Journal of Achievements in Materials and Manufacturing Engineering
VOLUME 43
ISSUE 1
November
2010

Friction Stir Welding of austenitic stainless steels

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Received 16.09.2010; published in revised form 01.11.2010

Manufacturing and processing

ABSTRACT

Purpose: Friction Stir Welding (FSW) was applied austenitic stainless steels that is difficult to weld using FSW technique. Proper weld can be obtained by using appropriate welding parameter. In this paper, the effect of different tool rotational speeds, traverse speeds, compressive tool forces, and tool angles was investigated.
Design/methodology/approach: The dimension of 3 mm x 75 mm x 150 mm two stainless steel plates were used and butt welded by FSW method using 7.5 kW vertical head milling machine. All welded test specimens were prepared perpendicular to the weld line in order to determine the mechanical properties and tested with 12 MPa/sec stress rate under stress control using a servo-hydraulic Instron 8801. Microstructure of the welding zone and macrograph of the heat affected zone was investigated by SEM.
Findings: The average grain size in the SZ was between 3 and 7 µm, which is smaller than that in the BM. The average grain size in the HAZ was about 20 µm, which is half of that in the BM.Fine-grained microstructures are present the welded area. The dark bands observed in the weld zone were also detected the microstructure of the transition zone. Dark and narrow bands do not consist of pores or cavities. It was determined that these bands do not process an ultra fine-grained microstructure. They are Cr_2O_3 oxide layers which over the surface of stainless steels may have been ruptured during friction stir welding and may form bands inside the welding bead due to stirring.
Research limitations/implications: The proper cooling system helps to prevent the stirrer tool from the deformation.
Practical implications: The strength of the welded zone of AISI 304 stainless steel can be easily found by implementing welding design parameters and high quality joints can be obtained.
Originality/value: This study was performed in the frame of the TUBITAK project no 106M504, „Friction Stir Weldability of Stainless Steels and Investigation of the Affected Parameters on the Welding Quality".
Keywords: Friction Stir Welding; AISI 304; Stainless steel; Rotational tool speed; Traverse speed

Reference to this paper should be given in the following way:
C. Meran, O.E. Canyurt, Friction Stir Welding of austenitic stainless steels, Journal of Achievements in Materials and Manufacturing Engineering 43/1 (2010) 432-439.

1. Introduction

Friction stir welding (FSW) is a solid-state joining process developed and patented by The Welding Institute (TWI) in UK in 1991[1]. In early years, it was introduced for light alloys. Recently, high performance tool materials are employed for FSW of high melting temperature materials such as titanium, nickel and steels. The process is based on heating the weld area by friction created by a rotating tool. The softened metal followed by giving the tool a forward movement to mix it by using a tool tip, which creates the welding. Because melting of the attached components do not occur, and therefore welding can be carried out easily in every position. In addition, the metals like copper, aluminum, magnesium and their alloys which are difficult to weld by performing conventional welding techniques, can be welded easily using this method. Non-consumable, rotating tools of various designs produced from different materials showing superior characteristics under high temperatures and pressures are suitable for this technique.

The most disadvantage of FSW technique is the formation of pores and voids when not the proper welding parameters will be applied during the operation. In general, these failures occur in the welding bead. Another disadvantage, as aforementioned, is the difficulty of joining metals with high melting temperatures. Special tools that can preserve their hardness under high temperature conditions and powerful welding machines are required for welding refractory metals and alloys.

Friction stir weldability of metals can be affected by many factors. The most important ones are: tool rotational and traverse speed, compressive tool force, tilt angle and plunge depth, tool tip length and diameter, and tool shoulder profile, respectively. The improvement of the friction stir weld (microstructure and mechanical properties) is dependent on the controlling the above mentioned process parameters [2-5]. It is well known that the studies on FSW of stainless steels are relatively restricted compared to those on materials having low melting points such as Aluminum and its alloys. Early research conducted on FSW using stainless steels indicated that the weldability is primarily depending on the welding parameters [6-13].

Material flow during friction stir welding is very complex and not fully understood. Most of studies in literature used threaded pins since most industrial applications currently use threaded pins. However, initially threaded tools may become unthreaded because of the tool wear when used for high melting point alloys or reinforced aluminum alloys. The material flow path of friction stir welding process using unthreaded tools were studied [14]. Material flow with unthreaded pin was found to have the same features as material flow using classical threaded pins. The product of the plunge force and the rotational speed was found to affect the size of the shoulder dominated zone. This effect is reduced using the cylindrical tapered pin with flats [14].

For FSW, both tool rotation rate and traverse speed exert a significant effect on the thermal input and mechanical properties. It was reported that the peak temperature in the FSW zone increases with increasing tool rotation rate [15]. It was found that rotational speed had a significant impact on microstructure and mechanical properties of the joints for Ti–6Al–4V titanium alloy. Joints were produced by employing rotational speeds ranging from 400 to 600 rpm at a constant welding speed of 75 mm/min. It was found that the hardness in the weld zone was lower than that in the base material, and decreased with increasing rotational speed. Results of transverse tensile test indicated that all the joints exhibited lower tensile strength than the base material and the tensile strength of the joints decreased with increasing rotational speed [16]. Zhang and Zhang [17] analyzed the effect of transverse speed on friction stir welding in detail for the controlling of this parameter by using a fully coupled thermo-mechanical model. It was found that when the transverse speed is higher, the stirring effect of the welding tool becomes weaker, which is the reason for the occurrence of weld flaw. When the transverse speed is increased, the contribution of the plastic deformation to the temperature rise is increased. But the variation of the transverse speed does not significantly affect the power needed for FSW [17]. Numerical results indicate that the maximum temperature in the FSW process can be increased with the increase of the rotating speed. Both the increase of the rotating speed and the decrease of the welding speed can lead to the increase of the stirring effect of the welding tool, which can improve the friction stir weld quality. When the welding speed becomes higher, the rotating speed must be increased simultaneously to avoid any possible welding defects such as void [18]. Friction stir tool is the key art of friction stir welding process. The geometry of the pin affects the heat generation and the flow of the plastic material. Eventually, the pin can affect the shape and the mechanical properties of the weld [19-23].

Literature studies also suggest that the stirring tool material is one of the topics widely studied on friction stir welding of high melting point materials such as stainless steels. The tool material is expected to possess the desired hardness, high stiffness and sufficient wear resistance 1000°C or at higher temperatures. Researchers studying this topic have used wolfram base alloys, specifically W-Re alloys, molybdenum alloys and polycrystalline cubic boron nitrides (PCBN) as tool materials. The behavior of the tool materials during welding was examined in various studies [24-27].

Nandan et al. mathematically modeled the flow and heat distribution that is formed during the three dimensional friction stir welding process of stainless steels. The numerical results were in good agreement with that of the experiments [28]. Numerical models have been developed for friction stir welding of stainless steels in terms of a visco plastic material behavior. Heat distribution and flow directions were examined [29].

Friction stir welding of steel pipes were carried out using PCBN tools with 25 mm in diameter and 5.5 mm in length by applying 500 – 600 rpm rotational speed and 100 -150 mm/min traverse speed. Different from similar studies, compressive tool force, that is a very important parameter for friction stir welding, has been kept constant at 10 kN during welding. In order, to prevent oxidation of the weld zone, a protecting argon gas atmosphere is necessary to cover the welding bead [30]. It has been observed that when the mixer tool temperature exceeds 1000°C and the compressive tool force was not correctly chosen, weld grooves were formed at the edge of the welding bead [31]. Similarly, the measurements performed by using thermo couples and infrared cameras showed that the tool shoulder temperature higher than 1000°C [32]. It has been determined that by preheating the metals of high melting temperatures such as steels, before friction stir welding, the traverse speed can be increased. This results in a decrease of the tool wearing [33].

In this study, the effect of welding process parameters on the performances of FSW was investigated. Suitable tool rotational and traverse speeds, compressive tool force and tool angle were determined in FSW of AISI 304 austenitic stainless steel. The best appearance (with surface and root penetrations, having no crevices, cracks or pores), good welding beads with improved mechanical properties can be obtained by the determination of the tool traverse speeds related to the tool rotational speeds, compressive tool force and tool angle.

2. Materials and method

Experiments in this study were performed in the FSW and Mechanics laboratory at the Department of Mechanical Engineering, Pamukkale University. The dimension of 3 mm x 75 mm x 150 mm two stainless steel plates were used and butt welded by FSW method using 7.5 kW vertical head milling machine. The experimental setup was shown in Fig. 1.

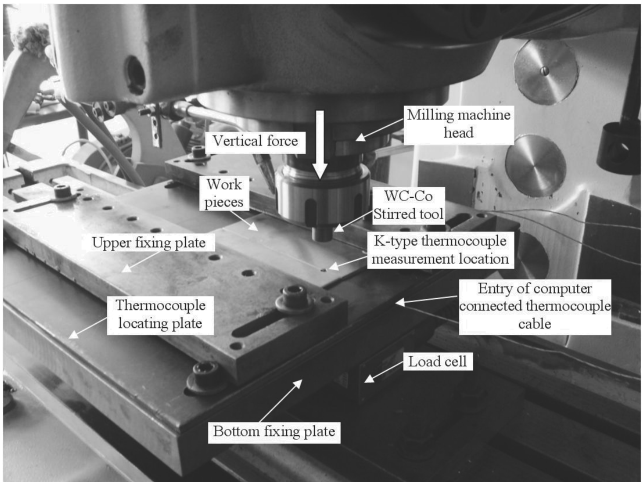


Fig. 1. Experimental setup using for friction stir welding

The temperature was obtained by only one fixed location. Temperature of the bottom surface of the joined materials was measured on the fixed location close to the start point hole by using K-type thermocouple that was placed on the bottom fixing plate shown in Fig. l. Compressive tool force is one of the important parameter that controlled the heat input to the welding zone during friction stir welding. Heating rate is depend on compressive tool force that was obtained by milling machine. The compressive tool force was measured by using two load cells located under bottom fixing plate that has the capacity of 10 tones, during entire welding operation and the data transferred to computer, Fig. 1.

In the performed studies AISI 304 (X5CrNi18-10, material identification number 1.4301) austenitic stainless steel plates with the chemical composition given in Table 1 and mechanical properties given in Table 2 were used. Two specimens in butt position with the dimensions of 3 mm x 75 mm x150 mm were joined by using FSW with different welding parameters. Initial holes were drilled into the specimens.

Equilateral triangle tip profile with 5 mm in diameter and 2.8 mm in height, and end mill cutter shank with 16 mm shoulder diameter (cemented carbide specifications: K10, 94% WC – 6% Co) were used during welding process. The tools were cooled by pressurized air during welding in order to extend their life. Friction stir welding process parameters are presented with tensile test results, and upper view of welded joint in Table 3.

Table 1.
The concentrations of the main elements of the AISI 304 stainless steel are given in mass %

C	Mn	Si	Cr	Ni	P	S
0.08	2	1	18-20	8-10.5	0.045	0.03

Table 2.
Mechanical properties of the AISI 304 stainless steel at room temperature

Density (g/cm^3)	E (GPa)	Rm (MPa)	$Rp_{0.2}$ (MPa)	A (%)	Hardness (HRB)
8	193	515	205	40	88

Three friction stir welded specimens with dimensions 3 mm x 150 mm x 150 mm were machined for tensile tests. All welded test specimens were prepared perpendicular to the weld line in order to determine the mechanical properties. The specimens were subjected to quasi static and mostly monotonic tension loading. All the tests were performed with 12 MPa/sec stress rate under stress control using a servo-hydraulic Instron 8801 universal uni-axial testing machine with a load capacity of 50 kN. Stress control mode was chosen over stroke or strain mode due to the convenience and smoothness of the operation.

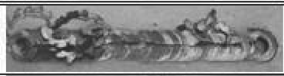
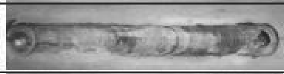
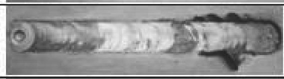
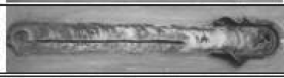
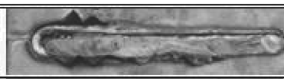
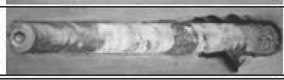
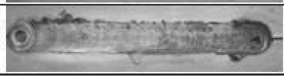
Microstructural examination was performed in order to check weld defects such as porosity, coarse dendrites etc. or poor penetration in the welding bead, and the grain structure of the heat-affected zone.

3. Results and discussion

3.1. The effect of the tool rotational speed on the weld performance

The results of tensile tests are given in Table 3. Values given in the Table 3 indicate the average of at least three tests. The effect of the rotational speed on specimens welded with the same traverse speed (60 mm/min), compressive tool force of 9 kN and tool tilt angle of 1.5° were examined. Fig. 2, shows a significant decrease in strength of the material weld zone at values of the rotational speed of below 750 rpm and above 1180 rpm, respectively. At lower rotational speed of 600 rpm, the heat required for softening the weld zone have not been achieved, therefore these results in a decrease of the weld strength. The good quality welding joint can be achieved with the proper softening temperature on the welding zone by supplying the proper combination compressive tool force, tool angle, rotational and traverse speed. The quality mixture of the joined parts microstructure results in an increase of the strength of welded joints. While, the low heat input in the welding zone result in insufficient softened materials that could cause to the porosity and low penetration, the excessive heat input result in the burr built up at the welding bead edges and also decrease the welding cross-section. Therefore, insufficient and excessive heat input result in the decrement on the tensile strength.

Table 3.
Friction stir welding process parameters, tensile test results, and upper view of welded joint

Revolutions	Traverse Speed	Compressive Tool Force	Tool Angle	Tensile Strength	Yield Strength	Upper view of welded joint
n	v_t	F	α	R_m	$R_{p0,2}$	
(rpm)	(mm/min)	(kN)	(°)	(MPa)	(MPa)	
Base materials				515	205	
600	60	9	1.5	300	232	
750	60	9	1.5	395	288	
950	60	9	1.5	430	340	
1180	60	9	1.5	421	318	
1500	60	9	1.5	246	207	
750	37.5	9	1.5	470	325	
750	47.5	9	1.5	484	356	
750	60	9	1.5	395	288	
1180	60	5	1.5	273	260	
1180	60	7	1.5	480	352	
1180	60	9	1.5	421	318	
1180	60	9	0	269	211	
1180	60	9	1	339	278	
1180	60	9	1.5	421	318	
1180	60	9	2	460	357	

The maximum strength of the weld zone was obtained at 950 rpm tool rotational speed with a traverse speed of 60 mm/min, compressive tool force of 9 kN and tool tilt angle of 1.5°. The tensile strength of the weld zone was determined to be 430 MPa, when applying 950 rpm rotational speed, whereas the tensile strength of the base material (R_m=505 MPa). The maximum tensile strength decreased of about 30.23 % and 42.7 % when the rotational speed was dropped from 950 rpm to 600 rpm or raised up to 1500 rpm respectively. In the weld zone the fine-grained microstructure was observed and the tensile strength of the welded joint was found higher than that of the base material.

It is obvious that the best macroscopic appearance was achieved in the weld joints produced with 950 and 1180 rpm rotational speeds. The welding burr built up at the welding bead edges occurred at 1180 rpm rotational speed. Therefore, the determined values of the tensile tests is slightly lower than the values of the tensile strength performed with 950 rpm. The lower and higher values of rotational speeds cause in sufficient penetration and quality of the welding. The lower (< 600 rpm) tool rotational speeds result in an insufficient source generation and the higher (> 1500 rpm) rotational tool speeds result in an excessive heat generation. Both process conditions parameters cause crevices and insufficient penetration in the welding bead.

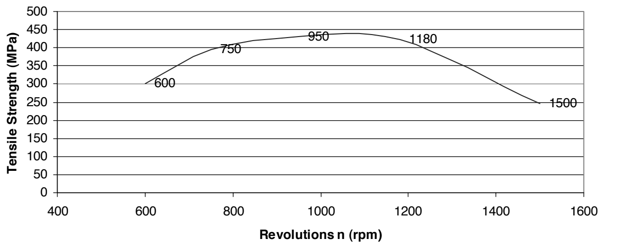


Fig. 2. The effect of the rotational tool speed on tensile strength of AISI 304 stainless steel processed by FSW with process parameters: vt=60 mm/min, F=9 kN, α=1.5°

3.2. The effect of traverse speed on the weld performances

The good quality weld zone can be achieved with the proper softening temperature on the welding zone. The traverse speed has effect on the temperature of the weld zone. The rotational shoulder and pin does not have enough time to heat the welding zone with higher the traverse speeds or too much heat on welding zone with lower traverse speeds. Therefore, there is an optimum value of the traverse speed in order to obtain quality joints.

The welding parameters were taken from Table 3. The same procedure with varying rotational speed was performed for the traverse speed. The compressive tool force of 9 kN was kept constant in the beginning of the welding, then the tool started and proceeded along the welding seam.

The effect of the traverse speed on the performance and mechanical properties of the welded specimens processed with the constant rotational speed (750 rpm), compressive tool force of 9 kN and tool tilt angle of 1.5° were examined. The maximum tensile strength of the weld zone was achieved by applying traverse speed of 47.5 mm/min, that is an optimum value with a rotational speed of 750 rpm, the compressive tool force of 9 kN and tool tilt angle of 1.5° as shown in Fig. 3. The lower and higher values of 47.5 mm/min cause a decrease in strength of the weld zone. The tensile strength increased from 470 MPa to 484 MPa due to an incremental increase of the traverse speed from 37.5 mm/min to 47.5 mm/min, respectively. When the traverse speed was raised from 47.5 mm/min to 60 mm/min, the tensile strength decreased 18.5% (484 MPa to 395 MPa Table 3).

The macroscopic appearances of the friction stir welded joints using different traverse of the tool are illustrated in Table 3. The best appearance revealed the weld joints processed with 47.5 mm/min traverse speed. Crevices were determined on the welds produced with a traverse speed of 60 mm/min.

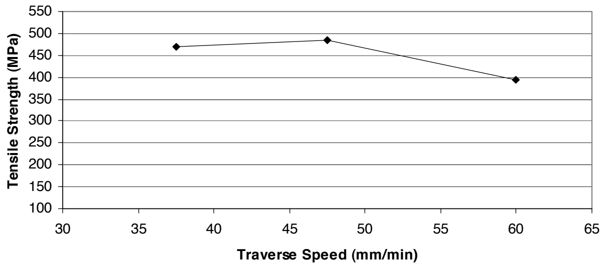


Fig. 3. Influence of the traverse speed on the tensile strength with FSW joints having n=750 rpm, F=9 kN, α=1.5°

3.3. The effect of the compressive tool force on the weld performance

Compressive force influences the welded strength of the joined parts. As shown in Fig. 4, the change of compressive force from 5 to 7 kN leads to a sharp raise in the strength value from 273 MPa to 479 MPa and the change of compressive force from 7 to 9 kN leads to a drop the strength value from 479 MPa to 421 MPa.

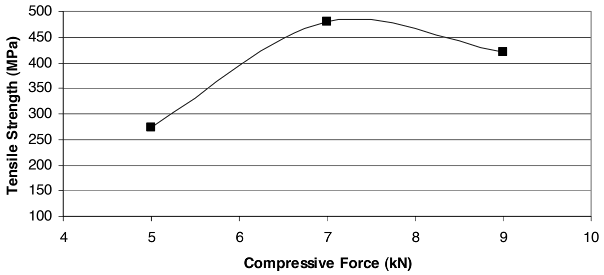


Fig. 4. Influence of the compressive tool force on the tensile strength with FSW joints having n=1180 rpm, vt= 60 mm/min, α=1.5°

3.4. The effect of the tool tilt angle on the weld performance

The strength of welded joints was affected from the tool tilt angle. The angle of 0o causes a serious problem in the weld areas. Small increment on the tilt angle helps to increase the joint strength until the tilt angle of 2 degrees. An optimum tilt angle was obtained at 2 degrees, lower and higher tilt angle cause a decrement on the joint strength. The joint strength was increased 71.34 % by selection of 2 degrees instead of 0 degrees shown in Fig. 5. It can be seen that design parameters have an influence on the strength of the welded joints. Selection of proper FSW design parameters result in an increase of the joint strength.

The microstructure of the weld zone is finer when compared to that of the base material. The grain size of the base material that is thermo mechanically affected and dynamically recrystallized is decreased. Microstructural examinations exhibit the weld zone (stir zone) the grain sizes are considerably fine. In addition, the grains of the weld zone are equiaxed and the grain size decreases gradually in the heat affected zone, Fig. 6. The distribution of the average grain size is more or less uniform in the stir zone, although the advancing side has a slightly larger grain size than the retreating side. The average grain size in the SZ ranges between 3 and 7μm, which is smaller than that in the BM. The average grain size in the HAZ was determined to be about 20 μm, which is half of that in the BM. The microstructure of the transition zone between the base material and the weld zone is different from the microstructures of both of the regions. The dark bands observed in the weld zone were also detected the microstructure of the transition zone, see Fig. 6b.

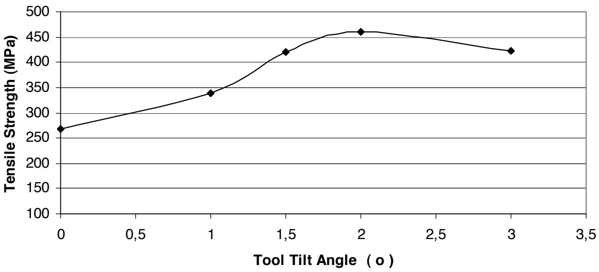


Fig. 5. Influence of the tool tilt angle on the tensile strength with FSW joints having n=1180 rpm, vt= 60 mm/min, F=9 kN

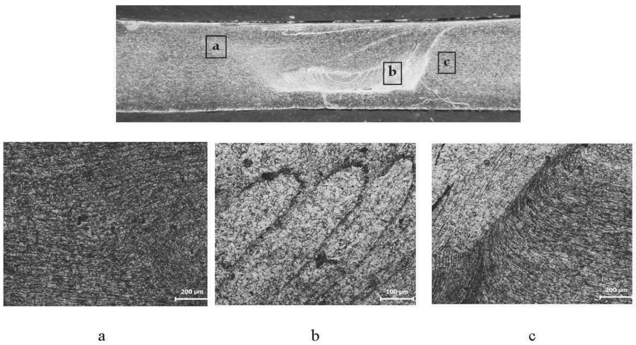


Fig. 6. Macrograph of the heat affected zone (HAZ) (a), weld zone (b) and base material (c), optical micrographs showing the microstructures of the stir welded zone processed with F=9 kN, vt=60 mm/min, n= 950 rpm, α=1.5°

The literature survey Ref. [34-35] reveals that some of the investigators claimed that these bands possess an ultra fine-grained microstructure due to recrystallization followed by severe cold working. These dark and narrow bands do not consist of pores or cavities. The SEM study showed, it was determined that these bands do not process an ultra fine-grained microstructure. They are Cr_2O_3 oxide layers which over the surface of stainless steels may have been ruptured during friction stir welding and may form bands inside the welding bead due to stirring [36].

4. Conclusions

The studies on friction stir welding (FSW) of stainless steels are not as comprehensive as those ones conducted on aluminum due to the some limitation and the high cost of tool material and the requirement of powerful milling machine. The following important conclusions will be drawn from the results of the present study:

- Several tool tip profiles as parameters were examined in the experimental study. Hard metal carbide tools (K10, 94% WC – 6% Co) with triangular tool tip profiles are suitable for friction stir welding of AISI 304 austenitic stainless steels.
- The maximum tensile strength in friction stir welded AISI 304 material produced with 950 rpm rotational speeds and 60 mm/min traverse speed, 9 kN compressive tool force, and 1.5° tool tilt angle the weld zone was determined to be as 430 MPa for the same process parameters while the tensile strength of the base material is 505 MPa.
- Fine-grained microstructures are present the welded area. From this it is concluded that the weld joints obtained by friction stir welding have higher tensile strength compared to that of the base material.
- The average grain size in the SZ was between 3 and 7 μm, which is smaller than that in the BM. The average grain size in the HAZ was about 20 μm, which is half of that in the BM.
- The dark bands observed in the weld zone were also detected the microstructure of the transition zone. These dark and narrow bands do not consist of pores or cavities. It was determined that these bands do not process an ultra fine-grained microstructure. They are Cr_2O_3 oxide layers which over the surface of stainless steels may have been ruptured during friction stir welding and may form bands inside the welding bead due to stirring.

Acknowledgements

This study was performed in the frame of the TUBITAK project no 106M504, "Friction Stir Weldability of Stainless Steels and Investigation of the Affected Parameters on the Welding Quality". The authors would express their thanks to TUBITAK for their kindly supports.

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