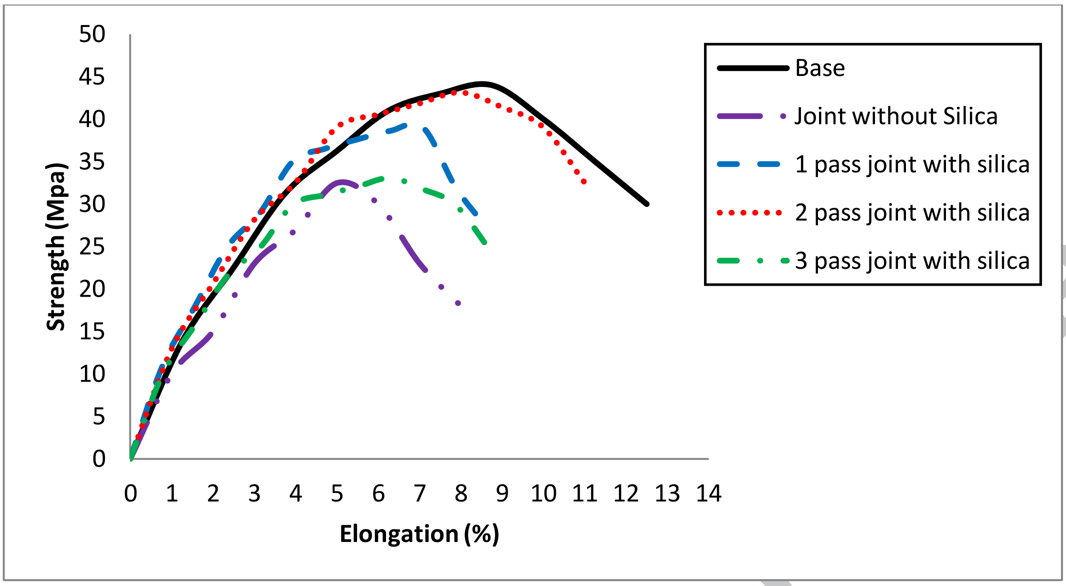

Fig. 7 Stress-strain curves of the joint fabricated by different pass number and silica addition

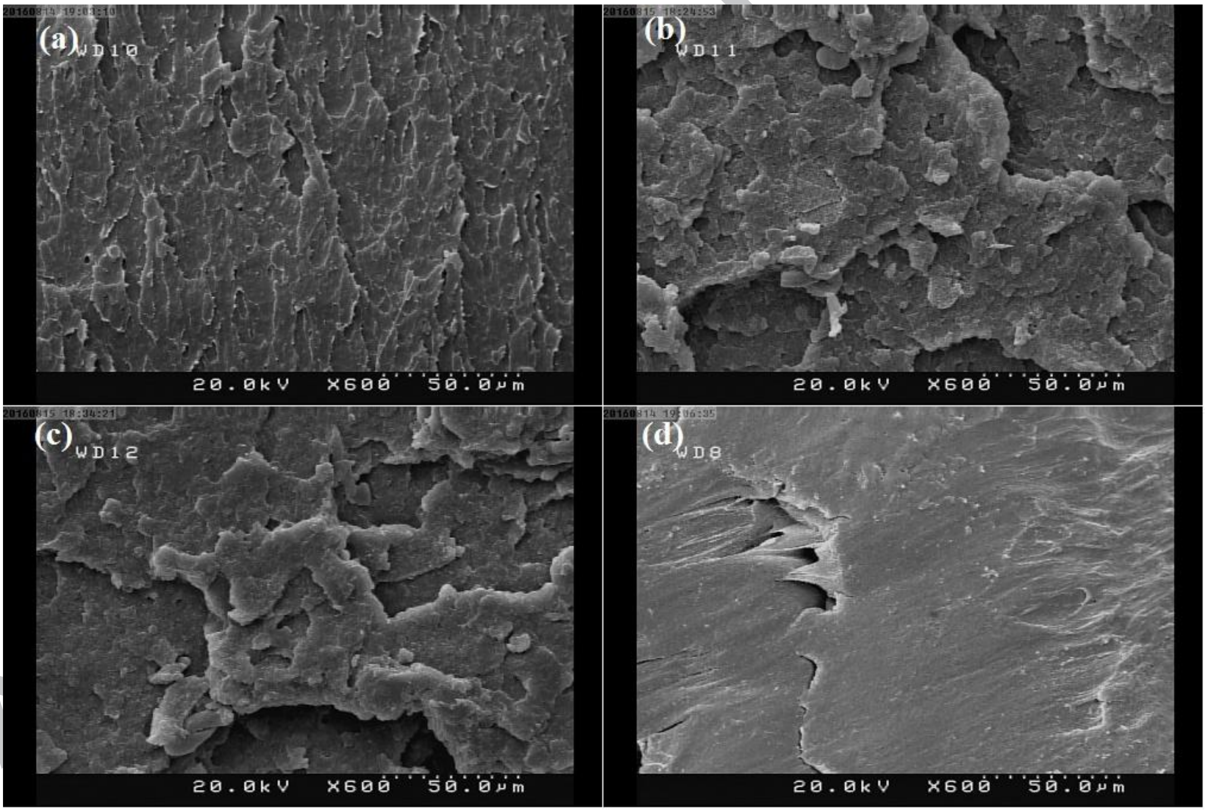

Fig. 8 SEM image from fracture surface after tensile testing for the joint fabricated via (a) 1 pass FSW without nanosilica addition (b) 1 pass FSW with nanosilica addition (c) 2 pass FSW with nanosilica addition (d) 3 pass FSW with nanosilica addition

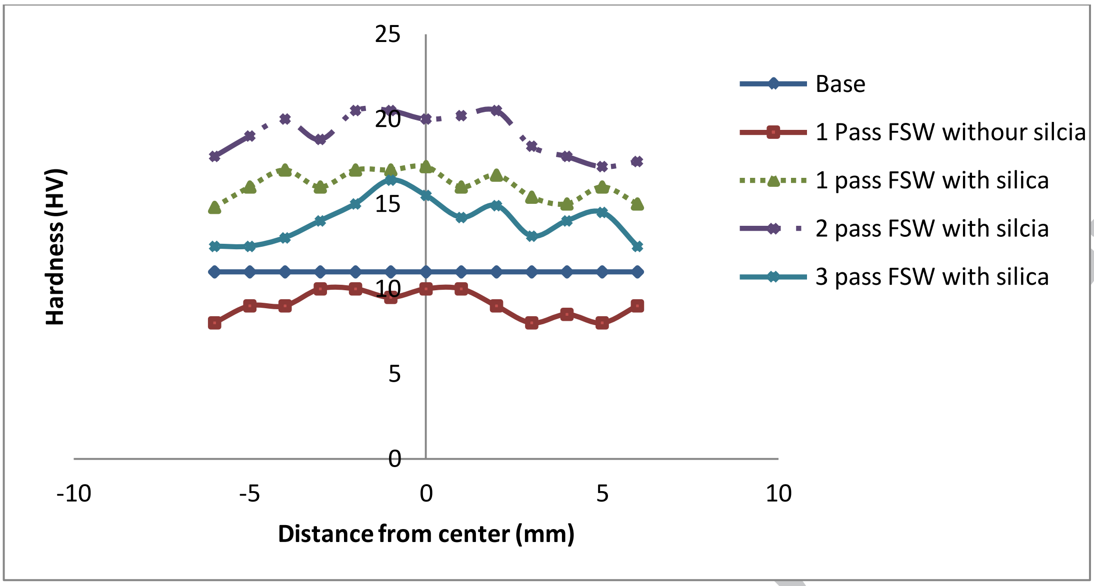

Fig. 9 Hardness profile of the joints fabricated by different pass numbers and silica addition

Tables

Table 1 Properties of ABS material

Tensile strength (MPa)	Hardness (HV)	Thermal expansion coefficient (m/mK)	Melt point (°C)	Density (g/cm^3)
43	11	73.8×10^{-6}	160	0.905