International Research Journal of Engineering Science, Technology and Innovation (IRJESTI) (ISSN-2315-5663)
Vol. 2(4) pp. 65-74, July, 2013
Available online http://www.interesjournals.org/IRJESTI

Full Length Research Paper

Mechanical and Microstructure Properties of 304 Stainless Steel Friction Welded Joint

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Accepted 26 June, 2013

In friction welding, the joints are formed in the solid state by utilizing the heat generated by friction, followed by compressive forging force. The continuous drive friction welding method (CDFW) appears to be an alternative to make use of stainless steel more widespread. This method is adopted in the present work, and Taguchi array L27 (3^3) orthogonal array is designed for conducting the experiments and from ANOM analysis and S/N ratio, the best set-up of operating parameters to produce AISI 304/304 stainless steel joints, these parameters was found as: P1=73.8 bar, P2=85 bar, and t1=1 sec, where t1 is the most influential factors on weld strength. The coupling effect of these parameters has a major effect on produced joint quality. The joined strength is with maximum efficiency of 105% that indicates, the austenitic stainless steel is highly tolerant to friction welding. Dynamic recrystallization is the major mechanism for the microstructural evolution at the joint centreline, which characterized by refined, equiaxed, and homogeneous microstructure.

Keywords: AISI 304, Dynamic re-crystallization, Friction welding, Taguchi array analysis, Tensile strength.

INTRODUCTION

Stainless steel is an important engineering material with multiple applications. For engineering processing, the requirement for welding techniques is preferable to preserve the desirable properties of such steel, as corrosion resistance, high strength and ductility, formability and good appearance. Any welding defect such as sensitization, delta ferrite phase, sigma phase and stress-corrosion cracking is desirable to be eliminated. This elimination can be achieved by friction welding (FW) due to the short time and rapid cooling of the process (Mumin, 2007). FW as a solid state welding by means, motion of two faying surfaces is generates heat, and below melting temperature compressive force applied to make welded joint (Zhou et al., 1995). The quality of weld joints is influenced by many parameters such as, rotational speed (N), friction pressure (P1), forging pressure (P2), friction time (t1) and forging time /duration of the forging force (t2). Many researchers have investigated the effect of friction welding parameters on the quality of steel joints (Ananthapadmanaban et al., 2009; Sathiya et al., 2005,2007; Insu et al., 2000,2002), the optimization of parameters is studied by using conventional techniques (Mumin, 2007; Satyanarayana et al., 2005; Murti and Sundarasan 1983; Kim et al., 2003; Sahin et al., 1996). Dennin 1979, presented the first attempt to establish welding parameters for new applications by numerical calculations without performing welding trials. Taguchi statistical design was developed to use a small number of experiments with simplicity of data analysis based on statistical tools (Lakshminarayanan and Balasubramanian, 2008; Vidal et al., 2009) The effect of FW parameters on the microstructures and mechanical properties of the weld joint is still a matter of investigation, where the influence of individual parameters is the key to decide the nature of the control to be established on production (Vidal et al., 2009) The published study on similar stainless steel is scarce. P. Sathiya et al. have demonstrated in a series of work, a promising feasibility of the process to join AISI 304 austenitic stainless steel (Sathiya et al., 2005,2008; Lakshminarayanan and Balasubramanian, 2008 and Sammaiah et al., 2010). To describe the micro-structural features of FW joint regarding the similar metals, it is convenient to adopt the nomenclature employed by Uenishi et al., 2000; Midding and Grong, 1994 these includes by name; region I, the fully plastically deformed region (PZ) on the either side of the weld interface, which contains small re-crystallized grains, region II where the grains are partly deformed (PDZ) by the action of forging pressure, with coarse grains structure, and region III the unreformed (UZ) base material microstructure. Uenishi et al., 2000 indicated that, the change in region I (PZ) microstructure is related to both, dynamic re-crystallization and dynamic recovery as a mechanisms for the micro-structural evolution of material at the joint centre line in rotary friction welds, and in the plasticized region formed during friction stir welding. By assuming the materials in the contact region are treated as a highly viscous fluid, North et al., 1998 modeled, the width of (PZ) in similar friction welds is inversely proportional to the applied P1. According to Ellis, 1972, welds made at higher pressures P1 show a narrower (PZ) region. Mumin, 2007; Sathiya et al., 2005,2007; Mumin et al., 2007 concluded that, for AISI 304 FW joints also exhibit a comparable strength with the base material, and the joint strength decrease with the increase in the t1. Mumin, 2007, has shown, the tensile strength of the joints increases with t1, as it rises to a maximum, and then decreases for longer t1. The strength of the joints was found to decrease, as t1 of the joints is increased more than the optimum value. Other authors (Sammaiah et al., 2010; Sujith, 1999; Sare and Ismail, 2009; Kato and Tokisue, 1994; Michael, 1992), assure that, tensile strength tends to be improved with an increase in P1, and also reported, in order to obtain joint strength equivalent to the base material, it is recommended to set a fairly high P2 without any excessively long t1 or high P1. Kato and Tokisue, 1994, found that tensile strength tend to be improved with an increase in the P1 and t1. In the present study, similar stainless steels AISI 304 were directly friction welded, and the tensile strength is taken as a main evaluation of joint efficiency and P1, P2, and t1 are taken as parametric design for Taguchi analysis to optimize the best welding setup.

MATERIALS AND EXPERIMENTAL PROCEDURES

The chemical composition and average tested tensile strength of used steel are shown in table (1).

The received material used are cylindrical bars of 200 mm in length, and 25 mm in diameter ,the samples were stress relieved to a temperature of 350˚C for 1 hour followed by still air cooling. Prior to friction welding, the mating faces of all samples were machined perpendicular to the rotational axis, and then cleaned with acetone just before welding.

Design of experiment and Friction welding: All welding was conducted on a continuous drive rotary friction welding machine, a number of parameter variations are obtained according to Taguchi statistical design. After welding, the joints were cooled in still air, followed by wire cutting and prepared for further mechanical and optic-metallographic investigations.

Selected Parameters: In this study, N and t2 are kept constant. The other parameters such as P1, P2 and t1 varied within the range available in the machine setting, the best parameters range is shown in table (2).

Chosen orthogonal array (OA) for experiments: The selection of any appropriate set of input parameters for friction welding indicated in table (3) to evaluate for optimum tensile strength the parameter combinations of A, B, and C are adopted to yield the best joint strength among all possible combinations.

The welding parameters are coded as (1), (2) and (3) that correspond to the low, medium and high levels are arranged in the OA, The parameters level ranges are presented in table (4).The result obtained from L27 orthogonal array are recorded and used for analysis.

Metallographic Examination: For this examination, each sample was mechanically cut from both sides of the weld joint, split longitudinally by wire cut, and the final shape and dimensions are presented in figure (1). All specimens were metallurgicaly polished and etched with a suitable agent (10 ml HNO_3, 10 ml acetic acid, 15 ml HCl, 2 to 5 drops glycerol), then examined with optical microscope.

Tensile Test: These tests were carried out in order to evaluate the tensile strength of joints. After turning off flashes, standard samples were machined, and weld interface kept at mid gage length as possible.

RESULTS AND DISCUSSION

Features of the Joint: according to the pre-selected condition and setup parameters, the flash obtained in all welded samples exhibited symmetrically shaped flash and the plastic deformation shaped in a homogenous way for both stationary and fixed parts, as in figure (1).

Microstructure of the Joints: the optical microstructures are shown in figure (2), a number of different microstructure regions are located relative to the bondline. A finer grain structure observed in PZ, where at PDZ consists of coarser grain structure. Within the PZ, the direction of original elongated grains gradually rotates through 90° to bar axis. These fine grains are present on both sides of friction plane, i.e. in the area of the most intensive friction where dynamic re-crystallization (DRX) took place, and this founding is clearly appeared in all welded samples, as in figure(3). Sathiya et al., 2005,2008;2004 also have observed fine grained structure in the PZ in AISI 304 welding stainless steel. This can be interpreted as the FW involves heavy plastic working at higher temperatures close to the melting point of the base materials. This plastic deformation introduces large number of dislocations in the materials. As the density of these dislocations increases, they tend to form sub-grain cell structure. These low-angle grains rotate to form high-angle strain free grains resulting in a zone of very fine equiaxed grains compared to the base materials, referred to as “DRX” grains, this proposition also reported by Dey et al., 2009. In the present work, the

Table 1. The Chemical Composition and Tensile Strength

Material	C	Si	Mn	P	S	Cr	Ni	Fe	σUTS , MPa
AISI 304	0.041	0.35	1.36	0.026	0.024	18.8	8.21	Bal.	653

Table 2. Best parameters range

Join Type	P1 bar	P2 bar	t1 sec	t2 sec	N rev/min
AISI 304/304	63.5	85	1	1.79	931

Table 3. Input parameters of friction welding

Parameter	Unite	Designation
Friction pressure,P1	bar	A
Forging pressure, P2	bar	B
Friction time, t1	sec	C
Forging time, t2	sec	D
Rotational speed, N	rmp/min	E

Table 4. The best welding parameters and their levels

Symbol	Parameter	Level		
		Low (1)	Medium (2)	High (3)
A	P1, bar	53.8	63.8	73.8
B	P2, bar	70	85	100
C	t1, sec	1	2	3
D	t2, sec	Constant = 1.79		
E	N, rmp/min	Constant = 931		

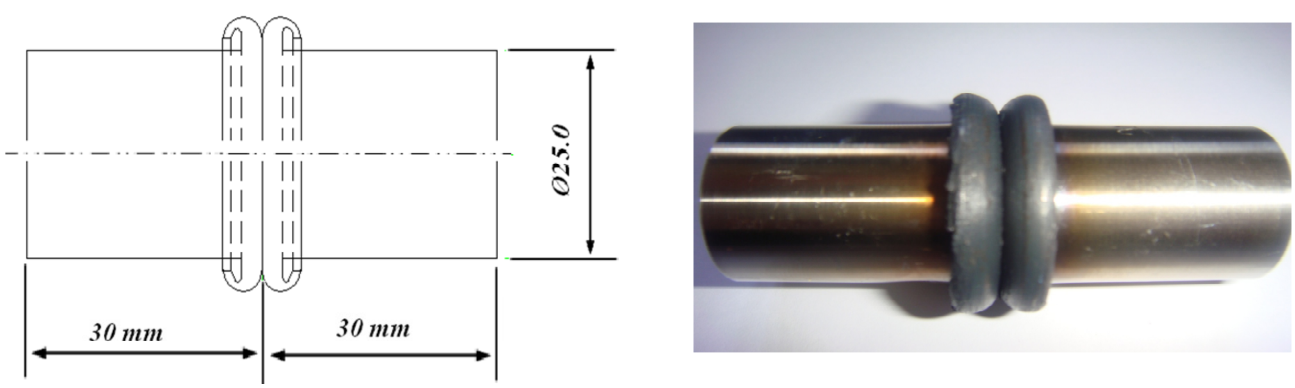
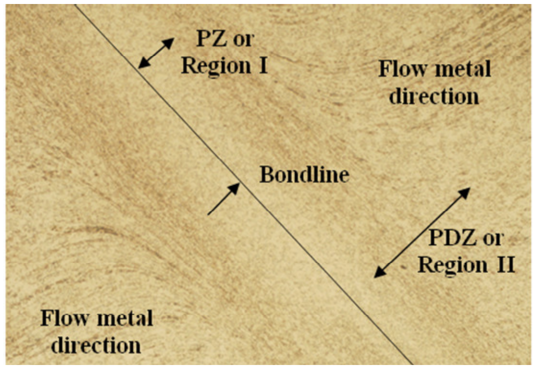
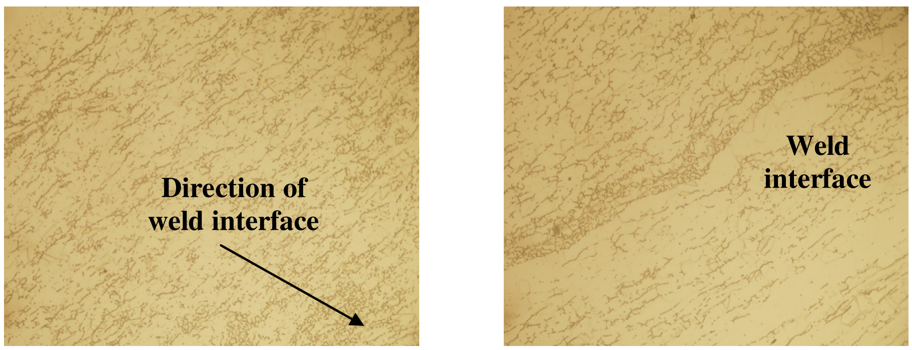


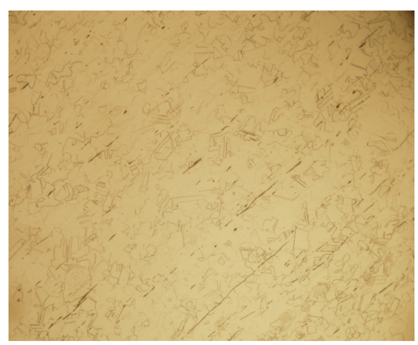
Figure 1. Configuration and dimension of metallographic sample (mm).



a. Microstructural development at the bondline and welding zones, 50X



b. Region I (PZ) at 500X



c. Region II (PDZ) at 500X **d. Region II (UZ) at 500X**

Figure 2. Microstructures at different zones.

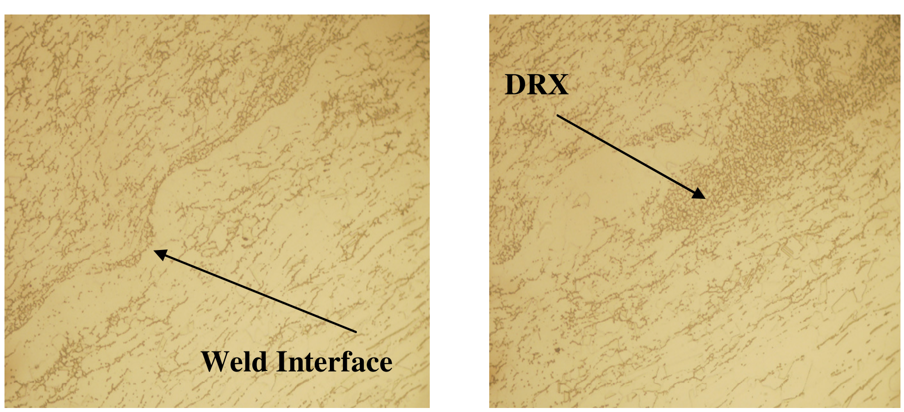


Figure 3. Refine grains on both sides of the bondline 500X.

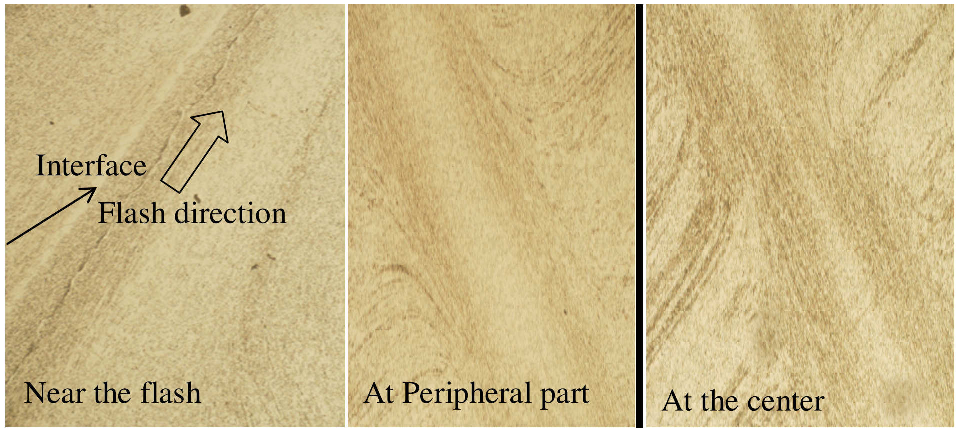


Figure 4. Deformed region widths of the peripheral and central region FW joint, 50X

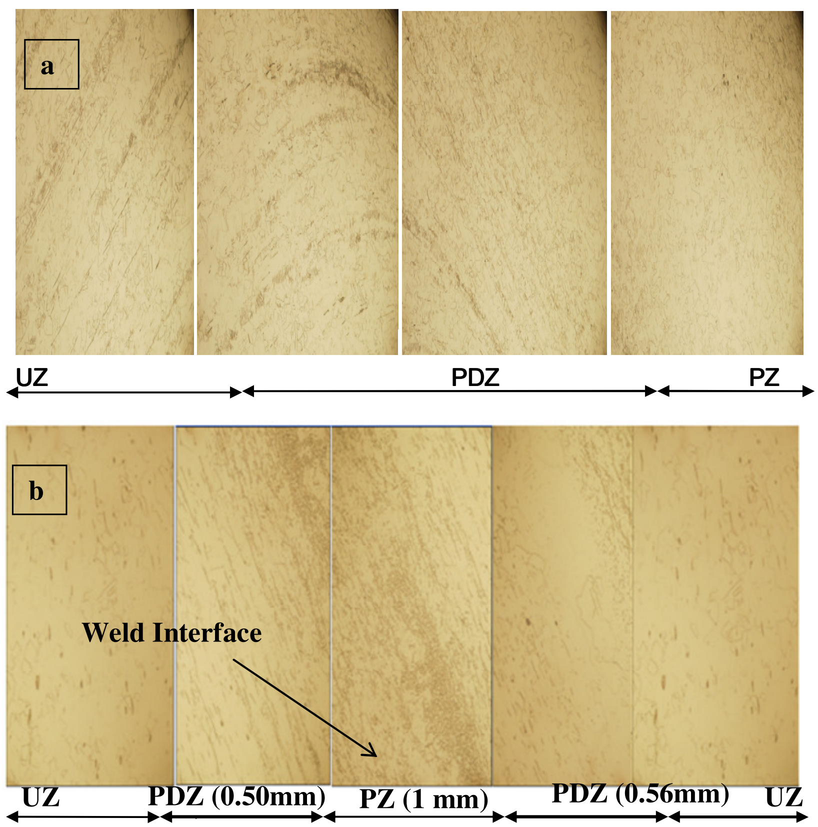


Figure 5. Axial section microstructure morphology (a)-100X and (b)-300X

effect of t1 on DRX clearly appears where the width of the DRX increased from the central to the peripheral region as the friction time increased. At the edge of the peripheral part, the DRX region was narrowed again because of the formation of the flash outside the interface. In contrast, as the t1 increased, the width of region PDZ tends to be reduced. Since the hot metal is squeezed out during the forging process the boundaries of the HAZ moves towards the interface. Thus the width of the weld metal becomes broader when increasing t1, as in figure (4).

Figure (5) shows the microstructure of PZ at approximately 1 mm from the bondline, the PDZ approximately 0.5 mm width, and the (UZ) is found at 1.5 mm away from the bondline. These measured results are well complied with finding of Sathiya et al., 2008; Insu et al., 2000 and Sathiya et al., 2005,2008 have observed; as the t1 increased, the PZ become broader, and in contrast, as the t1 increased, the width of region PDZ tend to be reduced. Table (5). summarize the microstructures zones and how space from bondline.

Table 5. Friction welds Microstructural zones.

Microstructural Zone	Distance from bondline	Grain morphology
PZ	0-0.5mm	Very fine Grains parallel to bond line
PDZ	0.5-1.0 mm	Grains slightly elongated parallel to bond line
UZ	>1.5 mm	Corse Grains elongated parallel to extrusion direction.

Table 6. The effect of P1 on tensile strength and joint efficiency (η %) joints

Specimen No.	P1, bar	P2, bar	t1, sec	σ_{UTS}, MPa	η %
S4	53.8	85	1	633.300	96.93
S13	63.8	85	1	686	105
S9	53.8	100	3	629.400	96.34
S18	63.8	100	3	673.700	103

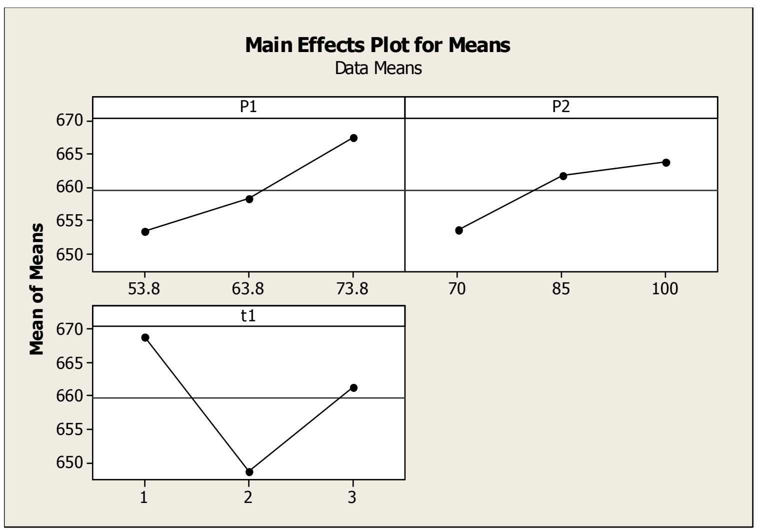


Figure 6. Main effects plot for Means of AISI 304/304 joint.

Tensile Test: tensile strength is the main characteristic evaluation considered in present study to identify the quality of FW joints. From the obtained tensile strength data for the OA L27 welded joints. it was found that, the highest strength are obtained in all runs with average efficiency of 100.73 % which indicates, the stainless steel is tolerant of FW and the CDFW method can successfully be adopted for performing weld joints of AISI 304. Thus, considerably, the strength of friction processed joints exhibited comparable strength with the base material as concluded in previous studies (Mumin, 2007; Sathiya et al., 2005;Mumin et al., 2007) and the highest tensile strength was acquired as 686 MPa for the joint with the setup conditions of; P1(63.8 bar) , P2 (85 bar), and t1 (1 second).

Analysis of the Means (ANOM): the effect of the individual selected parameters was investigated, as well as the combined effect of interaction of the two parameters that have notes able effect on the strength of the weld joint that was statistically calculated. Analysis of mean for each runs gives better combination of parameter levels, which is well matching with (Lakshminarayanan and Balasubramanian, 2008; Vidal et al., 2009 Yi et al., 2009) results. The optimal level of process parameters is the level of highest S/N ratio in the experimental region according to the larger the better type. From the analysis of obtained results as shown in figure (6) and in figure (7) for the mean and S/N ratio indicates that, the optimized tensile strength obtained at condition when: P1 (level C), 73.8 bar; P2 (level C), 100 bar; and t1 (level A), 1 second.

Effect of Friction Pressure P1: Table (6) shows the P1 has a good effect on joints strength, tensile strengths is directly improved as the P1 increased. The mean effect as in figure (6) and S/N ratio in figure (7), shows the matching manner of effect, where as P1 increased, the

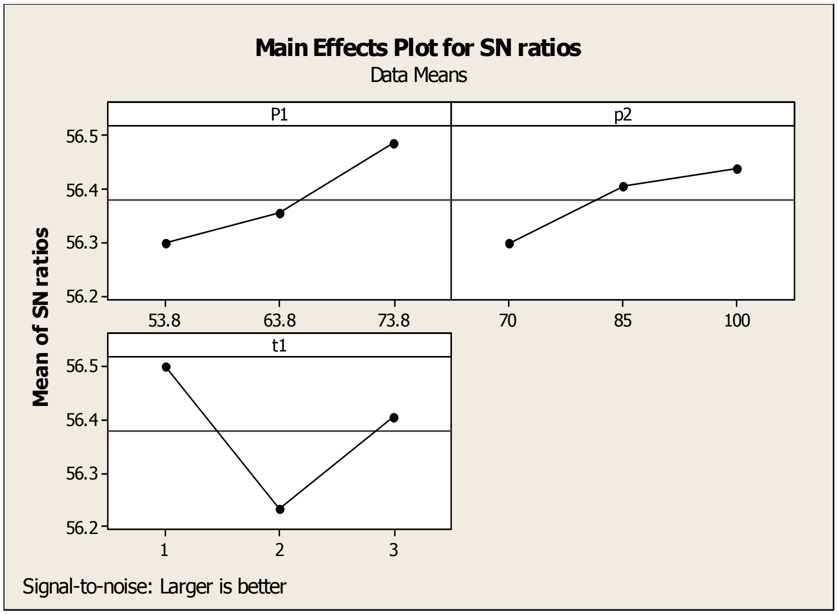


Figure 7. Main effects plot for S/N ratio of AISI 304/304 joint.

higher the strength value is obtained, and all strength of the welds varies with the P1 setting. The progressive increase of the strength observed when P1 range from 63.8 to 73.8 bar, due to the formation of narrow softened region along the bondline. Therefore, the present result as shown in the mentioned figures provides well support to (North et al., 1998) founding. A mathematical model has been proposed by North et al., 1998, and others (Uenishi et al., 2000; Sujith, 1999) agreed with this model, by assuming that the materials in the contact region are treated as a highly viscous fluid, and the width of the fully plasticized region in similar friction welds are found to be inversely proportional to the applied P1. This is well confirmed with the present results.

Effect of Forge Pressure P2: The general trend of the obtained strength data P2 is appeared to increase in a range of variations from 588.8 MPa to 686 MPa for specimens S11 and S13, respectively as the P2 increased from 70 to 100 bar, some of other joints data tabulated in table (7), reveals, the P2 has an excellent influence on strength of the joint efficiency which related to the amount of metal deformed and flowing out. Many authors (Sujith, 1999; Sare and Ismail, 2009; Michael, 1992; Pinheiro, 2008) reported that, in order to obtain joint strength equivalent to the base material, it is recommended to set a fairly high P2 without any excessively long t1 or high N.

From the mean effect and S/N ratio figure (6), and (7) it is clearly show, the joint strength increases as the P2 is increased, but this improvement in strength is clearly observed when P2 is increased from 70 to 85 bar. Between 85 up to 100 bar weld strength there is less significant effect observed.

Effect of Friction Time t1; in order to obtain an increased improvement in the quality of welded joints, Vill, 1962 recommended that, t1 has to be carefully selected, and it's desirable to have short heating times for better results. From table (8) it can be seen that, the obtained strength data represents a similar effect of t1 on joints strength, where parameters are slightly reduced, with an estimated percentage of increase by 9% when the t1 increased from 1 to 3 seconds. These founding is in a good agreement with results Sathiya et al., 2005, 2008.

The both figure (6) and (7) show that, as the t1 increases the tensile strength drop off, and as the friction time held for 1 sec, weld strength raises to maximum values. The reason for the strength and quality values drop can be attributed to the change in the amount of heat generated during the process lead to grain coarsening and consequent reduction in strength of weldment. Therefore, interface temperature increase, results a softening of the metal at that region. The formation of wide softened regions adjacent to the bondline associated with the reduction in tensile strength. A different way of behavior was developed when the t1 rose to 3 seconds; this reverse approach may be attributed to an increased amount of softened metal flown out as a flash, which produced an increase in joint strength. Mumin et al., 2007 has shown a similar approach.

Interactions of Design Parameters: the interaction plots of means and S/N ratios are shown in Figure (8) and (9), which indicate a strong interaction between P1 and the other two parameters: P2 and t1. With little indication between P2 and t1 which is well-known as coupling effect. The degree of effect of individual parameter on weld strength is higher in a sequence of

Table 7. Effect of forging pressure on tensile strength and joint efficiency

Specimen No.	P1, bar	P2, bar	t1, sec	σ_{UTS}, MPa	η %
S11	63.8	70	2	588.800	90.12
S14	63.8	85	2	633.800	97
S14	63.8	85	2	633.800	97

Table 8. Effect of friction time on tensile strength and joint efficiencies.

Specimen No.	P1, bar	P2, bar	t1, sec	σ_{UTS} , MPa	η %
S13	63.8	85	1	686	105
S14	63.8	85	2	633.800	97
S15	63.8	85	3	628.400	96

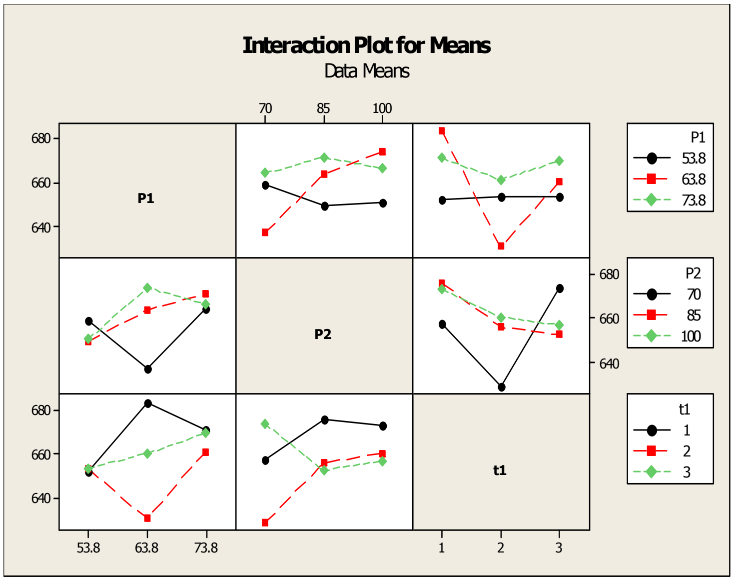


Figure 8. Interaction plots for Means of AISI 304/304 joint.

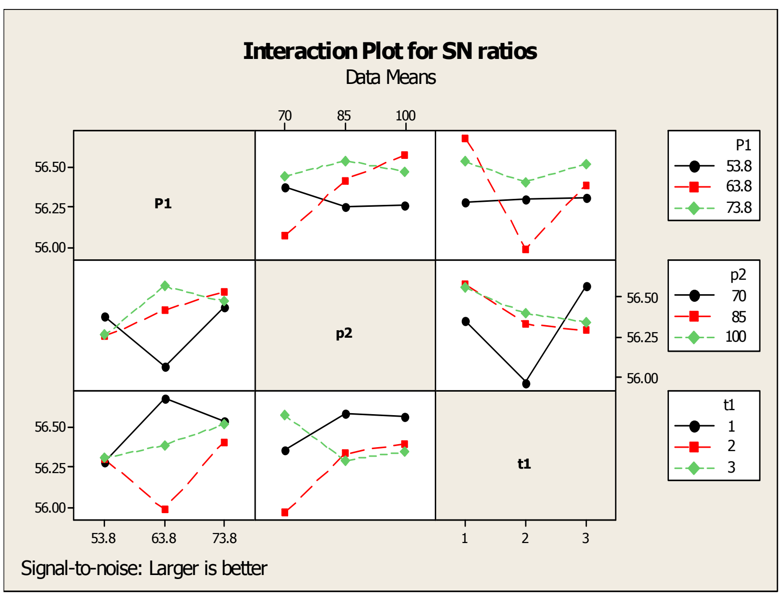


Figure 9. Interaction plots for S/N ratio of AISI 304/304 joint.

effect: t1, P1 and P2.

Weld strength is also higher when the level of each factor increases in the order of: short t1, high P1 &P2. By taking the capability of the friction machine used into consideration, the optimum tensile strength achieved when overall conditions are determined as follow: P1 (level C), 73.8 bar; P2 (level B), 85 bar; and t1 (level A), 1 sec, t2 (1.79) sec and N (931) rev/min. V.V. Satyanarayana et al., 2005, observed that individual parameters of friction welding of AISI 304/430 do not have an influence on notch tensile strength and only P1 and P2 exhibit an interactive effect. Kato and Tokisue, 1994, assure that tensile strength tend to be improved with an increase in the P1 and t1. These findings are in a good agreement with the present results.

CONCLUSIONS

The results and analyses obtained from these investigations lead to the following conclusions:

1. The microstructure of the deformed zone can be classified into three distinct regions, PZ adjacent to the weld interface, PDZ where the grains partly deformed, and UZ. The microstructure within the re-crystallized zone tends to increase with increasing t1.
2. The strength of weld joints exhibit a comparable strength with the base material with maximum efficiency of 105%, that indicates the austenitic stainless steel is quite tolerant with friction welding technique.
3. From ANOM analysis and S/N ratio, the optimized condition is:

P1 level C 73.8 bar
P2 level B 85 bar
t1 level A 1 sec

t1 is the most influential factors on weld strength. The interaction of these parameters has a major and strong effect on the weld joint quality.

ACKNOWLEDGEMENTS

The authors are kindly acknowledging help rendered by the Eng. Salah A. Elfarrah. Also the technical support of Mr. T. S. BABU is deeply appreciated. The authors would like to thank Eng. Mariam M. Morgham, Eng. Mohammed Twabi and Eng. Hassan Alsadawy, for their assistance during experimental part of this study.

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