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Effect of Mechanical Properties and Microstructural Characteristics of Friction Welded Austenitic Stainless Steel Joints

[1]N. Mathiazhagan, [2]T. Senthilkumar, [3]V. Balasubramanian

[1]*Associate Professor, Department of Mechanical Engineering, Meenakshi Ramaswamy Engineering College, Thathanur, Ariyalur DT, Tamil Nadu, India.*
[2]*Dean, Department of Mechanical and Automobile Engineering Anna University Chennai, BIT campus, Tricirappalli, Tamil Nadu, India.*
[3]*Professor, Center for Material Joining (CEMAJOR), Department of manufacturing Engineering, Annamalai university, Annamalai Nagar, Chidambaram, Tamil Nadu, India.*

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ABSTRACT

AISI 304 Austenitic stainless steels are common and familiar type of stainless steels possessing superior mechanical properties which validate their application in various fields like automotive, aerospace and nuclear applications. In this investigation, commercial AISI 304 austenitic stainless steel specimen were joined by Friction welding process and the joint performance were evaluated mechanically and metallurgically. Optimum welding parameters yielded almost 95% joint efficiency. The tensile strength of the welded joints was nearly compatible with that of the base material tensile strength. Highest Micro hardness was recorded across the weld center. The presence of four distinct regions, namely: Base Metal (BM), partially deformed zone (PDZ), Deformed zone (DZ) and transformed & recrystallized fully plasticized deformed zone (FPDZ) was evident from the microstructural studies. The XRD analysis revealed traces of α – Ferrite along with majority of γ-Ferrite at the weld joint which decreases the strength marginally. The tensile properties of the welded joints were correlated with the microstructure.

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INTRODUCION

Stainless steel, an iron based alloy, is produced with combinations of various elements to suit a wide range of applications. AISI 304 austenitic stainless steel that contain minimum of 18% chromium and 8% nickel is mainly used for nuclear and cryogenic applications (Philip D. Harvey, 1982). Selection of suitable welding process is inevitable so as to achieve high strength and quality. Solid state welding is often preferred than conventional fusion welding techniques due to simple heat flow patterns. Friction welding is a solid state joining process that produces coalescence by heat generated between two faying surfaces by a mechanical rubbing motion.

The frictional heat generated softens the material, at which the plasticized material begins to form layers that intervene with one another and results in high quality joint. Unique features of friction welding process are (1) surface cleanliness is not necessary, because friction welding squeezes and expels the softened interfacial zone out along with trapped oxides and contamination into the flash. (2) filler metal, flux and shielding gas are not required. (3) Friction welding does not melt at the bond. In friction welding process, materials are joined in series of 5 sequential stages. Stage 1: generation of heat by sliding friction while the torque reaches its maximum value. Stage 2: faying surfaces plasticizes due to heat generation by mechanical dissipation and softened material flows radially outwards. Stage 3: a steady state situation is attained and the torque, temperature distribution and rate of axial shortening (burn-off) are essentially constant. Stage 4: the rotation terminated. Stage 5: upsetting occurs (Nicholas, E.D.,; Lucas, W., 1971).

The critical parameters in the friction welding process, schematically represented in fig. 1, are Friction time, friction pressure, forging time, forging pressure and rotation speed. Advantages of Friction welding includes low production time, minimum material waste, effective control of welding parameters, low energy consumption for joining, excellent efficiency of work. Some important methods of relative movement between the faying surfaces in friction welding process are rotational, linear, angular or orbital types (Avinash, M., 2007).

Corresponding Author: N. Mathiazhagan, Associate Professor, Department of Mechanical Engineering, Meenakshi Ramaswamy Engineering College, Thathanur, Ariyalur DT, Tamil Nadu, India.

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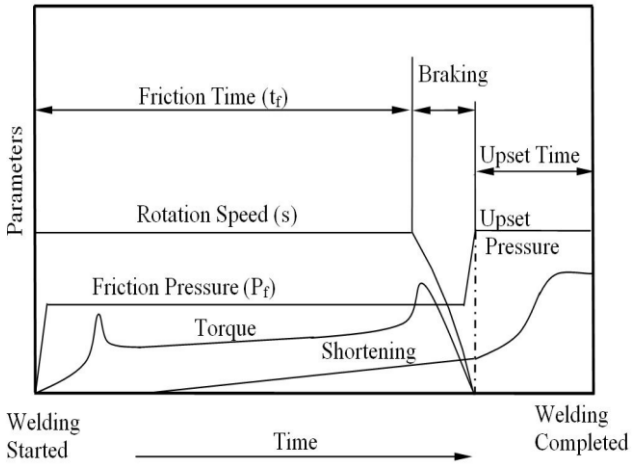

Fig. 1: Process parameters of continuous drive friction welding process (Mumin Sahin and Cenk Misirli,).

2. Literature Survey:

Several literatures highlight the effects of friction welding parameters on the quality of steel joints. Mortenson *et al* (2001) investigated, the friction welding of 416 stainless steel, its tensile strength and impact toughness, welding parameters, sulfur orientation, and brittle failure of friction weld. Takeshi *et al* (1994) studied the influence of welding parameters on tensile properties of friction welded joints by similar materials of spheroidal graphite iron casting and gray iron casting. Dunkerton *et al* (1986) investigated the effects of the parameters such as rotation speed, friction pressure, and forging pressure in friction welding methods for steel. Lippold *et al* (1984) investigated annealed 416 stainless steel welds, which would be susceptible to hot, or cold cracking, or heat affected zone micro fissures. M.Sahin *et al* (2003) analysed the mechanical properties of AISI 1040 medium carbon steel and concluded that the tensile strengths of the friction welded specimen were 95% as that of base metal.

Based on the literatures, extensive publication on friction welding of dissimilar stainless steel is observed. However, Evaluation of joint properties of similar welding of AISI 304 austenitic stainless steel can be counted in fingers. This investigation evaluates the tensile and metallurgical properties of friction welded austenitic stainless steel joints.

3. Experimental Procedure:

Table.1shows the chemical composition of the base metal used in this investigation. 20 kN, hydraulic controlled continuous drive friction welding machine, as shown in fig. 2, was used to fabricate cylindrical rods of 15mm diameter and 75 mm length. Several trails were performed to optimize the process parameters and the table 2 depicts the optimum parameters used in this study.

Table 1: Chemical composition of base metal

C	P	S	Mn	Si	Ni	Cr	Fe
0.046	0.044	0.006	1.20	0.44	8.17	18.33	Bal

Fig. 2: Continuous Drive Friction Welding Machine.

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Table 2: Optimized friction welding process parameters.

Rotational speed (rpm)	Friction pressure (MPa)	Forging pressure (MPa)	Friction time (s)	Forging time (s)
1100	50	50	3	3

Fig.3 depicts the photograph of friction welded joints. Conventional lathe machine was used to machine the flash in the welded joints and were smoothly grinded. ASTM E8 (2004) standards were followed to prepare two different sets of 12 mm diameter cylindrical tensile test specimens, Smooth and Notched, as presented in figures4a&b and tested in a 100kN, electro-mechanically controlled Universal Testing Machine(Make: FIE-BLUE STAR, India; Model: UNITEK-94100). The specimens were loaded at the rate of 1.5 kN/min so that the specimens undergo uniform deformation. The specimen finally failed after marginal necking and the load vs. displacement was recorded. 0.2% offset yield strength was derived from the graph. Vickers's microhardness testing machine (Model:3212 and Make:Zwick) was employed with 0.05 kg load applied for 15 sec time interval for measuring the micro hardness along the horizontal axis of the welded specimen. Optical microscopy of the joints was done to observe the changes in microstructure in the interface region using a light optical microscope (Model: ML7100 and Make: MEIJI, Japan) incorporated with Clemex vision image analyzing software. The specimen for microstructural analysis was sectioned from the joint comprising base metal, heat affected zone and weld interface. Aqua regia was used to etch the polished specimen so as to reveal the microstructure. Scanning electron microscopy (Model: 6410- LV; Make: JOEL, Japan) was employed to observe the fracture surface. X-ray diffraction analysis was done to identify the phases at the weld interface.

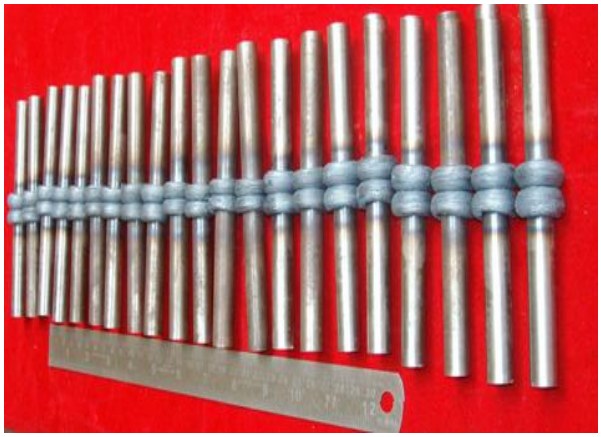
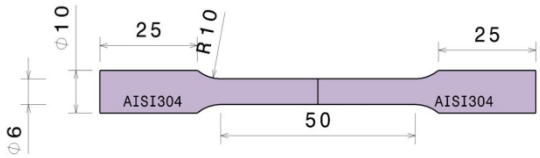
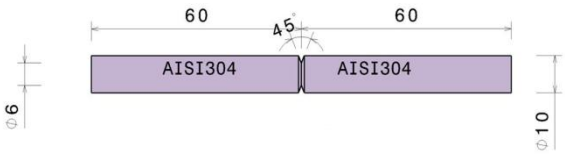


Fig. 3: Photographs of Friction Welded AISI 304 SS joints.



a. Tensile Specimen (Smooth)



b. Tensile Specimen (Notch)

Fig. 4: Tensile Test Specimen as per ASTM E8 Standards.

RESULTS AND DISCUSSION

4.1 Mechanical Properties:

In this investigation, forging pressure was varied from 30 MPa to 60 MPa and forging time used are 3, 4 and 5 seconds respectively. Of the five different rotational speeds (800, 900, 1000, 1100 and 1200) used, 1100 rotational speed with frictional pressure 50 MPa and friction time of 3 seconds yielded better tensile strength. Photographs of the tensile smooth

and notched specimen (before testing and after testing) are presented in fig 5. Average tensile strength of three similar friction welded specimen and the base material tensile strength are presented in table 3.All the specimen failed exactly at the weld interface. It is inferred from the results that friction welded specimen tensile strength are comparable with that of the base material. A linear relationship exists between tensile strength and rotational speed. With a rotational speed of 1100 rpm and forging pressure of 50 MPa, maximum tensile strength (713 MPa) is recorded. Higher rotational speeds (1200 rpm) resulted in reduced tensile strength due to wider heat affected zone (HAZ). Almost all specimens welded at rotational speeds of more than 1200 rpm failed in HAZ. Lower rotational speeds resulted in improper plastic deformation as the frictional effect is not sufficient for generating required heat. As reported by, Insu Woo *et al* (2002) poor tensile properties may be due to low friction or increase in nitride precipitation. Hence, the weldments could not sustain high tensile loads. The maximum joint efficiency obtained was 95% which indicates, AISI 304 can be successfully welded using friction welding process, similar with the previous studies of Mumin *et al*., (2007) and Hussein *et al*, (2013).

Elongation measured for the joint obtained at a rotational speed of 1100 rpm is higher than the other joints. However, the elongation obtained is lower than the base metal which is attributed to the grain refinement due to high plastic deformation.

a. Before Testing **b. After Testing**

Fig. 5: Photographs of Tensile Test Specimen.

Table 3: Mechanical properties of the base metal and friction welded joint.

Specimen	0.2% YS (MPa)	UTS (MPa)	NTS (MPa)	% Elongation	NSR	Joint Efficiency
BM	677	755	1250	39.5	1.66	-
Friction Welded Joint	645	713	1116	5.66	1.58	94.4 %

Notch sensitivity is the tendency of reduced ductility in the presence of triaxial stress field and steep stress gradients. As per ASTM guidelines, notch with 45^{o}angleand 0.025 mm root radius was introduced in the tensile specimen to evaluate notch sensitivity. The depth of the notch is such that the cross sectional area at the root of the notch is one-half the area in the unnotched section. The specimen is carefully aligned and loaded in tension until failure. Notch strength ratio (NSR) is the ratio of notch strength to the ultimate tensile strength of the unnotched specimen and is a measure of notch sensitivity. If it is greater than unity (NSR>1), then the material is notch ductile (Dieter, D.E., 1988). It is inferred from table 3 that NSR is greater than unity hence both the base material (AISI 304) and friction welded specimen are reasonably notch ductile.

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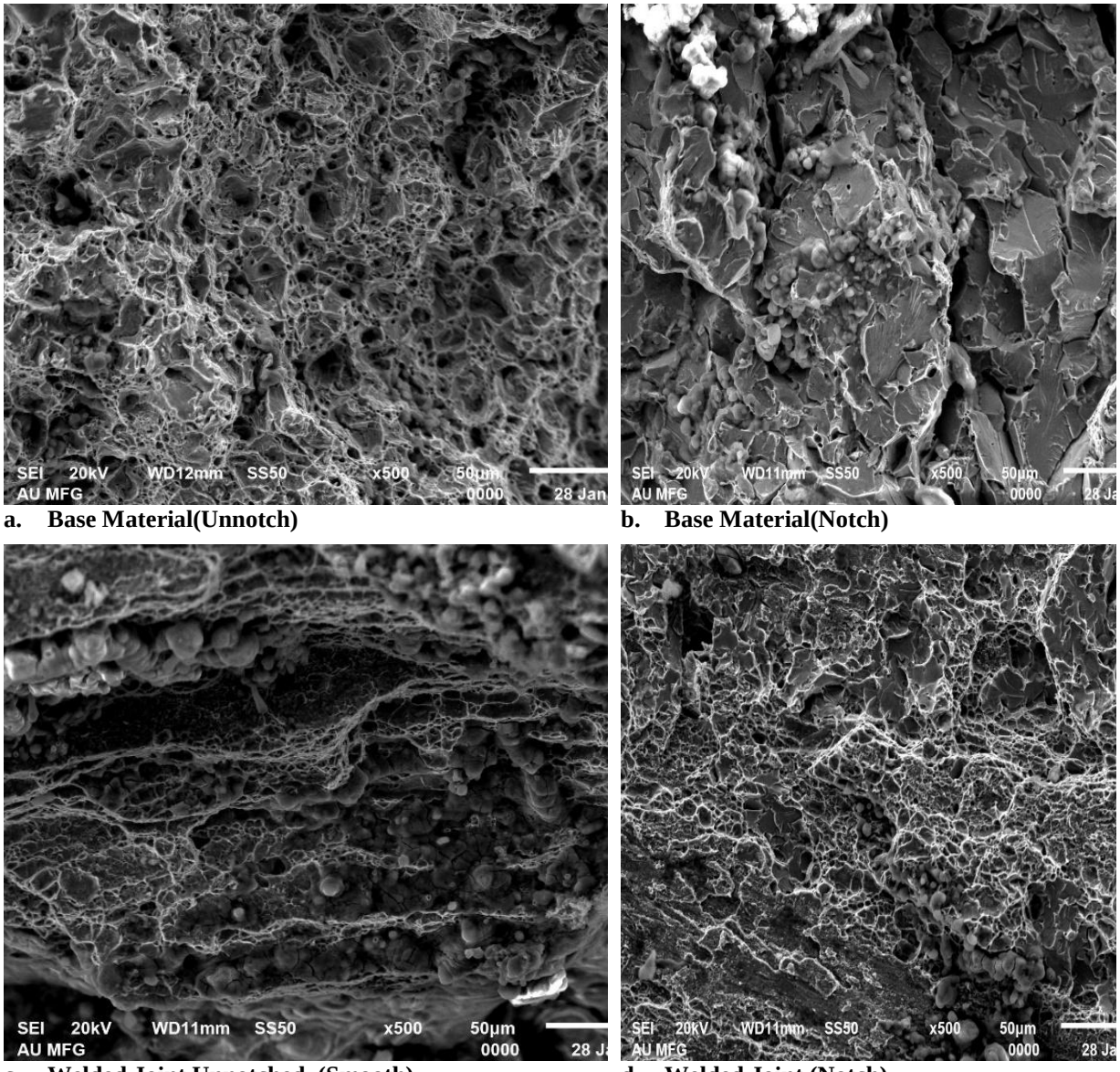
4.2 Fracture Surface Examination:

Figures (6 a- d) depicts the fractographs of smooth and notch tensile specimen of both base material and friction welded joints respectively. Ductile mode of failure is observed from smooth tensile specimen of the base material, fig (6-a). River markings can be seen which is a unique feature of the ductile fracture. Fig [6-b] represent the fractograph of base material in Notched condition where the specimen fractured by Cleavage mode. The surface of the specimen is totally ruptured due to loading. SEM micrograph of the welded specimen both unnotched and notched, as represented in figures [6c &6d] show cleavage mode of fracture. Dimples are not seen in the both the smooth and notch specimen. Weld region failures have been observed in all the friction welded specimen and similar trend was reported by Linert *et al* (1998).



a. Base Material(Unnotch) **b. Base Material(Notch)**

c. Welded Joint Unnotched (Smooth) **d. Welded Joint (Notch)**

Fig. 6: Fractographs of Base Material and welded joints.

4.3 Microhardness Survey:

The cross sectional hardness profile along the horizontal direction from the weld center is shown in fig. 7. Base material hardness is about 210 HV whereas the hardness of the weld region is higher than the base material hardness. Maximum hardness of 240 HV is recorded in the weld center which is due the peak temperatures attained during frictional contact at the faying surfaces. A decreasing trend from weld interface on either side is observed in the interface region. Interface hardness is 196 HV on either side. The hardness in the HAZ region varies. An increasing trend is observed in the positive distance (4mm) from the weld center and hardness decreases in the negative side. This is attributed to the spherical rings that are formed in the positive side

than in the negative side during the friction welding process. These rings offer a detrimental effect on the strength as reported by Linert *et al* (1998). Minimum hardness of 170 HV is recorded at a distance 4mm from the weld center in the negative direction Grain coarsening is evident in HAZ region and the varying thermal cycles has an influential effect in HAZ region.

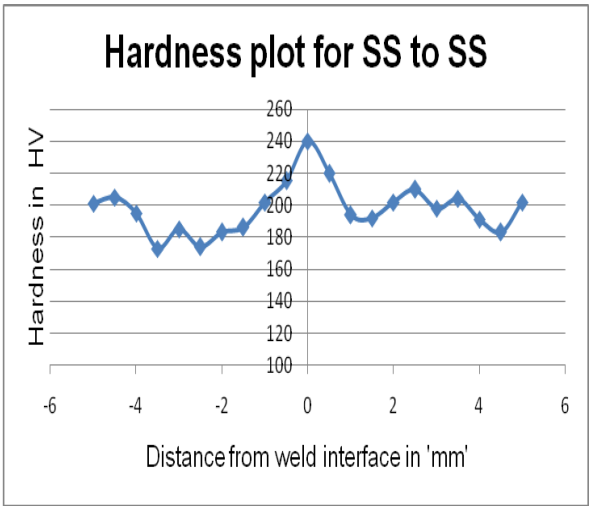


Fig. 7: MicroHardness Survey across the joint.

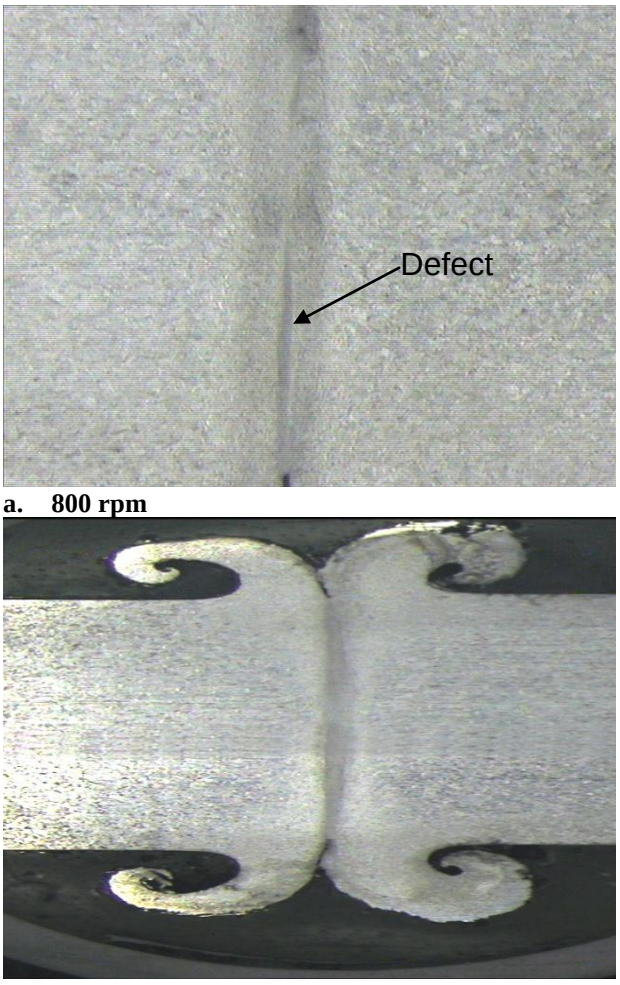
Many researchers have highlighted the relationship between flash formed and the friction pressure and friction time. Hazlett *et al* (1963) reported that the amount of flash formed is linearly proportional to friction time. This is attributed to the increased plastic deformation with increase in friction time and forging pressure. Fig. (8a) shows the unbonded macrostructure of the joint welded using 800 rpm and fig. (8b) depicts the defect free macrostructure of the friction welded joint with a rotational speed of 1100 rpm and friction time of 3 seconds. Rotational speeds of 800 and 1000 rpm resulted in insufficient bonding with minimum flash. Higher rotational speed of 1200 rpm increased the axial shortening by increasing the frictional heat between the faying surfaces. The average flash formed was measured to be 2.6 % more when friction time and friction pressure was increased to 5 sec and 60 MPa. Optimum rotational speed of 1100 rpm, friction time of 3 Sec and forging pressure of 50 MPa resulted in reasonable flash than other parameters.

Microstructural examination of the friction welded AISI 304 Stainless steel joints revealed four distinct regions, as presented in fig 9a-d, namely: Base Metal (BM), partially deformed zone (PDZ), Deformed zone (DZ) and transformed and recrystallized fully plasticized deformed zone (FPDZ). The mechanical deformation and frictional heat at the interface that dissipated through the base materials had resulted in temperature gradient causing zones with different microstructures (Andrzej Sualec, 1990). It is inferred that base material consists of coarse grains than the welded specimen. Depending on the angular velocity, in the weld interface, temperature at the center is minimum. While the temperature at the circumference is maximum. Higher microstructural changes took place in the FPDZ and DZ region. Weld region geometry and width is affected by rotational speed. High rotational speed causes local interface temperature to reach above critical (solidus). As a consequence of the increase in the interface temperature, more mass is transferred out of the interface thus the width of FPDZ region was narrowed. Most of the microstructural changes took place in FPDZ and DZ region as shown in fig 9b.Grain refinement is evident in FPDZ than PDZ. It is evident from the macrostructure that bonding is predominantly affected by the rotational speed and the forging pressure. The hardness results pointed out that a high rotational speed positively affects the hardness occurred in the weld interface for FW (Yilbas, B.S., 1995). It is well known that under pressure the interface undergo plastic deformation resulting in dynamic recrystallization leading to grain refinement in the weld interface as shown in fig 9a. From both the SEM pictures and hardness distributions, it is inferred that the rotational speed is very much influential on the microstructural changes formed at weld interface.

4.5 X-ray Diffraction Analysis:

Generally, mechanical properties of the friction welded joints has a linear relationship with rotational speed. Increase in rotational speed, causes the introduction of a higher interface temperature and repulsion of the brittle intermediate phase outside the interface and hence result in improved tensile properties. One of the main concern for many researchers (Ates, H., N. Kaya, 2014; Özdemir, N., F. SarsIlmaz, 2007; Eder Paduan Alves,2010;

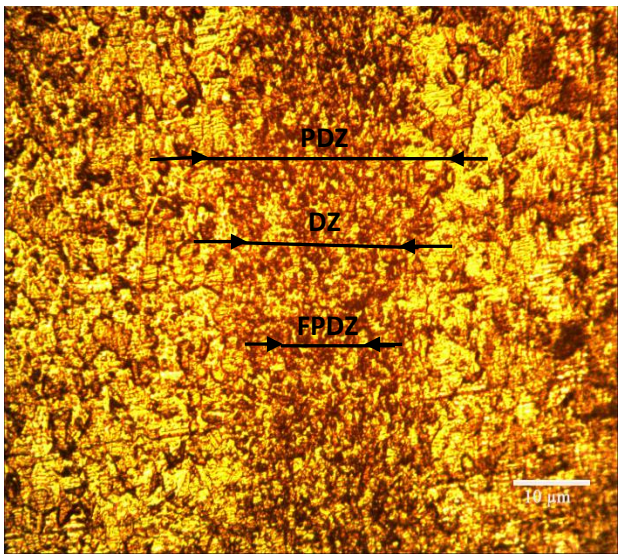
Sathiya, P., S. Aravindan, *et al*., 2008) in friction welding of AISI 304 stainless steel is the formation of σ-phase and fine grained brittle region which occurs with the effect of cold plastic deformation. Therefore it must be kept as narrow as possible.



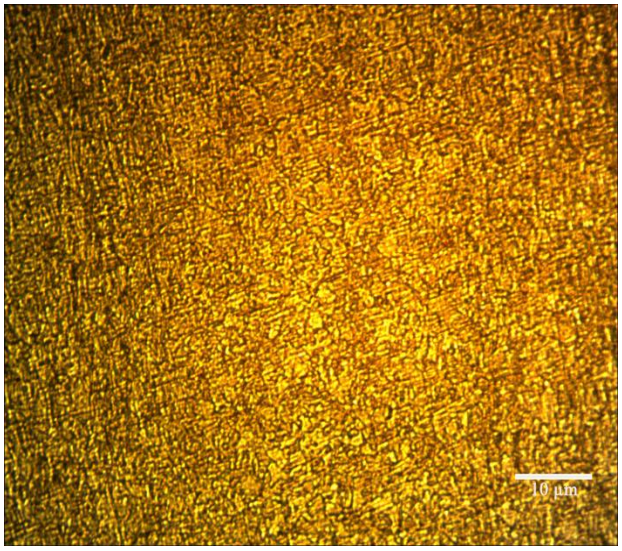
a. 800 rpm

b. 1100 rpm

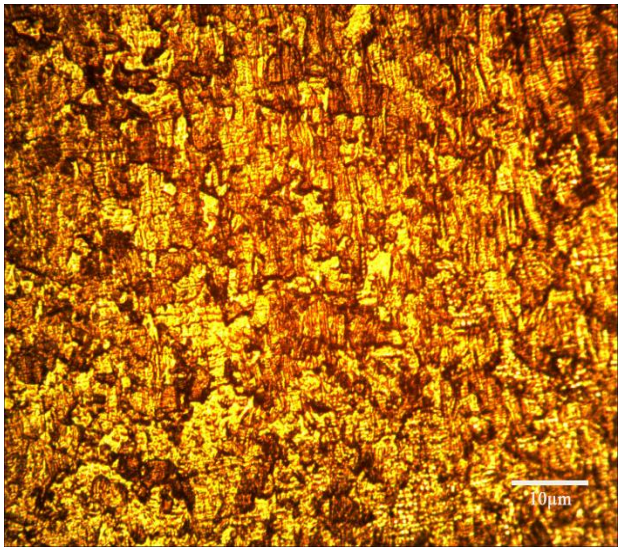
Fig. 8: Macrostructure of Friction Welded AISI 304 Stainless Steels.



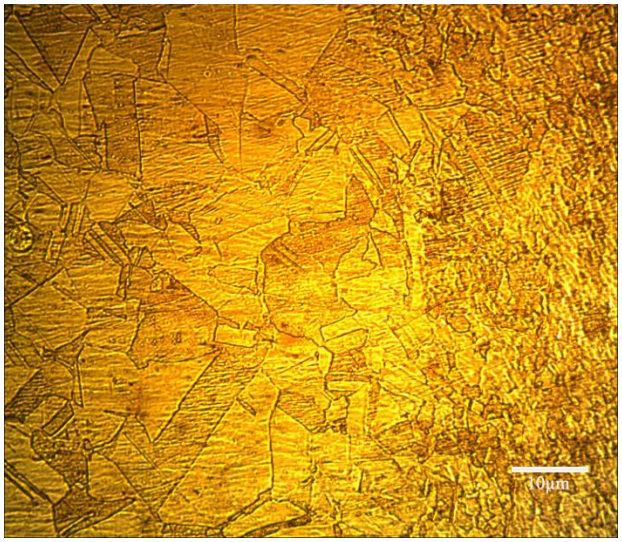
a. Weld Interface



b. FDZ



c. PDZ



d. HAZ

Fig. 9: Microstructure of the different zones of Friction Welded AISI 304 Stainless Steels.

Though the tensile strength is good, surprisingly elongation at break and the joint efficiency obtained are well below the expected value. An X-ray diffraction analysis of the welded specimen were carried out. Observed XRD patterns are displayed in fig 10 and the peaks are indexed to the γ -phase and α-ferrite (JCPDS: 33-0397 and 65-4899). It is inferred that for achieving high strength at welding interface, the brittle phases such as γ -phase and α-ferrite should be pushed out of the interface. Also, the degree of temperature that was introduced at welding interface by friction has an important effect on the plastic deformation. At rotational speeds of 1100 rpm the interface temperature is ambient for the formation of brittle region at the weld interface which resulted in failure without much ductility. This could be the reason for reduced joint efficiency and elongation. In case, if the friction time held is long, a broad HAZ with intermetallic, brittle phase can be generated for Friction Welded stainless steels. For short friction time, because of low interface temperature, and low plastic deformation, the bond is weak.2

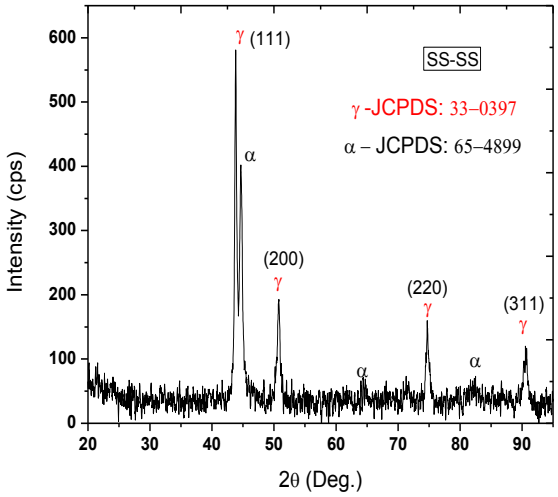


Fig. 10: XRD Pattern of the Weld Interface.

4. Conclusions:

The following important conclusions are derived from this investigation:

1. Optimum weld parameters of 1100 rpm with 50 MPa forging pressure and 3 Sec forging time resulted sound weld with 95% joint efficiency. Axial shortening increased exponentially with the increase in friction time. Introduction of notch at the interface does not influence the strength.
2. Extensive grain refinement in the interface at optimum rotational speed of 1100 rpm was observed. Formation of brittle intermetallic phase at the interface reduced the strength resulting in weld interface failures.
3. Maximum hardness of 240 HV was recorded at the weld center and varying thermal cycles influenced the HAZ and resulted in grain coarsening.

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