



Effect of Tool Rotational Speed on the Tensile and Microstructural Properties of Friction Stir Welded Different Grades of Stainless Steel Joints

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ABSTRACT

Friction stir welding is a relatively new solid state joining process, which is suitable for welding similar and dissimilar materials. The present research work concentrates on the effect of tool rotational speed on the tensile, microstructural properties and microhardness of the friction stir welded joints of different grades of austenitic stainless steel sheets. Four different tool rotational speeds are used in the experimentation while the other process parameters like traversing speed and the tool tilt angle are kept constant. The tensile testing, micrography and microhardness measurements were carried out in the welded samples. It is observed from the results of tensile testing that the joint made at the tool rotational speed of 1320 rpm has the maximum strength among the experimented speeds. The measured microhardness values at heat affected zone and parent metal zone have shown higher hardness than the weld zone. Fine and equi-axed grains are observed in the welded region at all experimented speeds with a negligible amount of transformation of austenite into martensite. These results have impact on the development of welding procedure for dissimilar stainless steel friction stir welding process.

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1. INTRODUCTION

Friction stir welding (FSW) is a non-traditional welding process of joining metals and alloys using the heat generated by the friction between the non-consumable tool and the work pieces. FSW produces a joint of improved properties and performance, lower distortion in the welded part when compared to the conventional welding processes [1]. Exhaustive studies have been carried out on FSW of lightweight materials especially aluminium alloys [1–9] and magnesium alloys [10, 11]. Very limited work has been carried out to investigate the FSW of steel [12], Zinc [13], Copper [14], Titanium [15] etc. Recently, the investigation on the welding of Metal matrix composite materials [16, 17], polymer matrix composite material [18–20], polymers [21] etc., have been focused. Few researchers have attempted to study the weld characteristics of FSW of different grades of the same material like AA2024-T3 and

AA5754-H22 [22], dissimilar materials joint like aluminum-magnesium [23], aluminum-stainless steel [24], aluminum-titanium [25] etc.

Design and process parameters play a very important role in quality characteristics of joints formed. Especially, the design of tool used for creating the friction and stirring action is very important factor. Different types of tool pin profiles, shoulder types and shoulder diameters were experimented to study their effect on the weld quality. Subramaniam et al. [3] have used different pin profiles to study the tensile strength of the joints produced by the FSW. From the investigation, it was concluded that the square pin profile tool produced higher strength as compared to triangular and circular profiles due to the pulsating action during welding. Apart from the investigation on the effect of different pin profiles on the efficiency of the welded joints, some researchers have attempted innovative tools for FSW. Kumari et al. [26] used newly designed counter-rotating twin tool and found that the generation of heat was much higher than the

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conventional tool which causes more plastic deformation in the stirred zone. Li et al. [27] utilized a tool configuration known as bobbin tool which consists of two rotating shoulders connected by a probe. The lower shoulder which acts on the lower surface of the parent material confines the process loads within the tool so that the joint with highest yield strength and ultimate tensile strength (UTS) was produced.

Rajakumar et al. [1] have reported that the maximum yield strength of 315 MPa, UTS of 373 MPa and 77% of joint efficiency was obtained with the rotational speed of 1400 rpm and welding speed of 60 mm/min in butt FSW of Al alloy. Campanile et al. [2] have shown that the highest values of UTS and yield strength are attained with high weld pitch and plunging depth. Sadeghi et al. [4] have used non destructive methods, Acoustic emission (AE) and Ultrasonic waves, for evaluating the residual stresses formed during FSW. Guoqing Wang et al. [5] have stated that the traditional non-destructive methods may not reveal the defects properly in FSW and so performed phased array ultrasonic testing (PUAT) to effectively identify the weld defects.

Alvand et al. [6] have studied the microstructure of the friction stir welded joints and found that the joints have exhibited the hard welded zones due to the formation of fine equiaxed grains structures in the stir zone. Also, they have concluded that the hardness of the stir zone was reduced when the tool rotational speed was increased. But, Langari et al. [7] have expressed from the investigation that there is no significant change in hardness of the stir zone with increase in tool rotational speed. Villegas et al. [9] have carried out numerical simulation to investigate the distribution of temperature generated in FSW using ANSYS software and showed that the measured and simulated peak temperature is reasonably correlated with 5 % variation. Forcellese et al. [11] have found from their measurements that the vertical force during welding was increased when decreasing the tool rotational speed and increasing the tool traversing speed. Huang et al. [23] have proposed a new design method for designing the high depth-to-width ratio FSW tools and summarized that the heat affected zone (HAZ) is reduced at a high depth-to-width ratio FSW. In order to get sound welds in thicker and high strength materials, Fonda et al. [15] have suggested that pre heating of weld surfaces by external source is necessary. Daryadel et al. have investigated the effect of process parameters and the weight percentage of nanoalumina on the FSW of polymeric nanocomposite [20] and reported that there is no significance effect of process parameters on mechanical properties of the joints made. Luo et al. [28] used hybrid welding process in which FSW was carried out along with the electric current heating. It was concluded that the current intensity influences the

welding seam shape features. Zhang et al. [29] have performed under water FSW (UWFSW) of Al alloy to pure Cu. The observations made in UWFSW in comparison with FSW in air are: decreased peak temperature, shortened thermal cycle time, improved tensile strength, controlled grain growth, less distortion and decreased plasticity. The intermetallic compound (IMC) layer formed is much thinner than that is formed in conventional FSW process.

From the literature survey, it is observed that very little information regarding FSW of stainless steel is available and there is a need for exploring the effect of different parameters on the quality of the welded joints. Hence, this investigation has been focused on the effect of tool rotational speed on the tensile, microstructural properties and microhardness measurement of the FSW joints of two grades of austenitic stainless steel sheet.

2. EXPERIMENTAL WORK

2. 1. Material Used Austenitic stainless steel AISI 304 and AISI 316 plates of 75 x 75 x 2 mm were used in this study. The chemical composition and mechanical properties of both the material are tabulated in Tables 1 and 2.

2. 2. FSW Tool The non-consumable cylindrical shaped tool without pin was used for FSW process. The dimensions of the tool are 8 mm shoulder diameter and 60 mm length. Tungsten Carbide is used as a tool material and it is hardened to 48-50 HRC.

2. 3. Experimental Setup The dissimilar butt welding experiments were performed using a conventional vertical milling machine. Villegas et al. [9] have experienced higher heat generation in the advancing side (AS) than that of retreating side (RS) during FSW of aluminium alloy. This effect has

TABLE 1. Chemical composition of two grades of stainless steels

Element	C	Mn	Si	Cr	Ni	Mo
Wt AISI 316	0.020	1.501	0.471	16.57	10.09	2.051
% AISI 304	0.046	1.288	0.212	18.32	8.052	0.213

TABLE 2. Important mechanical properties of two grades of stainless steels

Property	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	%Elongation
AISI 316	205	510	41.00
AISI 304	261	528	42.75

significant influence on welded joints when two dissimilar materials having different plasticizing temperature; but, it has no effect when the same material of different grades are used. In this experimentation, the sheet of AISI 316 was kept in the AS and AISI 304 in the RS of the rotating tool. In order to fix the values of tool rotational speed and tool traversing speed, trial experiments were carried out at initial tool rotational speed of 600 rpm and varying the traversing speed until the successful weld was made. In case of failure in getting a sound weld, either the rotational speed is increased or decreased or traversing speed is increased or decreased till the first good weld was obtained. From the trial experiments, the expected weld free from visual defects were obtained at the tool rotational speed of 930 rpm and tool traversing speed of 32 mm/min. The selected tool rotational speeds for further experimentation were 930, 1100 and 1320 rpm and other parameters like tool traversing speed (32 mm/min) and Plunge depth (1.8 mm) were kept constant. The tilt angle of the tool was 0°. Figure 1 shows the experimental set up of FSW process.

After welding process, the specimens (three test coupons for each speed) for tensile testing were prepared according to the American Society for Testing and Materials (ASTM). The specimens were cut to the required standard dimensions as per ASTM E8 from the welded sheets using wire electrical discharge machine (WEDM). Tensile tests were conducted in 50 kN universal tensile testing machine with the traversing speed of 2.5 mm/min. After the welding process, the joints were cross sectioned at right angle to the welding direction for microstructural analysis and microhardness measurements. The cut sectioned portions were polished by standard methods, etched with Glyceregia solution and microstructures were observed using optical microscope. The Vickers microhardness measurements were made in 3 samples at 3 different positions in weld nugget zone (NZ) or thermo mechanically affected zone (TMAZ), heat affected zone (HAZ) and parent materials nearer to the HAZ using the Vickers microhardness testing machine with a 1 Kg load and the average values were computed.



Figure 1. FSW experimental set up

3. RESULTS AND DISCUSSION

3. 1. Tensile Properties of the Welded Joints

The friction stir welding of dissimilar stainless steel sheets were carried out successfully at all experimented tool rotational speeds. From visual inspection, the welded joints were found to be without any external weld defects. The FSW joints made at different tool rotational speeds are shown in Figure 2.

The specimens after tensile testing are shown in Figure 3. The measured values of yield strength, ultimate tensile strength and % elongation of the welded joints of dissimilar stainless steel sheets are shown in Table 3.

The observed yield strength, ultimate tensile strength and % elongation of the FSW joints at different tool rotational speeds are shown in Figure 4(a-c).

It is observed from Figures 4(a) and 4(b) that the yield strength and ultimate tensile strength is decreased when the tool rotational speed is increased from 930 to 1100 rpm. Eventhough, increase in speed increases the

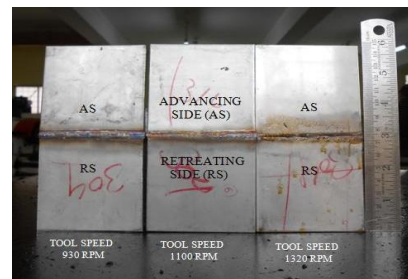


Figure 2. FSW joints at different tool rotational speeds



Figure 3. Specimens after tensile testing

TABLE 3. Measured Tensile properties of FSW joints

S.no	Tool rotational speed (rpm)	Yield strength (MPa)	Ultimate tensile strength (MPa)	% Elongation
1	930	310	364	16.33
2	1100	132	313	5.5
3	1320	417	503	11.33

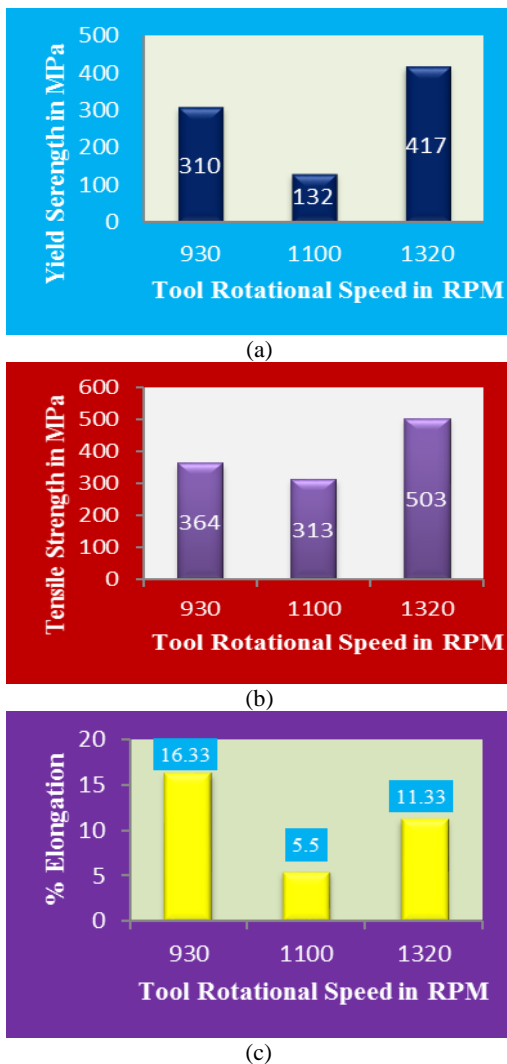


Figure 4. Tensile properties of welded joints at different tool rotational speeds; (a) Yield strength; (b) Ultimate tensile strength; (c) % Elongation

heat generation; while, decrease in the tensile properties may be attributed to the following two reasons: firstly, the local heating of material decreases the coefficient of friction as well as shear stress which in turn decreases the local heat input; secondly, certain amount of heat is absorbed by the latent heat. So, the heat generated due to friction may not be sufficient enough to plasticize the material to produce a sound welded joint.

Further increase in speed from 1100 to 1320 rpm, generates additional heat which produces a soft plasticized region of material around the rotating tool and mixes it due to the intense stirring of the tool at higher rotational speed. Also, the circular shape of the tool has larger contact area which produces more friction and continuous stirring action. Thus, a sound welded joint with higher yield strength and ultimate tensile strength is obtained at 1320 rpm. The %

elongation of the welded joint produced at 1100 rpm is very much lower when compared with the joints made at 930 and 1320 rpm. This may be attributed to the reason that the ultimate tensile strength is much lower at this speed when compared with the values observed at other two speeds, which causes the fracture to occur earlier. In all cases, the fracture has occurred during tensile testing either in the weld line or very close to the weld line.

3. 2. Microstructural Properties of the Welded Joints

The optical microscopic images of microstructures of the parent metals (SS 304 and SS 316) and the friction stir welded regions at three different experimented tool rotational speeds are shown in Figure 5 (a-e). The microstructure of the parent metal (Figure 5 (a, b)) shows the grain flow along the direction of rolling and the austenite grains which are fine and equi-axed which are distributed uniformly. The microstructures of the welded joints at different speeds show, in general, that the constituents of the weld nugget zone are the combination of the two austenitic stainless steels used. Thermo mechanical transformation had taken place in the shoulder region and the orientation of the plastically deformed grains has changed due to the spinning of the tool. The observed microstructure of welded joints indicates that proper mixing of materials in the weld zone without any defects at 930 and 1320 rpm whereas, the microstructure formed at 1100 rpm shows small cracks in the weld zone. The presence of cracks at 1100 rpm may be due to insufficient heat input to plasticize the materials so that the materials are not flown properly and mixed. In stir zone, the softening of the material takes place due to the heat generated at this tool rotational speed and cause thermal stresses to get relieved to some extent. But, the presence of the thermal stresses at HAZ may cause crack to develop due to the uneven thermal stresses between stir zone and HAZ regions. The reduction in yield strength, UTS and % elongation at 1100 rpm may be due to the occurrence of these cracks.

The black spots observed in Figure 5 (c-e) indicate that the transformation of austenite into martensite due to the thermo- mechanical action of the tool. The grains are distorted, finer and uniformly distributed throughout the weld zone due to the stirring action of the rotating tool at all the three experimented speeds.

3. 3. Microhardness Measurement

The observed microhardness of the parent metals SS 304 and SS 316 are 185 and 190HV, respectively. The average microhardness measured in the weld zone, HAZ and parent metal zone at different tool rotational speeds are shown in Figure 6. From Figure 6, it is observed that the measured average microhardness

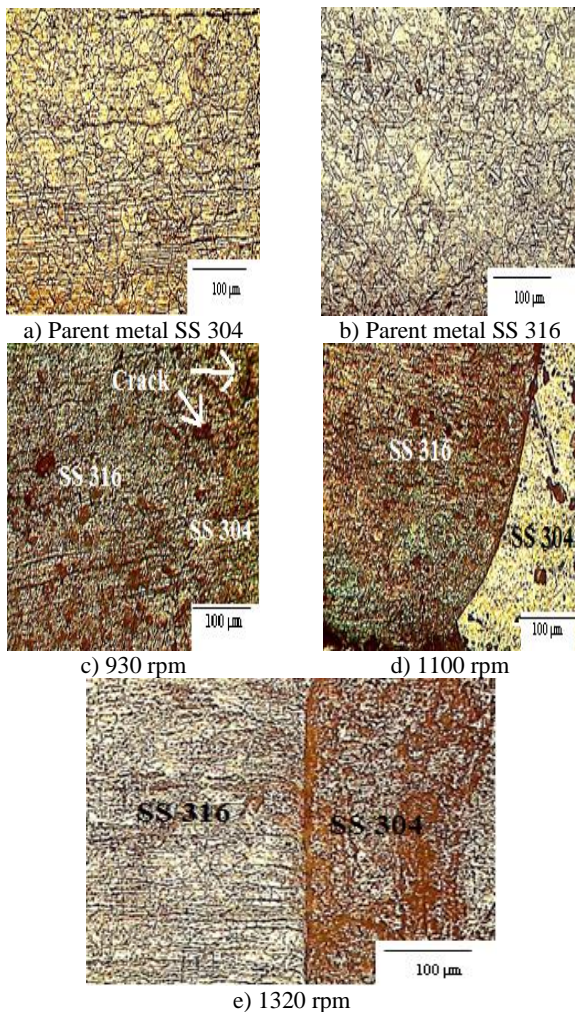


Figure 5. Observed microscopic images by optical microscopy: (a-b) parent metals, (c-e) friction stir welded zones at different rotational speeds

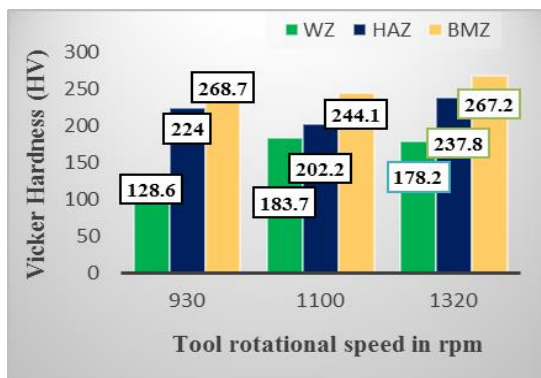


Figure 6. Distribution of average vickers hardness at different tool rotational speeds

value of the weld zone is lower than that of HAZ and PMZ in all experimented speeds. This may be attributed to the reason that the softening effect of the material in

the stirred zone by the rotating tool. The hardness value increases at weld zone when the rotational speed is increased from 930 to 1100 rpm and decreases by a little amount when the speed is increased from 1100 to 1320 rpm. The drop in the hardness value at 1320 rpm may be due to the reason that the heat generated at this speed is much higher than that of other speeds which makes the material softer. The average hardness values of HAZ and PMZ is much higher at 1320 rpm than that of other two speeds due to the faster dissipation of generated heat at these zones than the weld zone. Eventhough the hardness in the weld zone is much lower, the higher hardness in the other surrounding zones prevents the yielding of material may be reason for increase in yield strength and UTS at 1320 rpm. Lower hardness at the NZ cause the material to deform at a higher rate than the TMAZ and HAZ under tensile loading and the fracture occur at the NZ when the tool rotational speed is lower. Increase in hardness at NZ when the rotational speed is increased cause deformation slightly less than that of TMAZ and HAZ under tensile loading. Also, the presence of cracks in TMAZ or nearby HAZ may assist the fracture to occur at this region.

4. CONCLUSIONS

FSW of two grades of stainless steels was carried out to study the effect of tool rotational speed on the tensile properties of the joints. The study results can be summarized as follows:

- 1) No external weld defects were observed in visual inspection in all joints that are made.
- 2) A sound weld with the maximum strength properties of 417 MPa yield strength and 503 MPa of ultimate tensile strength was achieved at the tool rotational speed of 1320rpm.
- 3) Fine and equi-axed grains were observed in the welded region at all experimented speeds with a negligible amount of transformation of austenite into martensite.
- 4) Small cracks were observed in the microstructure of welded joints formed at the tool rotational speed of 1100 rpm and which may be the reason for the decrease in tensile strength.
- 5) The average microhardness at the weld zone is lower than that of HAZ and PMZ at all experimented tool rotational speeds.

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ABSTRACT

جوشکاری همزن اصطکاک یک فرآیند اتصال به حالت جامد نسبتاً جدید است که برای جوشکاری مواد مشابه و غیر مشابه مناسب است. پژوهش حاضر بر تأثیر سرعت چرخش ابزار بر روی کشش، خاصیت ریزساختاری و ریزسختی اصطکاک مفاصل جوش داده شده در رده های مختلف ورق های استیل مقاوم به خوردگی تمرکز دارد. چهار سرعت مختلف چرخش ابزار مورد آزمایش قرار گرفت در حالی که سایر پارامترهای فرآیند مانند سرعت حرکت و زاویه شیب ابزار ثابت نگه داشته می شوند. آزمایش کشش، میکروگرافی و اندازه گیری ریزسختگی در نمونه های جوش داده شده انجام گردید. از نتایج آزمایش کششی مشاهده شده است که مفصل ساخته شده در سرعت چرخش ابزار ۱۳۲۰ دور در دقیقه دارای حداکثر مقاومت در بین سرعتهای آزمایش شده است. مقادیر ریزسختی اندازه گیری شده در ناحیه تحت تأثیر گرما و منطقه فلزی مولد سختی بالاتری نسبت به منطقه جوش نشان میدهد. دانه های ریز و محور در منطقه جوش داده شده با سرعت زیاد آزمایش شده با مقدار قابل ملاحظه ای از تبدیل آستنیت به مارتنزیت مشاهده می شود. این نتایج تأثیر بر توسعه روش جوشکاری برای فرآیند جوشکاری اصطکاک استنلس استیل متفاوت است.

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