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Joining of Dissimilar Steels by Friction Stir Welding: Process and Property Evaluation

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ABSTRACT

Initially friction stir welding (FSW) was mainly used for welding of aluminium and its alloys but for last few years great interest has been seen to join high strength metals by this process. Industries producing space satellite and airplane, nuclear reactors, heat exchanger, boiler have shown increasing interest in the friction stir welding process to join dissimilar metals because of its clear advantages compared with fusion welding processes. This joining technique is energy efficient, environment friendly, and versatile. This study tried to use FSW process for joining of dissimilar steels and properties of weld were studied.

1. INTRODUCTION

In early days FSW was mainly used for welding of aluminum and its alloys but from last few years great interest is seen to join high strength metals by friction stir welding. The main advantage of friction stir welding is that joints is produced below the melting temperature of the metals so the fear of elimination of the alloying element is totally eliminated which is the major problem of the fusion welding processes.

In this report the various friction stir welded metal system is studies. In the second part of the report the welding of dissimilar metals by laser beam welding was focused. Laser welding is also considered a great technique in radiant energy welding process. In this process the beam position and mode of operation has a great effect on weld quality. It was seen that in pulse mode of operation better weld quality was obtained than the continuous mode of operation. The microstructure of the various welds was studies and found that the cooling rate has a great effect on grain formation. If the cooling rate is high then fine grain formation will take place.

Effect of peak power also shows a proportional effect on penetration depth. The various mechanical property of weld was also study in this study. FSP uses the same methodology as friction stir welding (FSW), but FSP is used to modify the local microstructure and does not join metals together [1]. FSP provides the ability to thermo mechanically process selective locations on the structure's surface and to some considerable depth (>25mm) to enhance specific properties [2]. The amount the tool shoulder is plunged into the work piece is known as the heel plunge depth. Tool features such as scrolls, flats, thread, etc. have been defined, says Thread gill, adequately though alternative use and thus continued usage of these terms is permissible [3].

Dissimilar materials often enable the attainment of high structural efficiency in several ways. Dissimilar materials also might provide damage tolerance to the overall structure by changing the material and elastic properties along a potential crack path. Dissimilar materials can also optimize a design by matching the correct material to the needed property or behaviour (e.g., refractoriness, electrical conductivity, thermal or electrical insulation, or corrosion or wear resistance), rather than compromising some areas of the design (or structure) by settling for a less-than-optimal material to fabricate the entire structure. In addition to these important property advantages, the use of dissimilar materials often allows the costs of raw materials and/or fabrication and/or operation in service to be minimized by allowing optimal materials to be used in specific areas of the design [4]. Thus this increased and often simultaneous demands for higher quality, better performance, longer life, higher reliability, and lower cost are causing the joining of dissimilar materials to become increasingly important.

The fundamental challenge of joining dissimilar materials is compatibility. In order to produce an acceptable joint in terms of structural strength, structural integrity (i.e., quality and reliability), and structural efficiency, the different chemical, physical, and mechanical properties of the various materials being joined must be compatible. In conventional welding problems such as the carbon migration from the higher carbon containing alloy to the relatively lower carbon alloy steel may occur, the differences in thermal expansion coefficients, the difficulty in executing the post-weld heat treatment and the electrochemical property variations in the weld [5-7].

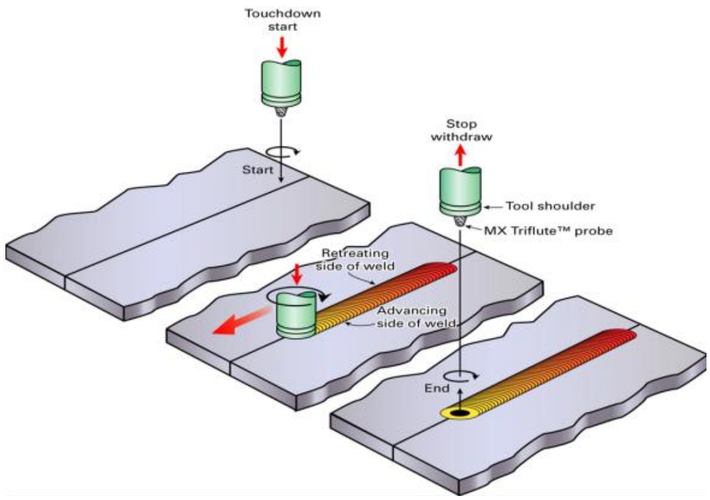

Figure 1: Schematic of FSW [1].

2. LITERATURE SURVEY

Microstructure evolution

Due to the plastic deformation and high-temperature within the stirred zone during FSW results in re crystallization and development of texture within the stirred zone and precipitate dissolution and coarsening within and around the stirred zone. Based on microstructural characterization of grains and precipitates, three distinct zones, stirred (nugget) zone, thermo-mechanically affected zone (TMAZ), and heat-affected zone (HAZ), have been identified as shown in Fig.2.

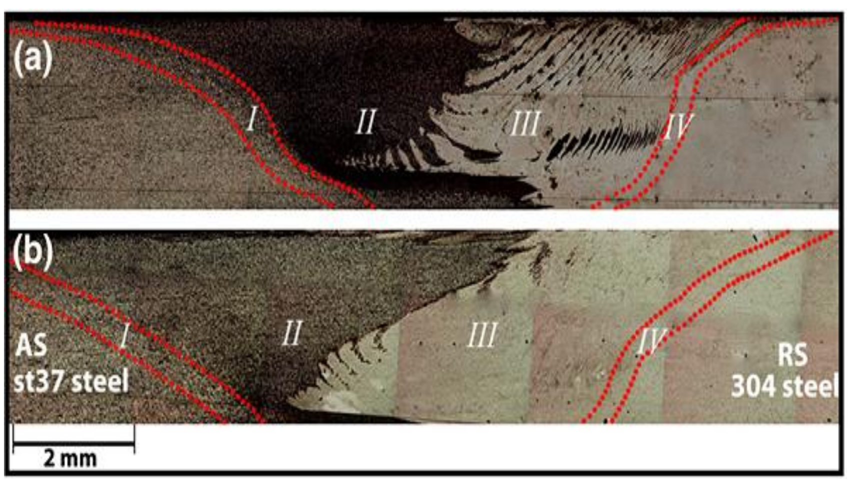

Figure 2: Different micro structural regions in the cross-section of the welds [10].

M. Jafarzadegan et al [1] Studied FSW of 304ASS and St-37 steels by using a tool of WC-Co with a welding speed of 50mm/min at varying (400-800) rpm and found that there is no onion ring structure. A K Lakshminarayanan et al [2] reported the study the variation of welding speed on 1060 aluminum alloy and pure copper by a quenched and tampered steel tool and found that at high welding speed cavity defect was seen in the stir zone due to insufficient heat input at high welding speed.

Sanghoon Noh et al [3] studied the effect of tool plunging and position of steel on F82H and SUS304 steels and reported Optical microscopy and EDX analysis to characterize the dissimilar joint microstructures and the interface. When the dissimilar FSW was performed with soft materials on the advancing side and the tool plunged on the soft materials side at the welding temperature, the interface as clearly divided into the soft and hard materials and no mixed structure was observed

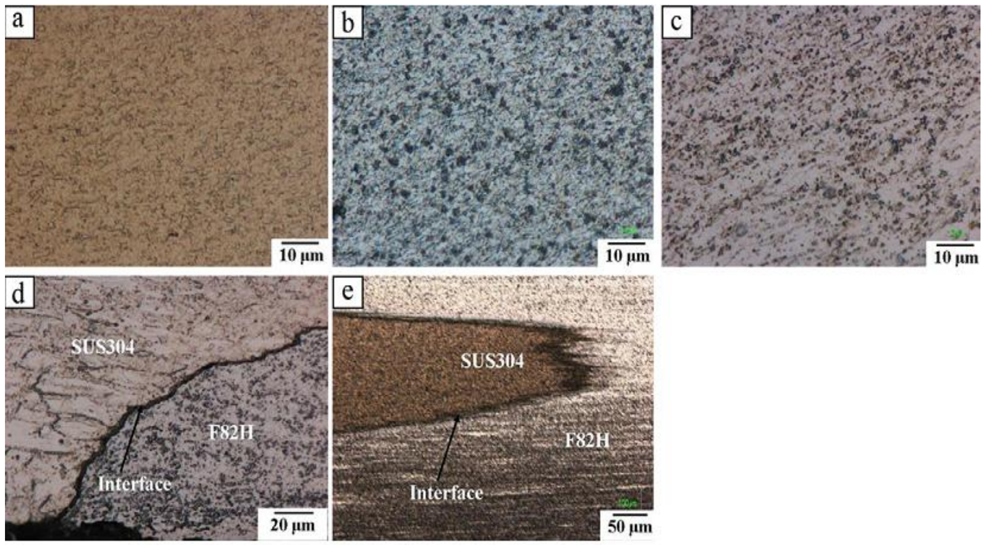

Figure 3: Microstructures of FSW joint under condition of : (a) stir zone in SUS304, (b) stir zone in F82H, (c) HAZ on the advancing side (F82H), (d) interface inSUS304/F82H and (e) microstructure of SUS304/F82H [11].

R.S. Mishra, et al [5] studied the effect of tool plunging on dissimilar metals FSW weld of pure copper/1350 aluminium and found that when offset was 2.6mm groove defect formed but at 2mm offset a sound weld was obtained. The grains of both materials were greatly refined in SZ due to dynamic recrystallization. Young Dong Chung et al [6] performed FSW on 14YWT ferritic alloy and F82H tempered martensitic steel by a tool of polycrystalline cubic boron nitride and saw the Joints and interfaces by light microscopy and SEM analysis to be narrow in width. Z.Y. Ma et al [12] conducted FSP on sand-cast A356 plates under wide FSP parameters. Their results indicated that FSP resulted in the significant breakup of coarse acicular Si particles and coarse primary aluminum dendrites, the closure of casting porosities, and the uniform distribution of broken Si particles in the aluminum matrix (Figure 2.1). Increasing the rotation rate and number of FSP passes resulted in a decrease in the size and aspect ratio of the Si particles and the porosity level, due to the intensified stirring effect.

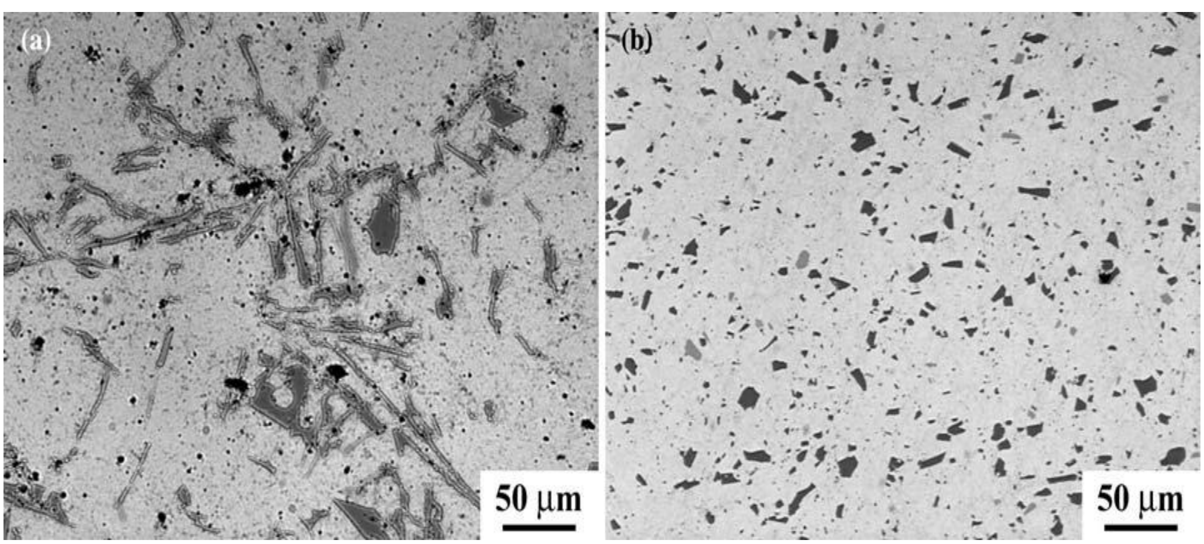

Fig. 4: Optical micrographs showing morphology and distribution of Si particles in A356 samples: (a) as-cast and (b) FSP at 900 rpm and 203 mm/min.[3]

T.S. Mahmoud et al [10] show the effect of the tool rotational and traverse speeds as well as the number of passes on the microstructure of the modified surfaces was investigated. The as-cast A390 alloy exhibited mean size and aspect ratio of Si particulates of about 59 ± 24 μm and 3.56 ± 1.9, respectively. In an another study A.G. Rao, et al [16] demonstrates the effect of two pass overlap friction stir processing on micro structural refinement of Al–30Si alloy, which delineates significant reduction in size and aspect ratio of silicon particles from average 200 to 2 μm and 4.93 to 1.75 μm respectively. In a continuation with the previous investigation the author found that the micro structural evolution and related dynamic recrystallization phenomena were investigated in overlapping multipass FSP of hypereutectic Al-30 Si alloy [17-19].

Mechanical properties
Hardness

M. Jafarzadegan et al [1] Studied FSW of 304ASS and ST-37 steels and found that the hardness of SZ of both metals increased. The hardness of ST-37 steel BM was approximately 120 HV. As mentioned above, the SZ of ST-37 steel had a refined ferrite and pearlite structure. The reason for hardness increase to about 160 HV in ST-37 steel SZ was the strength of low-carbon steel which is sensitive to grain size. The hardness of 304 steel BM was about 180 HV. The grain refinement increased the hardness to 240 HV in 304 steel.

R. Nandan et al [7] studied the effect of position of steel on strength of F82H and SUS304 steels weld and found that F82H on the advancing side and tool plunged on the F82H plate was more appropriate for the dissimilar friction stir welding conditions. The tensile strength of the dissimilar friction stir welded SUS304/F82H joints (F82H on the advancing side) was same with the base metal because the dissimilar welded SUS304/F82H joints fractured on the F82H side base metal as given in table below.

Table 1: Tensile strength and appearance of joints after tensile test [20]

		Tensile Strength (MPa)	Elongation (mm)	Fracture Appearance
Base metal		610	20	—
RS	AS	RS		AS
SUS304	F82H	610	11	
F82H	SUS304	182	0.48	

Strength and ductility

M. Jafarzadegan et al [1] Studied FSW of 304ASS and St-37 steels and found that the weld had good strength and ductility. The 304 steel BM has the same YS and relatively high ultimate tensile strength, compared to ST-37 steel BM. The FSW sample has higher yield strength in SZ than that of BM due to the formation of fine grains and lower UTS than 304 steel but higher than that of ST-37 steel. D.T. Hoelzer et al [21] studied on dissimilar weld of pure copper/1350 aluminum they found that the strength of dissimilar joints is relatively good with an ultimate tensile strength (UTS) of 152 MPa, which is 74% that of the 1350Al BM. The elongation of the dissimilar joints was 6.3%. Due to the inhomogeneous microstructure, the strength of the dissimilar FSW joint is generally lower than that of the base materials.

Fatigue

For many applications like aerospace structures, transport vehicles, platforms, and bridge constructions, fatigue properties are critical. Therefore, it is important to understand the fatigue characteristics of FSW welds due to potentially wide range of engineering applications of FSW technique. Friction stir welding (FSW) has good fatigue resistance for aluminium and magnesium alloys, with respect to traditional fusion techniques.

T. J. LIENERT et al [22] studied the fatigue behaviour of dissimilar weld on AA2024-AA7075 for position of tool from the centre line of the weld. The fatigue limit estimated at 1×10E6 cycles at all positioned in between 70 MPa and 110 MPa stress amplitude, showing good fatigue performance of FSW joints as shown in figure below.

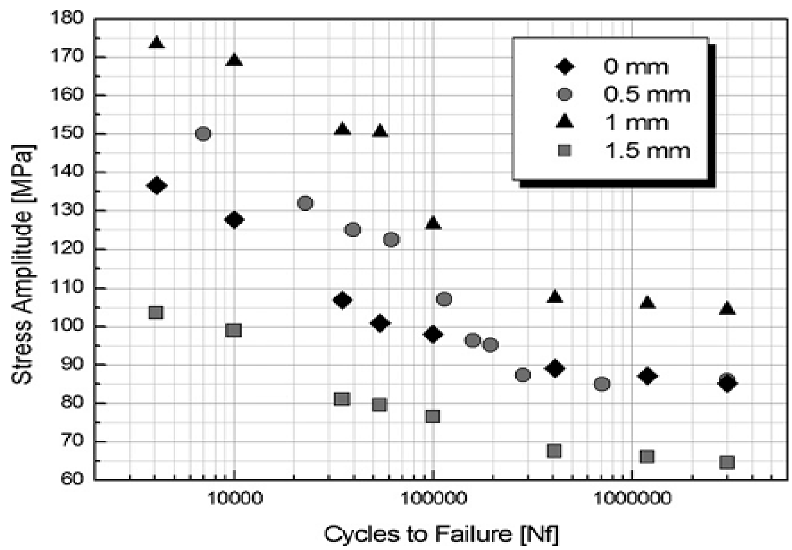

Fig. 5: S–N curves of the different studied joints [23].

In this study the fatigue crack growth was also observed a lower crack growth rate in the samples welded with the tool at a distance of 1 mm from the joint line as shown in figure 5.

3. EXPERIMENTAL WORK

Friction stir welds were produced on plates of mild steel and ferritic stainless steel in both similar and dissimilar manner of 3mm thickness with welding direction parallel to the rolling direction by friction stir welding machine shown in figure below. The composition of the base materials is shown in the table.

Table 2: Measured composition of base metals.

BM	C	Mn	S	Si	P	Cr	Ni
FSS	0.03	0.8-1.5	0.03	1	0.05	10.8-12.8	1.5
MS	.243	1.06	.016	.097	.018	.047	.022

Figure 6: FSW tool preparation.

The welds were made in the square groove butt joint configuration on the samples of 150mm*50mm*3mm. The welding of the mild steel plates was done in annealed condition whereas of stainless steel plates were welded in as given rolled condition. Annealing of mild steel plates was done at 750°C for 1 hour followed by furnace cooling. In furnace cooling the cooling rate was maintained at 50°C -60°C/hour [28]. First a tool having probe of WC and remaining body of tool steel (H-

13) was used to perform welding but the tool failed due to excessive heat generation when transverse speed was given to the tool after plunging. After this tool failure WC-4.5%TiC tool was used for welding.

Process parameters

Trial experiments were conducted to select the tool material and process parameters. Initially tungsten carbide pin was used with mild steel tool but this tool failed as shown in the figure below. Also macro structural analysis was carried to find out the optimum process parameters. The optimized process parameters and welding conditions were used to weld the plates for further investigation. The effect of tool transverse speed on weld properties of dissimilar weld was also investigated in this study.

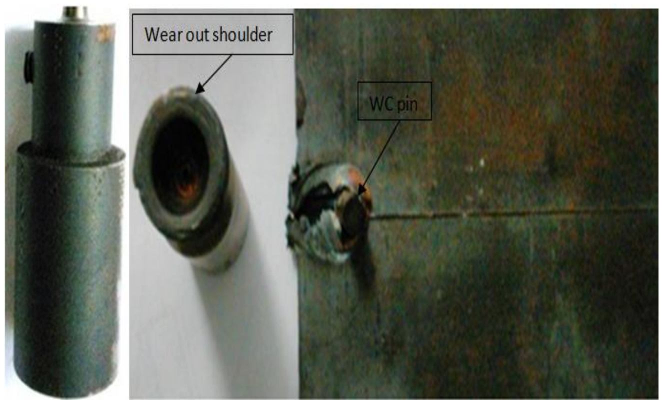

Fig. 7: Trial tool of tool steel with WC probe and wear out tool.

At too low traverse speed there was failure of base plate i.e. plate melted down due to excessive heat during the welding process as shown in the figure 7.

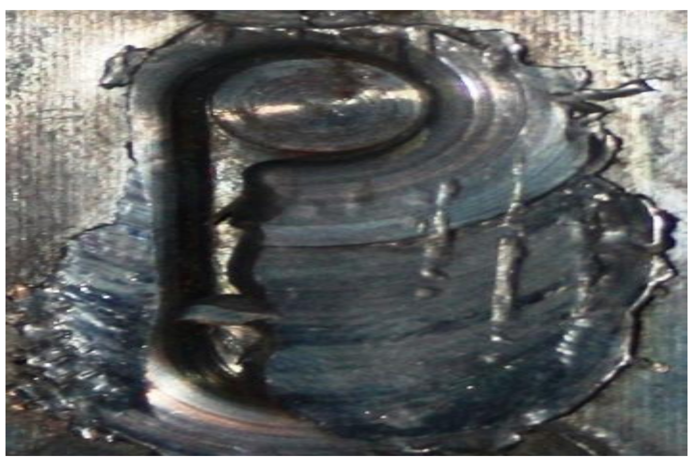

Fig. 8: Plate melted down at low traverse speed.

Table 3: Welding conditions and process parameters.

Sr. no.	Parameter	Welding condition
1.	Welding speed	22 mm/min
2.	Rotational speed	512 rpm
3.	Tool shoulder diameter	24 mm
4.	Pin diameter	7-10 mm
5.	Pin length	2.8 mm

Fig. 9: FSW machine during the weld.

FSW process Samples for testing

During the friction stir welding of photograph was taken, Tool wear and deformations are the two important issues for FSW of steels because they affect the weld quality. The rate of tool wear was found higher in the initial stage of plunging. To reduce the tool wear compressed air was used for cooling purpose of tool.

Fig. 10: Tensile test specimen.

The microstructural study of the weld was carried out by optical microscope and scanning electron microscope. The transverse section of weld was polished by emery papers till 2000 grit size and then etched by 2% nital solution for mild steel and by Villella for stainless steel similar and dissimilar welds to reveal the macro and micro structures [11-13]. The analysis of the microstructure was done by image j software. To study the mechanical property hardness and tensile test were carried out. By using Vickers indenter micro-hardness profile of the joint interface was measured at the weld centre with 200gm load and dwell time of 10 second at a regular interval of 1mm**.**The welded joint was cut into required dimension for further testing. For preparing transverse and longitudinal (all weld sample) tensile test specimens ASTM E-8 guidelines was followed and yield strength, tensile strength and elongation were measured. The tensile testing was performed on universal testing machine (Make: Instron USA; model-5980) of capacity 100KN. The tensile testing was carried out at room temperature at strain rate of 1mm/min.

Fig. 11: UTM used for tensile strength test.

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4. RESULTS AND DISCUSSION

FSW was performed on mild steel and ferritic stainless steel plates to produce dissimilar weld. A sound weld was produced by FSW with no surface irregularities (12). The effect of traverse speed on weld properties was also studied and found that as traverse speed increases, stirring and mixing of material decrease due to which strength of the weld decreases. Table 4. shows the low macroscopic image of transverse section of the welds.

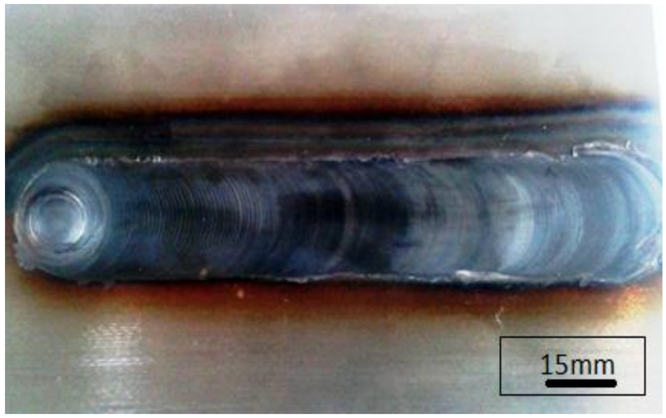
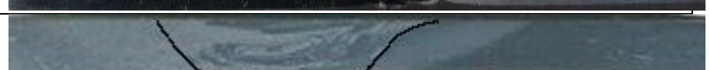
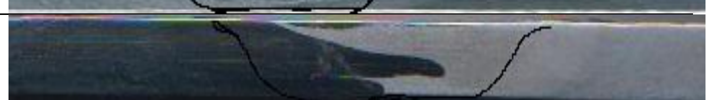


Fig. 12: Weld appearance without surface defect.

Effect of traverse speed on strength of joint

The effect of traverse speed on weld strength and ductility was also studied and found that on increasing traverse speed strength of the weld decreases whereas ductility increases. Due to the increase in traverse speed heat going to work per unit time decreases and proper stirring and mixing of the material in not take place [29-32].

Table 4: Effect of traverse speed on macrostructure.

Traverse speed	Macrostructure of weld
22 mm/min	
25 mm/min	
28 mm/min	

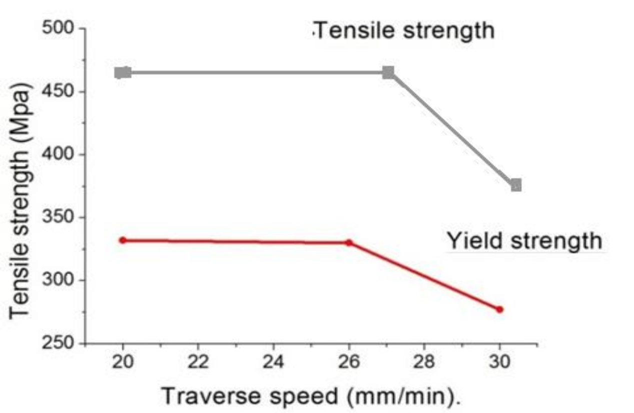


Fig. 13: Effect of traverse speed on tensile strength.

Microstructure study

The sound weld joints of mild steel were produced by friction stir welding. The microstructural study revealed five distinct zones namely stir zone, HAZ in MS and in FSS surrounding to the stir zone and the base metals. Starting from retreating side the optical micrograph of base metal of mild steel exhibited equiaxed ferritic grains of average size of 37 µm as measured by line intercept method besides little amount of fine pearlite as discussed earlier The frictional and deformational heat has been reported to increase the of HAZ beyond lower critical temperature which becomes high enough to cause recrystallization of grains and grain growth. The microstructure of the stir zone on ferritic stainless steel side was characterized by presence of highly refined (4 µm) equiaxed ferritic and grain boundary martensite and exhibited fine ferrite and pearlite grains on mild steel side [33]. Fig. 14 shows high magnification optical microstructures of different region of the weld in as welded condition.

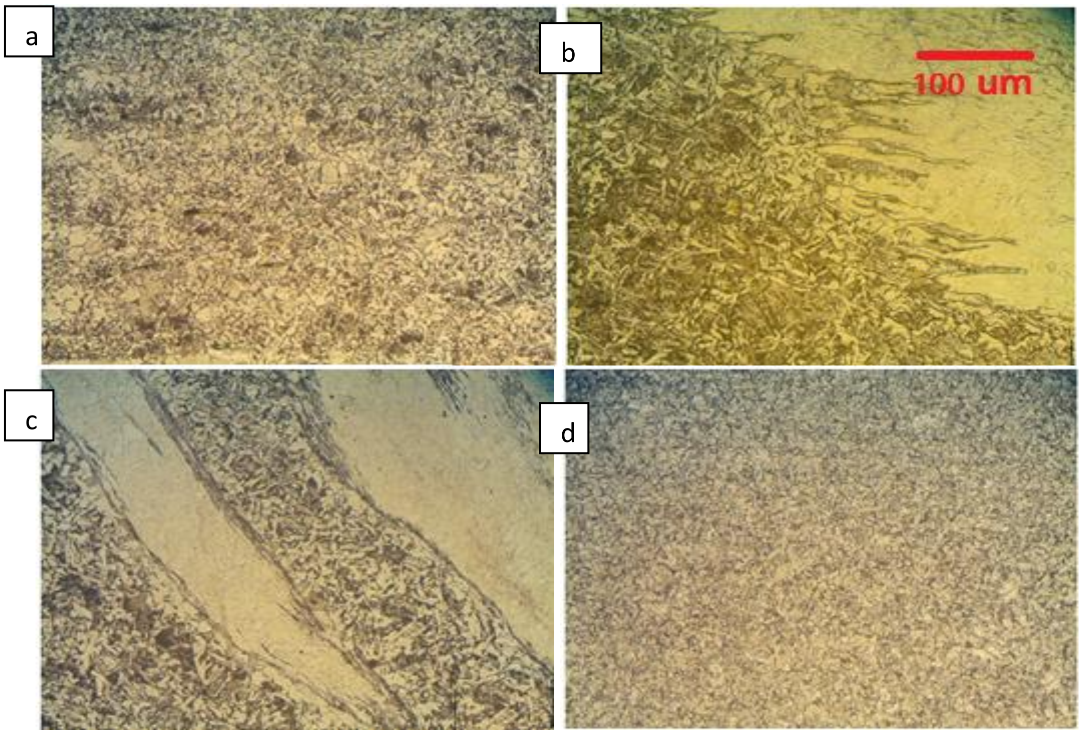


Fig. 14: Optical micrographs of friction stir dissimilar weld a) HAZ of MS, b) metal flow in stir zone, c) interface between MS and FSS and d) HAZ of FSS side.

Mechanical properties

In order to study the mechanical property of weld joint hardness and tensile testing was carried out after optimization of welding parameters. Vickers micro hardness was measured at middle of weld at an interval of 1 mm as shown in Fig. 15. Starting from retreating side (mild steel) towards the advancing side the first zone is base of mild steel having average hardness approximately 140 HV.

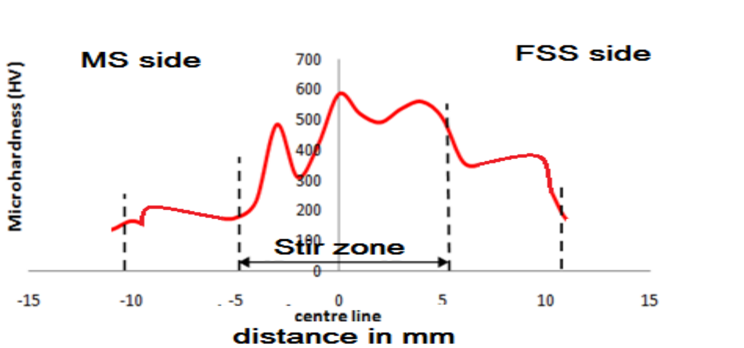


Fig. 15: Hardness profile at the mid thickness of weld.

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This is the part of weld consists lowest hardness i.e. weakest part of the weld. Due to partial or full grain refinement, the hardness of HAZ on MS side increased slightly to 170 HV. The hardness of stir zone was found in a range from 198 to 584 HV depending on the material and phase on each indentation because it consists of two different steel. The next zone was the HAZ of ferritic stainless steel consisted ferritic grains. This zone was narrow in size and its hardness was more than FSS base and HAZ of mild steel [34]. The last part was the base metal of FSS having large ferritic grains compared with stir zone and its hardness was about 225 HV.

Tensile property / Joint type		Tensile strength (Mpa)	Yield strength (Mpa)	Weld efficiency%
Base metal	MS	410.7	260.5	-
	FSS	514.8	362.0	-
Transverse orientation		465.7	325.0	113
Longitudinal orientation		1020.0	289.0	248

Fig. 16: Weld strength comparisons with base metals.

The tensile properties such as yield strength, tensile strength, and % elongation of the transverse and longitudinal weld samples were evaluated at optimized process parameter and the same are reported in. The transverse weld samples had higher yield and ultimate tensile strength than the mild steel base metal but lower than the ferritic stainless steel samples. Fracture in transverse samples was taking from mild steel base metal side. In order to calculate the joint strength of weld longitudinal samples were extract out from all weld metal. Fig. 16 shows the stress-strain curve of both transverse and longitudinal samples and base metal. Due to the higher hardness in the stir zone ductility of the weld was found significantly lower than that of base metal [35-36].

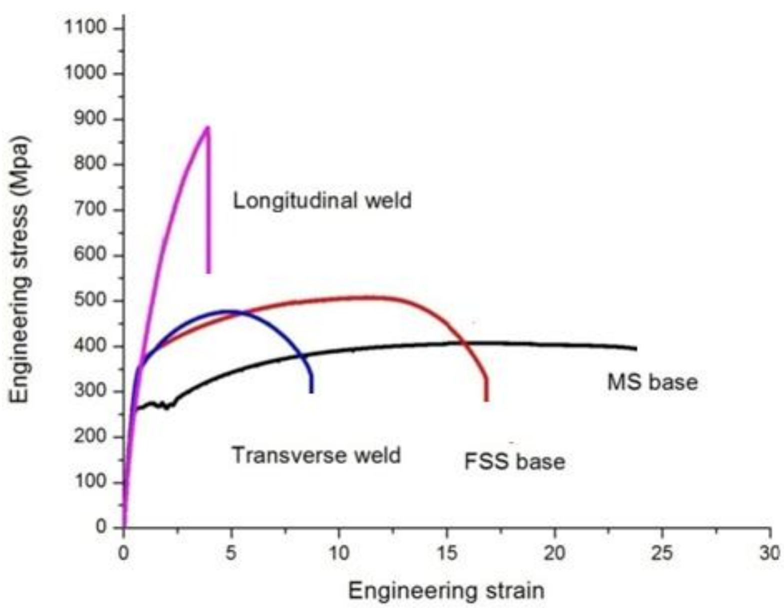

Fig. 17: Stress Vs Strain curve for FSS welds.

CONCLUSIONS

1. Defect free and sound weld of mild steel and ferritic stainless steel plates of thickness 3mm was produced in dissimilar steels by friction stir welding at 512 rpm and 22 mm/min. traverse speed.
2. From microstructural study it was found that grain refinement was taking place which results an increase in hardness and tensile strength of stir zone. Due to the increase in hardness of stir zone ductility of the stir zone was decreased. The weld efficiency of dissimilar weld was obtained as 113 %.

3. An increase in traverse speed results to decrease in strength of the weld because proper stirring of the weld is not take place.

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