A Novel Technique for Keyhole-Less Reinforced Friction Stir Spot Welding of Polyethylene Sheets

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Received: 4 July 2019, Revised: 30 October 2019, Accepted: 9 November 2019

Abstract: Two main problems exist with friction stir spot welded joints; remaining of a keyhole after welding and low strength of joints. In this paper, a novel method is proposed to address both problems in a simple and cost-effective way. This process is named “Reinforced Friction Stir Spot Welding” or “RFSSW” which is based on recently introduced “TFSSW” process. SiC powder was added to the friction stir spot joints of polyethylene sheets with a thickness of 3 mm. First, the sheets were welded using conventional friction stir spot welding tool with a cylindrical pin. Then, the keyhole was filled with SiC powder. In the second stage, for stirring of SiC particles in the nugget and refilling the keyhole as well, a pinless tool was utilized. A homogenized distribution of reinforcing powder was obtained in the nugget. The effect of welding parameters including refilling tool shoulder diameter, refilling dwell time, and refilling tool rotational speed were evaluated in both TFSSW and RFSSW. In both processes, the refilling tool shoulder diameter was the most effective parameter. The strength was increased by 40% applying TFSSW and a further increase by 20% was obtained by reinforcing. Optimized parameter levels are refilling tool shoulder diameter of 24 mm, refilling tool rotational speed of 800 rpm, and refilling dwell time of 50s which result in shear strength of 1079 N.

Keywords: Friction Stir Spot Welding, Polyethylene, Refilled Joint, Reinforced Joint, SiC Powder

Reference: Sajed, M., and Seyedkashi, S.M.H., “A Novel Technique for Keyhole-Less Reinforced Friction Stir Spot Welding of Polyethylene Sheets”, Int J of Advanced Design and Manufacturing Technology, Vol. 12/No. 4, 2019, pp. 47–56.

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1 INTRODUCTION

Friction stir welding (FSW), as a solid-state welding process, can be applied on a wide range of materials including lightweight metals, steel and polymers [1]. Friction stir spot welding (FSSW) is a variant of main process which is used to make spot joints. The difference is that there is no traverse motion of the welding tool in spot welding. There are two drawbacks that limit the application of FSSW namely keyhole and low strength. The first one occurs because of the pin of the welding tool, and the other one because of the limited joint area. Thus, although FSSW is an interesting process both in industry and research, these drawbacks limit its application. Thus, it is important to overcome these limitations and also widen the range of material that this process can be applied to achieve an industrial process. Although many efforts have focused on elimination of the keyhole in FSSW, however, most of them are so costly and complicated. On the other hand, many authors focused on the application of this technique on aluminium alloys while it is important to discuss the application of this process on wider range of materials and especially polymers. This becomes more important considering the recent interest in utilization of polymers due to their advantages such as lightweight, low cost, corrosion resistance and etc.

Reimman et al. [2] introduced keyhole closuring to achieve refilled joints. In this process, a plug same to the welding material was used to refill the joint. Dong et al. [3] studied aluminium and galvanized steel joints. They used a well-known refilling tool to achieve joints without keyhole. The application of this tool on a conventional milling machine is impossible and fabrication of this tool is complicated, too. Uematsu et al. [4] utilized a tool with a moveable pin to eliminate the keyhole. Utilization of this special tool needs a special machine. Dourandish et al. [5] applied protrusion friction stir spot welding to eliminate the keyhole. In this process a protrusion with a height of less than 1 mm is produced and then, the welding takes place using a pinless tool. The authors reported that superior strength was achieved in comparison with conventional FSSW. Sajed [6] introduced a Two-Stage Refilling Friction Stir Spot Welding (TFSSW) which uses two separate tools in welding and refilling steps. This process uses simple tools and can be performed on a conventional milling machine. Jeon et al. [7] fabricated graphite/Al MMC spot joints. They applied graphite/water colloid on the upper sheet during spot welding. In addition, this process was successful in the fabrication of composite joints, but the process itself is costly, needs some kind of shield to keep the colloid on the sheets, and is not a clean process. Hong et al. [8] applied carbon Nano-particles on aluminium sheets before spot joining using a Nano-particle deposition system. The process was successful in production of reinforced joints and is a clean process, but Nano-particles deposition system needs special machines and instruments that make it so costly. Bilici and Yukler [9] concluded that the dwell time, tool rotational speed and plunge depth affect the nugget formation and strength of spot joints of HDPE sheets. They also indicated that melting occurs in the vicinity of tool pin. Friction stir welding and friction stir spot welding parameters were optimized using L9 orthogonal array and Taguchi method for high-density polyethylene sheets [10-11]. Bilici et al. [11] reported the optimized fracture force as 3315 N for spot joints of HDPE with a thickness of 4mm, which were welded by friction stir technique. Bozkurt et al. [10], [12] believe that tool rotational speed is the most important parameter, while Bilici et al. [11], [13] introduced the dwell time as the main parameter, and Rezaee Hajideh et al. [14] introduced the pin shape as the most influential parameter. Aghajani Derazkola et al. [15] studied feasibility of friction stir welding (FSW) of poly (methyl methacrylate) sheets experimentally along with application of a thermomechanical simulation. Khodabakhshi et al. [16] studied dissimilar welding of aluminium/polymer. They suggested interfacial chemical reaction and secondary Van der Waals bonding as the main joining mechanisms. Singh et al. [17] studied the effect of reinforcement with Fe powder on HDPE and LDPE dissimilar sheets friction stir welding. They reported increase in mechanical properties of the base material with the reinforcement. Gao et al. [18] introduced the multi-walled carbon nanotubes (MWCNTs) into the HDPE/ABS joints and reported 65.3% higher strength compared to the base HDPE.

As mentioned above, keyhole and low bonding area lead to low-strength joints. Although there are several reports of friction stir welding of polyethylene sheets and also some reports of enhancing the strength of FSWed polyethylene sheets in the literature, however, there is no report concerning with keyhole-less spot joining of polyethylene sheets nor a method to enhance the strength of spot joints in polyethylene sheets and just several efforts have been done to introduce reinforcing particles to spot welds in metal sheets in order to achieve stronger joints. These techniques require a considerable pre-process operation. In this research, a novel method entitled Reinforced Friction Stir Spot Welding (RFSSW) is introduced based on Two-Stage Friction Stir Spot Welding (TFSSW). In this process, a two-stage process is applied. The first step is conventional Friction Stir Spot Welding (FSSW). Then, the keyhole is filled with a reinforcing powder. Finally, a pinless tool is used to refill the keyhole and distribute the reinforcing powder in the nugget. According to the literature, the joint diameter determines its strength [19]. In spot joints, the bonding area cannot be increased, however, application of this process makes it possible to add reinforcing powder to the nugget before refilling step which can compensate the effect of the low bonding area. The new process was applied to produce spot joints in polyethylene sheets which were reinforced with SiC powder. These joints are stronger and have no keyhole, too. The main advantage of RFSSW is that it is a very simple process and can be easily performed on a conventional milling machine with simple tools. It is also a clean process because there is no need for application of colloids or water. This process can be used to fabricate composite joints by using metals or polymers as parent material with any kind of reinforcing particles. Thus, the main novelties of the present study are as follows:

- Introduction of a novel two-stage process to eliminate the keyhole and simultaneously reinforce the spot joint.
- Producing a spot joint without a keyhole in polyethylene sheets (TFSSW) and also reinforcing the spot joint of polyethylene sheets with SiC particles.
- An investigation on the effect of process parameters in both TFSSW and RFSSW of polyethylene sheets.

2 MATERIALS AND METHODS

Polyethylene sheets with a thickness of 3 mm were used as the base material. The schematic of the RFSSW process is presented in "Fig. 1".

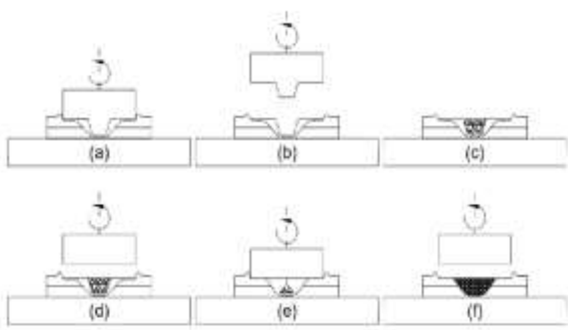

Fig. 1 Schematic illustration of the RFSSW process.

As can be seen, this process is performed with two distinct tools. The first step is just like conventional FSSW. A rotating tool with a cylindrical pin penetrates two overlapped sheets. Then, heat is generated as a result of high friction force plasticizing the nugget material resulting in a joint ("Fig. 1(a) and (b)"). A keyhole remains on the weld nugget which would be filled with reinforcement powder; see "Fig. 1 (c)". In this study, SiC powder with an average grain size of 10 µm was used as the reinforcing particles. To distribute reinforcement powder in the weld nugget, a pinless tool is utilized which refills the keyhole, simultaneously. This tool plunges in the weld nugget and rotates on it resulting in material flow. This accomplishes both powder distribution and refilling; see "Fig. 1(d) to (f)". It should be noted that for polymeric materials, local melting occurs, too.

As aforementioned, two tools are needed for RFSSW: welding tool and refilling tool. In this approach, tools were machined from a mild steel bar. A welding tool and three refilling tools with different shoulder diameters were prepared as shown in "Fig. 2". For metals, concave tool shoulder geometry is usually used in order to enhance joint strength [19]. However, in this study, preliminary tests indicated that performance of flat shoulder is better than concave one in the case of polyethylene sheets. So, the flat shoulder was used for all tools.

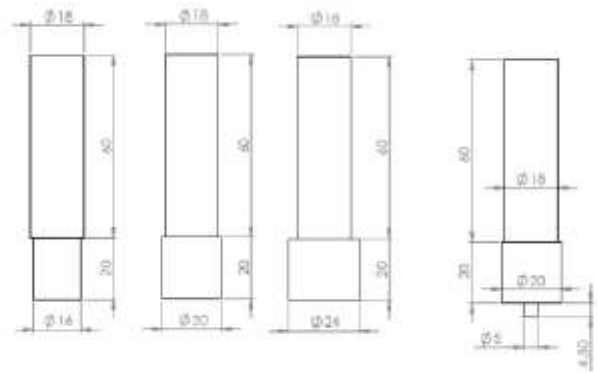

Fig. 2 Welding tools.

To scientifically design the experiments for the refilling process, the Taguchi method with an L9 orthogonal array was applied. Refilling parameters are summarized in "Table 1".

Table 1 Welding parameters

No.	TR*(rpm)	DW**(s)	RTSD***(mm)
1	800	50	16
2	800	70	20
3	800	100	24
4	1250	50	20
5	1250	70	24
6	1250	100	16
7	1600	50	24
8	1600	70	16
9	1600	100	20

* Tool Rotational speed
** Dwell time
*** Refilling Tool Shoulder Diameter

First, all specimens were welded with the same parameters. This step was done with 800 rpm tool rotational speed, 30s dwell time and 5 mm tool plunge depth. Amstar HA250 tensile test machine with a Zwick controller was used to evaluate the tensile-shear strength of the welded specimens.

All specimens were tested with a constant speed of 0.5 mm/s. For FSSWed specimens without refilling and reinforcing, the average tensile shear strength of 733 N was obtained.
For each specimen, signal to noise ratio (S/N) can be calculated using the following equation:

$$\frac{\mathrm{S}}{\mathrm{N}} = -10\ \log\left(\frac{1}{\mathrm{m}}\sum_{i=1}^{m} 1/T_i^2\right) \quad (1)$$

where, m is the number of tests and T_i is the shear strength of the i-th specimen. Analysis of variance (ANOVA) was applied to determine the contribution of studied parameters on the joint strength. It is a well-known statistical method to determine the relative importance among the effective parameters. The total sum of squared deviations (S_T) should be calculated by "Eq. (2)":

$$S_T = \sum_{i=1}^{n}(\alpha_i - \alpha_m)^2 \quad (2)$$

where, n is the number of experiments, α_i is the mean S/N for the i-th experiment and α_m is the total mean of S/N ratios. In this study, n is nine because the L9 orthogonal array was used. The contribution percentage is the sum of squared divisions due to each design parameter (S_d) divided by the total sum of squared deviations (S_T). Another method is application of F-test. For this, the ratio of the mean of squared deviations (S_m) to mean squared error is calculated. S_m is the ratio of sum of squared deviations (S_d) to the number of degrees of freedom for each design parameter. The last step is prediction and verification of the optimal level of design parameters. Estimated S/N ratios can be calculated as [13]:

$$(S/N)_e = (S/N)_m + \sum_{i=0}^{u}\left(\overline{(S/N)}_i - (S/N)_m\right) \quad (3)$$

where, $(S/N)_e$, $(S/N)_m$ and $\overline{(S/N)}_i$ are the estimated mean and the total mean, and mean at optimal level signal to noise ratios, respectively. u is the number of the main design parameters which is three in this study. Minitab statistical software was implemented for Taguchi analyses. Joint diameter can be used as an index of welding strength. Joint diameter is the linear distance of two crack tips in two sides of the keyhole [19]. To measure joint diameters, joints were cross-sectioned through the center of welds and measurement was applied using OM images, see "Fig. 3".

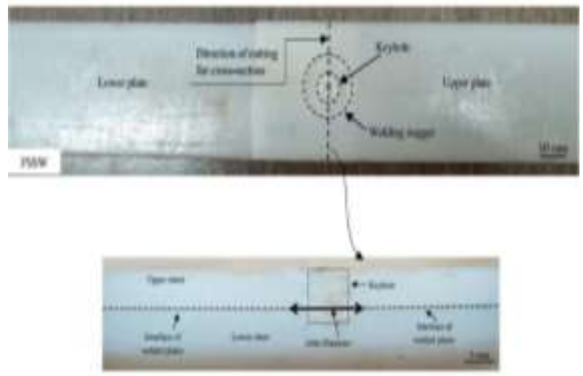

Fig. 3 Cross-section of conventionally welded specimen.

3 RESULTS

In this paper, two kinds of joints are analysed; keyhole-less joints and reinforced joints. The aim is to introduce a new method of production of reinforced friction stir spot welds and analyse of effects of main parameters on mechanical properties of welded joints. The results of experiments are summarized in "Table 2".

Table 2 Strength of joints, joint diameters, and signal to noise ratios

No.	SS[I](N)	SSR[II](N)	(SSR/SS)%	JDT[III](mm)	JDR[IV](mm)	$(S/N)_T$[V](dB)	$(S/N)_R$[VI](dB)
1	895	949	6.03	13.30	15.91	59.05	59.55
2	724	790	9.12	12.57	14.25	57.19	57.95
3	924	907	-1.84	13.85	16.56	59.31	59.15
4	560	735	31.25	6.81	9.23	54.96	57.33
5	544	826	51.84	11.43	12.38	54.71	58.34
6	661	693	4.84	13.29	13.92	56.40	56.81
7	1019	1021	0.2	13.62	15.58	60.16	60.18
8	590	781	32.37	13.22	11.16	55.42	57.85
9	384	337	-12.24	11.64	12.60	51.69	50.55

I. Shear strength of TFSSWed specimens
II. Shear strength of RFSSWed specimens
III. Joint Diameter of TFSSWed specimens
IV. Joint Diameter of RFSSWed specimens
V. Signal to Noise ratio of TFSSWed specimens
VI. Signal to Noise ratio of RFSSWed specimens

According to “Table 2”, the largest difference between the strength of TFSSWed and RFSSWed specimens stands for test No. 5. The strength of the RFSSWed specimen is 826 N while that is 544 N for TFSSWed one. This means 51.84% increase of strength by reinforcement. On the other hand, for test No. 9, shear strength of TFSSWed specimen is 384 N while it is 337 N for RFSSWed one, which means decreasing of strength by 12.24% with reinforcement. For test No. 3 and test No. 7, shear strength of TFSSWed and RFSSWed specimens are almost equal. Shear strength of RFSSWed sample 7 is the highest which is 1021 N.

Reinforcement resulted in higher strengths for six experiments, lower strength for one experiment and similar strength for two tests. The average increase in those six tests is 22.58%. Keeping in mind that for the highest strength (test No. 7), performance of TFSSW and RFSSW are the same, it can be concluded that optimization of parameter levels is more important than reinforcement to enhance a higher strength, for the material and parameters that were studied in the current research.

TFSSW or two-stage refilling friction stir spot welding is a process to produce keyhole-less spot joints using a friction stir welding process [6]. One important issue is to find the contribution percentage of each parameter affecting the joint strength. It is clear that all parameters do not have the same significance level. According to results obtained by Taguchi method, refilling tool shoulder diameter is the most important parameter that affects the weld strength. Tool rotational speed and dwell time are the second and third ones; see “Table 3”.

Table 3 ANOVA results for S/N ratios of TFSSWed specimens

Source	DF	Seq SS	Adj MS	F-Value	P-Value	Contribution
TR	2	17.76	8.882	1.55	0.393	30.55%
DW	2	10.31	5.153	0.90	0.527	17.73%
RTSD	2	18.59	9.294	1.62	0.382	31.97%
Error	2	11.48	5.742			19.75%
Total	8	58.14				100.00%

As can be seen in “Fig. 4”, increasing tool rotational speed from 800 to 1250 rpm leads to a high reduction of joint strength. Further increase in tool rotational speed improves the joint strength, but it is still much lower than what was achieved with the first level. So, the lowest tool rotational speed results in the best joint strength. The Effect of dwell time on joint strength is similar to the tool rotational speed, i.e. the lowest is the best and the middle level is the worst. Although the effect of the refilling tool shoulder diameter is different. Here, the highest level gives the best strength. So, to achieve the highest shear strength which is 1101 N with 61.55 dB signal to noise ratio, 800 rpm, 50s and 24 mm are suggested for tool rotational speed, dwell time and refilling tool shoulder diameter, respectively. Experimental tests confirmed these results so that the real shear strength was obtained 1079 N which is about 2% lower than the predicted value.

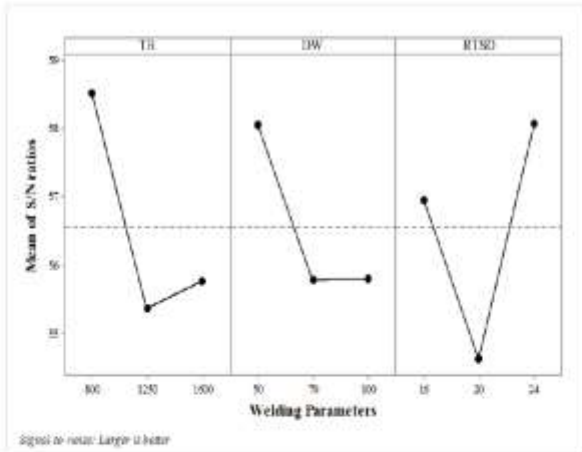

Fig. 4 Main effects plot for S/N ratios of TFSSWed specimens.

The reinforcement of joints is a common method for production of strong joints. There is no report on literature about reinforcement of friction stir spot joints of polymers. In this paper, a novel method has been introduced which can be used to produce reinforced joints from polymers. Although, it can be applied to metals as well.

Table 4 ANOVA results for S/N ratios of RFSSWed specimens

Source	DF	Seq SS	Adj MS	F-Value	P-Value	Contribution
TR	2	10.842	5.421	1.26	0.443	16.97%
DW	2	19.725	9.863	2.29	0.304	30.87%
RTSD	2	24.716	12.35	2.87	0.258	38.68%
Error	2	8.611	4.305			13.48%
Total	8	63.894				100.00%

“Table 4” presents the results of ANOVA for reinforced specimens. Refilling tool shoulder diameter with contribution percentage of 38.68% is the most significant factor that affects the joint strength followed by dwell time and tool rotational speed with 30.87% and 16.97% contribution percentages, respectively. As can be seen, for polyethylene, in spite of metals, tool rotational speed is not the most important factor and its contribution to joint strength is less than dwell time and refilling tool shoulder diameter.

The main effects plot for the mean of S/N ratios of RFSSWed specimens is presented in “Fig. 5”. Just like TFSSW, the lowest tool rotational speed and dwell time and the highest refilling tool shoulder diameter yield the highest shear strength. These results indicate that the effect of tool rotational speed and dwell time on joint strength of reinforced specimens can be considered linear inverse, but this conclusion is not correct for refilling tool shoulder diameter, because its effect is nonlinear and the worst strength is obtained by middle level.

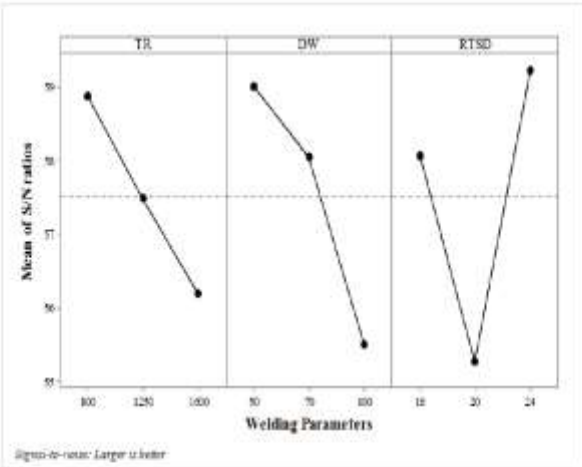

Fig. 5 Main effects plot for S/N ratios of RFSSWed specimens.

4 DISCUSSION

Welding parameters determine the joint strength for a given material. So, the optimal level of these parameters is very important. For Two-Stage Friction Stir Spot Welding (TFSSW), according to previous studies, refilling tool rotational speed and shoulder diameter are the main parameters that affect the joint strength [6]. Dwell time does not have a significant effect on refilled spot joints of aluminium alloys, but it becomes significant when polymers are welded [13]. In this study, three main parameters including the refilling tool rotational speed, refilling tool shoulder diameter and dwell time are considered.

The main problems of FSSW are the remaining of a keyhole after welding and low strength of the welded joint. The former problem occurs because of the pin of the FSSW tool and the latter occurs because the joint takes place at just one point. For polymeric joints, the strength of the joint is even lower because of low strength of the base material. Reinforcement of the joint can be a good solution for this defect. Reinforced friction stir spot welding or RFSSW is a method of spot joining based on conventional friction stir spot welding that can eliminate both aforementioned defects. Conventional FSSW is the first step, and the keyhole is filled with reinforcement powder after that. Nugget is stirred by a pinless tool which propagates reinforcing powder uniformly in the nugget and refills it, as well. The result is a keyhole-less and reinforced joint which is stronger than conventionally FSSWed joint. Figure 6 shows the refilled specimens with and without reinforcement powders.

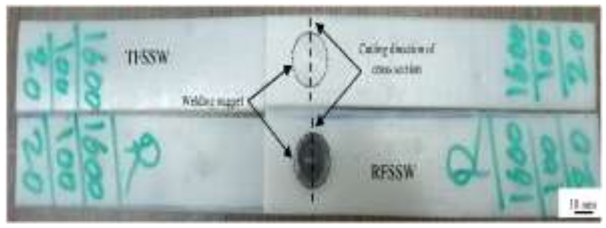

Fig. 6 TFSSWed and RFSSWed specimens.

Figure 7 shows a comparison of shear strength and joint diameter of TFSSWed and RFSSWed specimens.

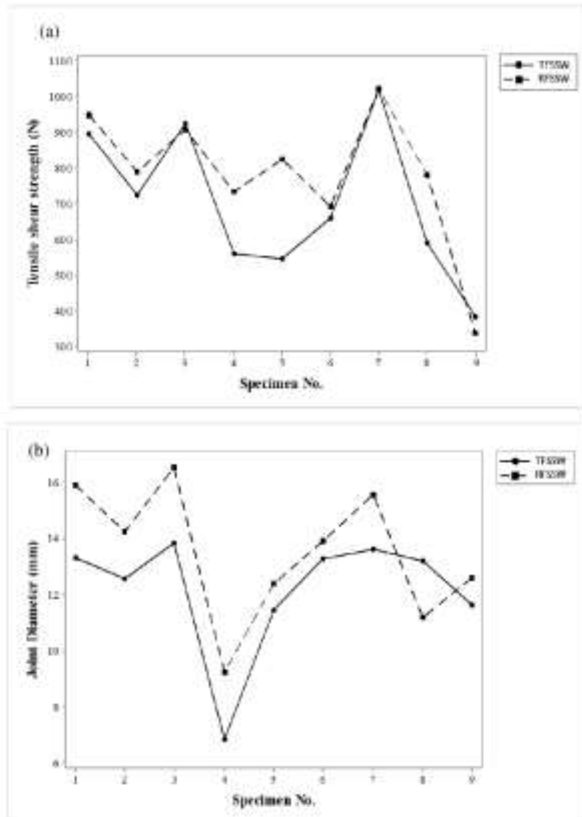

Fig. 7 Comparison of TFSSWed and RFSSWed specimens: (a): tensile shear strength and (b): joint diameter.

It is clear that reinforcement resulted in higher strength, for most welding parameter levels. Joint diameter is defined as a linear distance of separation points in weld cross-section, see "Fig. 3". This figure shows the cross-section of a welded sample after the first step. As can be seen, keyhole is created due to pin penetration. Joint diameter can be considered as an index of joint strength [19]. Joint diameter for conventionally welded specimen, i.e. after first step, is 8.04 mm. This diameter increases approximately1.5 times by refilling. It could be said that in TFSSW and RFSSW, more heat is generated during the second step compared to conventional FSSW which melts more material and results in a bigger joint diameter.

As can be seen in “Fig. 7(b)”, all reinforced specimens except specimen No. 8, have bigger joint diameters in comparison with refilled ones. Friction between SiC powder and steel results higher forces compared to polymer-steel friction which induces more heat in the nugget. This may be the reason for bigger joint diameters of reinforced joints compared to refilled ones.

Higher shear strength of reinforced specimens compared to simply refilled ones can be explained by failure morphology, too. As can be seen in “Fig. 8”, shear failure was occurred for the TFSSWed specimen while failure morphology of reinforced specimen was nugget pull out type. Stronger joints failure mode is nugget pull out rather than shear type [19]. So, it could be concluded that addition of SiC powder in nugget during the refilling process changes the failure type from shear mode to nugget pull out which means that reinforcement makes joints stronger. This can be related to changing nuggets to polymer-based composites by the addition of SiC powder which makes nugget material stronger.

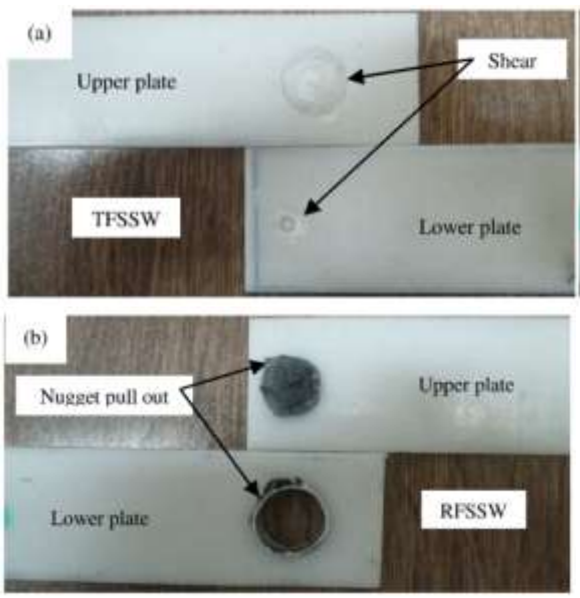

Fig. 8 Upper and lower sheets after the tensile test: (a): TFSSWed specimen and (b): RFSSWed specimen.

If the welding parameters are not chosen correctly, refilling would not take place with strong bonding. Figure 9(a) presents the cross-section of the TFSSWed sample No. 2. In the figure, it is evident that the filled material was removed from the keyhole during the polishing process which indicates that there was not a good bonding between the filling material and the keyhole wall. This sample was welded with a refilling tool rotational speed of 800 rpm, refilling dwell time of 70 s, and refilling tool shoulder diameter of 20 mm. The shear strength is 724 N which is very close to the strength of the conventionally welded sample (733 N). A fully filled keyhole could be obtained using proper parameters. Figure 9(b) presents the cross-section of TFSSWed sample No. 7 which was welded with a refilling tool rotational speed of 1600 rpm, refilling dwell time of 50 s, and refilling tool shoulder diameter of 24 mm. The shear strength is 1019 N. Although there is a small zone with a weak bonding at the bottom of the keyhole, it could be concluded that the keyhole was fully refilled.

The refilling process is depended on the heat generation. All three parameters affect heat generation during the refilling process. Higher tool rotational speed, dwell time, and tool shoulder diameter result in more heat input. The tool rotational speed in specimen No. 7 is twice of that in sample No. 2 (1600 vs. 800 rpm), the tool shoulder diameter is also bigger (24 vs. 20 mm), however, the dwell time is shorter (50 vs. 70 s). Thus, better refilling is the result of higher heat input which was obtained with a higher tool rotational speed and bigger tool shoulder diameter. Better refilling resulted in bigger joint diameter and bigger zone which is subjected to stress in the tensile-shear test. This is the reason for higher strength of specimen No. 7.

A triangle filling pattern was detected in this process. The filling starts from the top of the keyhole and continues to the bottom in the case of the presence of enough heat input. This pattern could be seen in the cross-section of sample No. 1, in both TFSSWed and RFSSWed specimens, see “Fig. 9(c)” and “Fig. 10(b)”. Higher strength is expected with refilling due to bigger joint diameter and stress carrying area. However, several refilled samples have lower strength in comparison with the conventionally welded sample. Figure 9(d) presents the cross-section of sample No. 4 which was refilled with a tool rotational speed of 1250 rpm, dwell time of 50 s, and tool shoulder diameter of 20 mm. The tensile shear strength is 560 N. Comparing the refilling parameters of sample No. 4 and No. 7 (the specimen with the highest strength), the dwell times are the same. However, the tool rotational speed and shoulder diameter are higher which indicate that these two parameters have more influence on heat production, refilling, and joint strength. Low heat input restricts the material flow and results in improper filling. In the refilling stage, some cracks start to grow due to the weak bonding of material in the nugget which is presented in “Figs. 9 (b) and (d)”. In the case of presence of enough heat input, there is no downward crack growth which is evident in “Fig. 9 (b)”. However, with less heat input, the crack growth continues from the surface of the nugget to the keyhole wall as it is presented in “Fig. 9 (d)”, which weakens the joint. Thus, it could be concluded that the lower strength of several refilled specimens in comparison to the conventionally welded specimen is due to this downward crack growth.

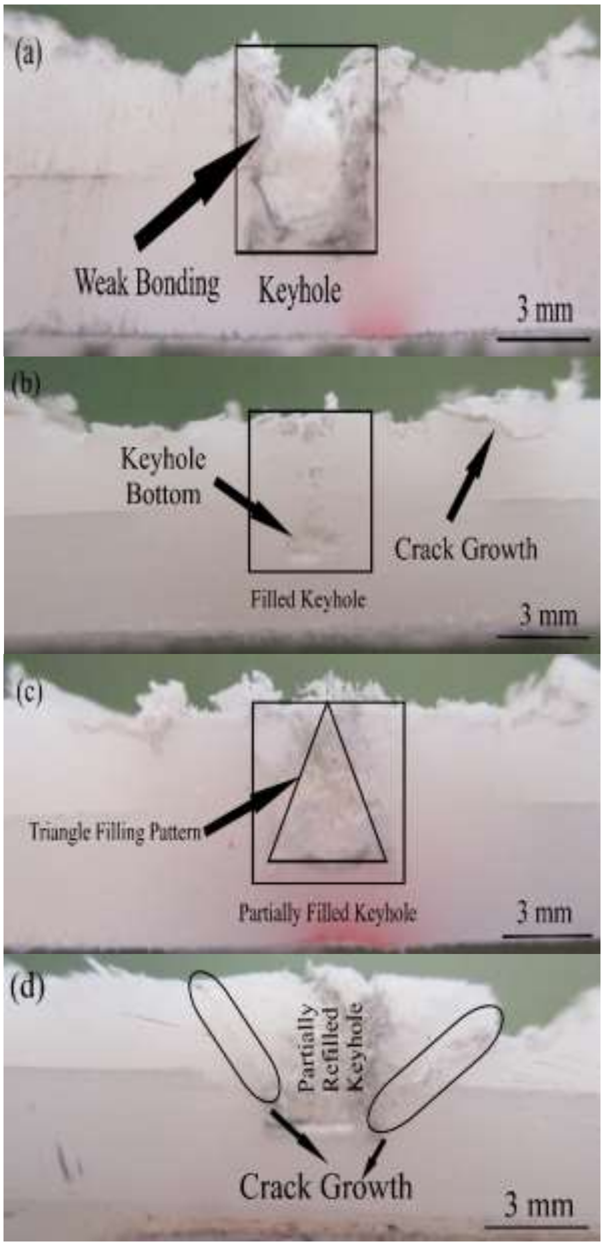

Fig. 9 Cross-section of TFSSWed specimens: (a): test No. 2, (b): test No. 7, (c): test No. 1, and (d): test No. 4.

In the present study, the keyhole was used as a container to add SiC particles to the welding area. Figure 10(a) presents the cross-section of RFSSWed sample No. 7. The keyhole was refilled except the bottom. The SiC powder was distributed well in the nugget. This specimen was the strongest joint with the biggest joint diameter. The shear strength and the joint diameter are 1021 N and 15.58 mm, respectively. As mentioned before, the joint diameter was defined as the linear distance of two separation points in the right and left sides of the keyhole which are pointed in “Fig. 10(b)” as crack tips. The refilling parameters were refilling tool rotational speed of 1600 rpm, refilling dwell time of 50 s, and refilling tool shoulder diameter of 24 mm. The above-mentioned triangle material flow was also presented in “Fig. 10(b)”.

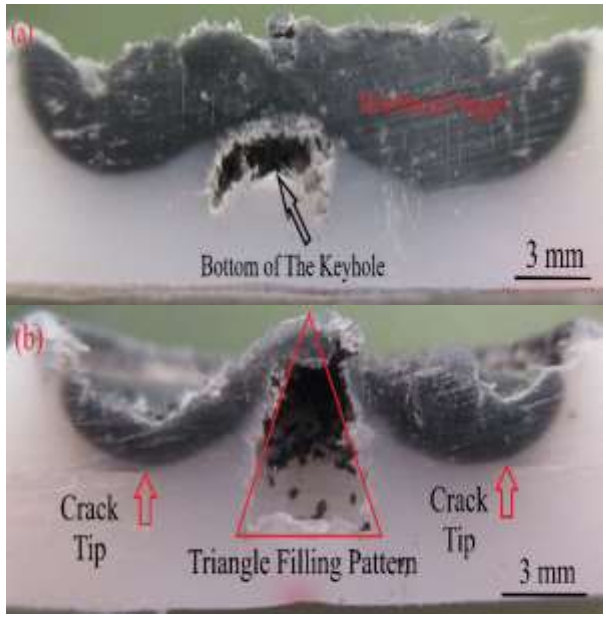

Fig. 10 The cross-section of the RFSSWed samples: (a): test No. 7 and (b): test No. 1.

The success of reinforcement is dependent on heat input. Test No. 1 which was refilled with a refilling tool had the rotational speed of 800 rpm, refilling dwell time of 50 s, and refilling tool shoulder diameter of 16 mm. Lower tool rotational speed and smaller tool shoulder diameter result in lower heat input which restricts the refilling and reinforcing processes. In the refilling process, the SiC particles move upward, first. Then, they penetrate the upper plate and then, in the lower one. Penetration to the lower plate is dependent on the heat input. By enough heat input, the penetration to the lower plate takes place (see “Fig. 10(a)”) while penetration is limited to the upper plate when the heat input is insufficient (“Fig. 10(b)”).

4 CONCLUSION

In this study, a novel method called Reinforced Friction Stir Spot Welding (RFSSW) is proposed to eliminate the keyhole of FSSWed specimens and increase joint strength. The main results of this research are as follows:
- By selection of appropriate parameter levels, Two-Stage Refilled Friction Stir Spot Welding (TFSSW) can improve the joint strength by 40%, approximately, in addition to keyhole elimination.

- For TFSSW, the contribution order of welding parameters is refilling tool shoulder diameter, refilling tool rotational speed and dwell time. Optimized parameter levels, resulting in shear strength of 1079 N for the current research are 24 mm, 800 rpm and 50s, respectively.
- For RFSSW, the contribution order of welding parameters is refilling tool shoulder diameter, dwell time and refilling tool rotational speed.
- In most cases, reinforcement increased joint strength. The average increase in RFSSWed specimens compared to TFSSWed specimens is by 20%, approximately. It should be noted that welding parameters have a stronger effect than reinforcement on joint strength.
- Reinforcement not only makes nugget composite and changes failure mode of joints but also makes joints bigger, inducing more frictional heat and leads to stronger joints

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