Optimization of Process Parameters during Friction Stir Welding of Stainless Steel: A Review

Umesh Mali[1], Hemant Deore[2]

[1]*Department of Mechanical Engineering, Smt. Kashibai Navale College of Engineering,*
umeshmali422@gmail.com
[2]*Department of Mechanical Engineering, Smt. Kashibai Navale College of Engineering,*
hadeore@sinhgad.edu

ABSTRACT

The basic purpose of this review is to study the effect of the process parameters of Friction Stir Welding, namely, shoulder diameter rotational speed, welding speed and tool material on the properties such as tensile strength, impact toughness, notch tensile strength and degree of sensitization of stainless steels. The properties are correlated with the macrostructure and microstructural characteristics of different zones of FSW joints to understand the effect of process parameters. Multi- criteria optimization to obtain optimum welding conditions that can yield superior properties of FSW joints is also discussed. Methods for process selection are explained and future challenges for research on joining stainless steels by FSW are summarized.

Keywords*: Friction stir welding, Stainless steel, Optimization of process parameters, sensitization, Tool degradation.*

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1. Introduction

Friction stir welding (FSW) of high melting temperature materials is gaining significance among the researchers for its high end applications like nuclear, aerospace and defence. This process is commercially available for soft materials like aluminium, magnesium and copper alloys with numerous applications in aircrafts structures, rolling stock, ocean vessels, petrochemicals, food processing industries and car body constructions [1–3]. The very first feasibility study on FSW of high melting temperature materials was done by Thomas et al. [4], but the applicability of this process to weld steels is at the infant stage. There are four types of stainless steels like Ferritic, Martensitic, Austenitic and precipitation hardenable. Out of these, Austenitic stainless steels finds wide range of applications in components with high operating temperature such as reactors, heat exchanger, nuclear power plants, and pressure vessels etc., due to its higher strength at elevated temperature, improved creep strength, and corrosion resistance when compared to other steels [5]. However, the structural application profoundly depends on the performance of welded joint. Though, these steels are readily weldable by conventional welding processes such as metal inert gas welding (MIG), tungsten inert gas welding (TIG), shielded metal arc welding (SMAW), and flux cored arc welding (FAW), the welded joints still suffers from the loss of corrosion resistance due to the effect of carbon and oxygen, hot cracking susceptibility, precipitation of secondary phase, micro segregation and susceptible microstructure to intergrannular corrosion [6]. Hence, more careful precautions are needed to retain both mechanical properties and corrosion resistance. To lighten or even eradicate the problems mentioned above, solid state welding process is preferred. In the recent years, attempts were made by researchers to study the effect of friction stir welding parameters on the microstructural changes, micro hardness variations, tensile strength and sensitization resistance of austenitic stainless steels.

Friction Stir Welding (FSW) - a solid state process is regarded as solution for joining the alloys which cannot be joined by fusion welding as process temperature being below melting temperature [7,8]. This process improves mechanical properties as well as produces weldment free from porosity. There is no loss of alloying elements, excellent metallurgical structure and good dimensional stability is achieved. Numerous researchers has done experimentation on FSW of Stainless steels with various process parameters so an attempt is made to study the combined effect of process parameters on mechanical and chemical properties of welded joint.

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1. Literature Survey

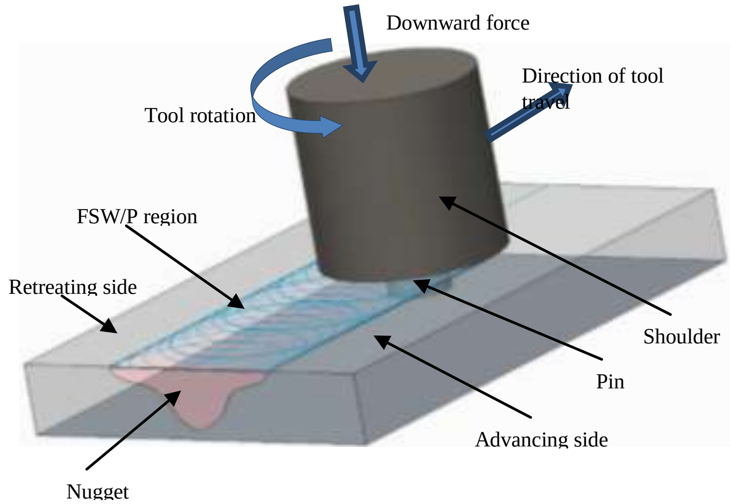

Fig-1: FSW process

Fig.1 shows FSW process. In FSW rotating tool with specially designed pin and shoulder is plunged between abutting edges of workpiece and made to traverse in weld direction. Rotating tool performs two functions i) Frictional heating of workpiece. ii) Stirring of material to achieve coalescence so as to form joint. During the FSW of stainless steel workpiece is heated to the temperature which is 70% to 80% of melting temperature and peak temperature reached is 1200^0C [9], due to this rotating and translating tool is subjected to very harsh working conditions hence proper selection of tool material and process parameters is necessary to produce sound welds.

1.1 Process Parameters

Following are the important process parameters in FSW of stainless steels:
1. Rotational speed: by increasing the rotational speed the temperature rise increases, so proper rotational speed should be selected.
2. Welding speed: with the slower welding speed tool stays longer in contact thus increases the temperature, so proper welding speed is required.
3. Depth of cut: the depth of cut should be according to the thickness of the plate to be welded.
4. Tool profiles: different tool profiles interact differently with material of plates to be welded thus optimum tool profile should be selected.

Park et al. [10] observed sigma phase at the advancing side of FSW joints made from 304 grade stainless steel and claimed that, these phases were formed due to the higher strain rate and dynamic recrystallization duringtransformation of austenite to delta ferrite. Park et al. [11] found that theadvancingside of weld was significantly affected by sensitization due to the formation of chromium sigma phases and carbides. Small ferrite along the grain boundaries of austenitic phase were observed by Kokawa et al. [12] in the advancing side of FSW joint made from thin sheets. However, sigma phase was observed in the same region of thick plate welds and which was interrelated with the cooling rate after welding. The corrosion resistance of friction stir welded stainless steel joints can be improved with higher welding speed and thereby reducing the sigma phase band width at the advancing side. The effect of post weld heat treatment on the sensitization resistance of FSW joints made of 304 grade stainless steel were also studied and observed higher sensitization resistance of stir zone, when compared to the base metal [13]. The friction stir welded stainless steel joints fabricated using too low or too high rotational and welding speeds showed lower joint strength due to the poor material consolidation[14]. From the literature available to date on FSW of stainless steels, it was inferred that, the weld metal tensile properties are compared with respect to the base metal and the failure during tensile testing were always located at the base metal (BM) region. In the investigation by Sabooni et al., [15] showed that, the FSW weld metal are under matched, when compared to the ultrafine grained 304 L grade stainless steel base metal. This was mainly due to the grain coarsening effect caused due to friction stirring. Hence, it was clear that, the failure location mainly depends on the process parameters and base metal initial conditions like grain size, composition etc. For any successful structural application, in addition to

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the tensile strength based jointefficiency of 100% other aspects like toughness and corrosion resistance areneeded to be considered. Even though several investigations on FSW of stainless steel were done, and most of them were limited to a single response optimization procedure based on the joint tensile strength. However, the effect of friction stir welding processparameters on the several quality characteristics must be studied for achieving wide range of structural applications.

In the investigation done by A. K. Lakshminarayanan et al.,[16] four responses such as tensile strength, notch tensile strength, impact toughnessand degree of sensitization were considered for friction stir welded austenitic stainless steel joints and relationships were developed based on the process parameters such as rotational speed, welding speed and tool shoulder diameter. Further numerical optimization was done to simultaneously optimize the multiple quality characteristics of friction stir welded austenitic stainless steel joints.

1.2 Effect of individual parameter

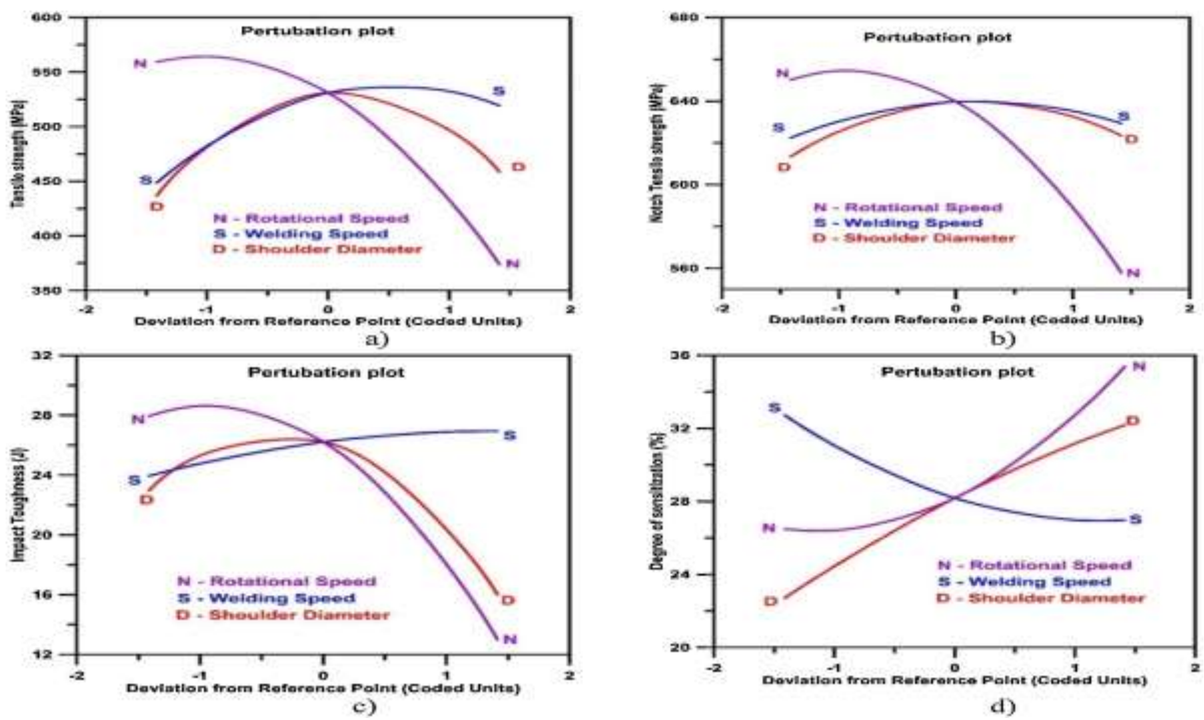

Fig- 2: Effect of individual parameters on the properties. [16]

As seen in Fig- 2, the increase in the rotational speed (N), shoulder diameter (D) and decrease in the welding speed (S) unvaryingly deteriorated the ultimate tensile strength, notch tensile strength, and impact toughness and sensitization resistance respectively. To understand this behaviour, the effect of process parameters namely rotational speed, welding speed and shoulder diameter on the macrostructure, stir zone microstructure, band formation at advancing side and failure location were studied.

The **stir zone** in FSW is generally made up of dynamically recrystallized austenitic grains. The stir zone grain size of friction stir welded steels is inversely proportional to the heat supplied during the process, which is in turn decided by the process parameters used. The dynamic recrystallized grain size in friction stir welded joints is governed by Zener Holloman parameter, which is calculated by formula given by equation (1)

$$Z = \varepsilon \exp\left(\frac{Q}{RT}\right) = \mathrm{A}[\sinh(\alpha\sigma)]^{n} \ldots (1)\ [17]$$

Where ε is strain rate, Q is activation energy, R is universal gas constant, T is deformation temperature, α, n& A are material constants.It has been reported that the friction stir processed regions in 316 L stainless steel showed fine and homogeneous distribution of grains for medium to higher Z values[18]. Hence, the process parameters must be optimized to obtain proper Z values to prevent inhomogeneous grain size distribution.

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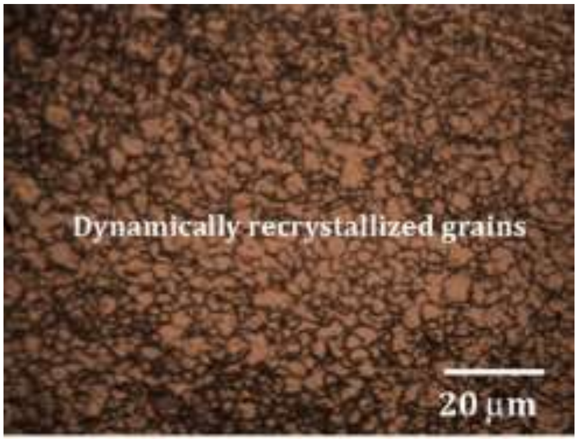

Fig-3: Stirzone microstructure [16]

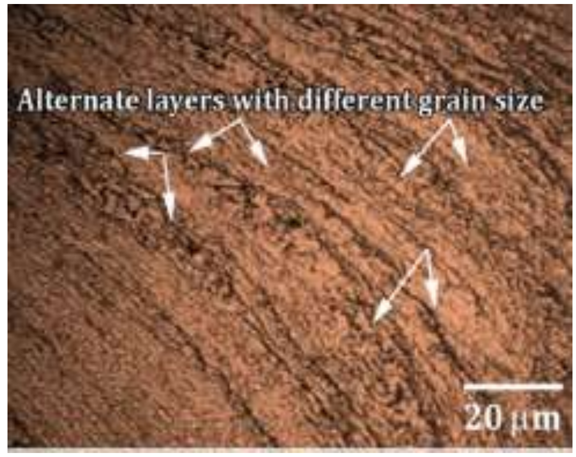

Fig-4: Band structure [16]

The stir zone of joints fabricated using higher rotational speed, lower welding speed and larger shoulder diameter reached higher peak temperature compared to other joints. It also resulted in comparatively slower cooling cycle due to lower thermal conductivity of austenitic stainless steel which increased exposure time, which pave away for grain growth due to static recrystallization.

The advancing side of stir zone showed a **banded structure** and there was a significant difference in the band width with respect to the process parameters used. Cr-rich borides and tungsten induced massive ferrite due to tool wear, sigma phase and retained delta ferrite along the austenitic grain boundaries were the various reasons for the formation of this banded structure. With the increase in rotational speed, shoulder diameter and decrease in welding speed wider bands in the advancing side were observed which subsequently affected the joint performance.

The **failure location** during tensile testing of friction stir welded stainless steel joints was decided by the process parameters, which lead to the variation in local mechanical properties and stir zone microstructural features.Failure can take place in both at stir zone &unaffected base metal. As per the available literature data, failure takes place in base metal when stir zone consists of fine grain and minimum band formation without any defect. Also failure can take place in stir zone due to thinning of the zone due to higher axial pressure, due to formation of hard Cr rich phase in soft matrix, inclusions from tool wear which lead to undesirable phase change like tungsten induced ferrite, microlevel defects in banded microstructures due to uneven stacking of layers, sharp edges of bands which acts as crack initiation factors. The**tensile strength**values of the joints depend on the failure location and its local microstructural characteristics. The ultimate tensile strength found to be decreased because of coarsening of banded structure with the increase in rotational speed and decrease in the welding speed. The failure occurred in the advancing side of weld metal region due to the presence of banded structure. The difference in **notch tensile strength** values are mostly depends on the grain size and carbide distribution. Finer grain size with uniform carbide distribution showed superior notch tensile strength. Though significant variations in notch tensile strength can be observed among the joints fabricated, joints were considered as notch ductile, since the notch sensitivity ratio was greater than unity. Increase in rotational speed, shoulder diameter and decrease in welding speed resulted in deterioration of **sensitization resistanc**e due to the wider ferrite band with carbide precipitation. At lower rotational speed, higher welding speed and optimum shoulder diameter, finer grains with thin band in the stir zone offered improved sensitization resistance as thechromium depletion was reduced by the increase in the grain boundary area per unit volume. Similarly the **impact toughness** was lower for all the joints, when compared to the base metal. However, variation in toughness values depends on the amount of ferrite formation and nature of interface between the carbides and grain boundaries.

The effects of individual FSW process parameter on the metallurgical and mechanical properties of welded joints were found to be complex and always there existed some interaction effects between them. The combined effect of two parameters with the third parameter at its middle level on the quality characteristics was analyzed, the ultimate tensile strength, notch tensile strength, impact toughness and degree of sensitization with respect to the FSW parameters (e.g. rotational speed and welding speed) was not following the same trend as that of shown by individual at different levels of third parameter (e.g. shoulder diameter) (As shown in Fig.5). This was mainly due to the strong interaction effect, which exists between the process parameters. The interaction effects were observed for tensile strength and degree of sensitization at lower welding and rotational speed. But, for notch tensile strength and impact toughness this effect was highly significant.

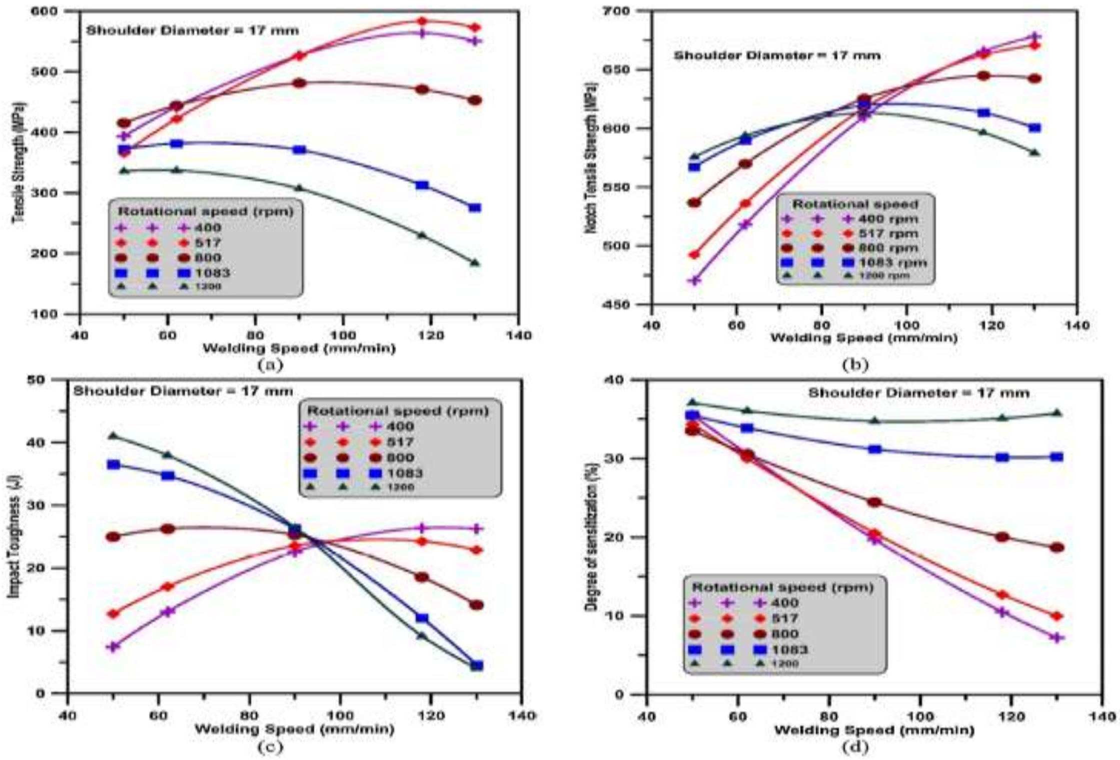

Fig-5: Parametric interaction effects on properties [14]

2.4 Parameter optimization with multiple objectives

For the optimization purpose, ultimate tensile strength (UTS), notch tensile strength (NTS) and impact toughness (IT) of joints needed to be maximized. On the other hand, degree of sensitization (DOS) needed to be minimized, since it was an indication of environmental degradation. There are various methods available for optimization like, Taguchi method of optimization and different software like design expert V.8.0 etc. For numerical optimization, the goal for the process parameters such as rotational speed, welding speed and shoulder diameter were kept at its range considered, in which defect free welds were obtained, whereas the goal for the responses were set to maximize the UTS, NTS and IT and to minimize the DOS. Design Expert V.8.0 was used to optimize the process parameters, which uses downhill pattern search algorithm finds an optimum solution around the stationary point to maximize or minimize the objective function. For multi response optimization, an overall desirability function needed to be calculated by the combining the goals to find optimized solution.

2.5 Effect of tool material

Rai et al.[19] studied various aspects like geometry of tool, tool material selection, mechanisms of tool degradation and economics with regard FSW of high melting materials like steels. The authors concluded that usability of this process highly depend upon proper tool design and proper tool material selection, as these factor affect performance of tool, overall process cost and the quality of welded joint. It has been found that FSW tools developed with highly refractory materials like iridium, rhenium etc. and abrasive materials such as PcBN have shown its supremacy in producing better welded joints with good tool durability. But, these tools are not cost worthy as compared to tungsten (W) based tools. The tungsten based tool materials have shown the capability of showing high toughness, strength and hardness at high temperatures [20].Gan et al. [21] has done studies on tool degradation analysis and proposed two modes of tool degradations namely the deformation and wear. Deformation occurs by two modes wiz. Slipping and twining. Wear also takes place by two modes wiz. Abrasive wear and adhesive wear. The deformation in tools indicates the change of geometric parameters and tool wear indicates the mass loss from the tool.

In an investigation done by S. S. Kumar et al. [22],FSW tools made up of two different tungsten(W) based materials Tungsten lanthanum oxide (T1) and Tungsten heavy alloy (T2) were compared for their performance and joint characteristics. Fig-6 shows pin and shoulder profiles ofFSW tools after welding one joint each for same welding run.

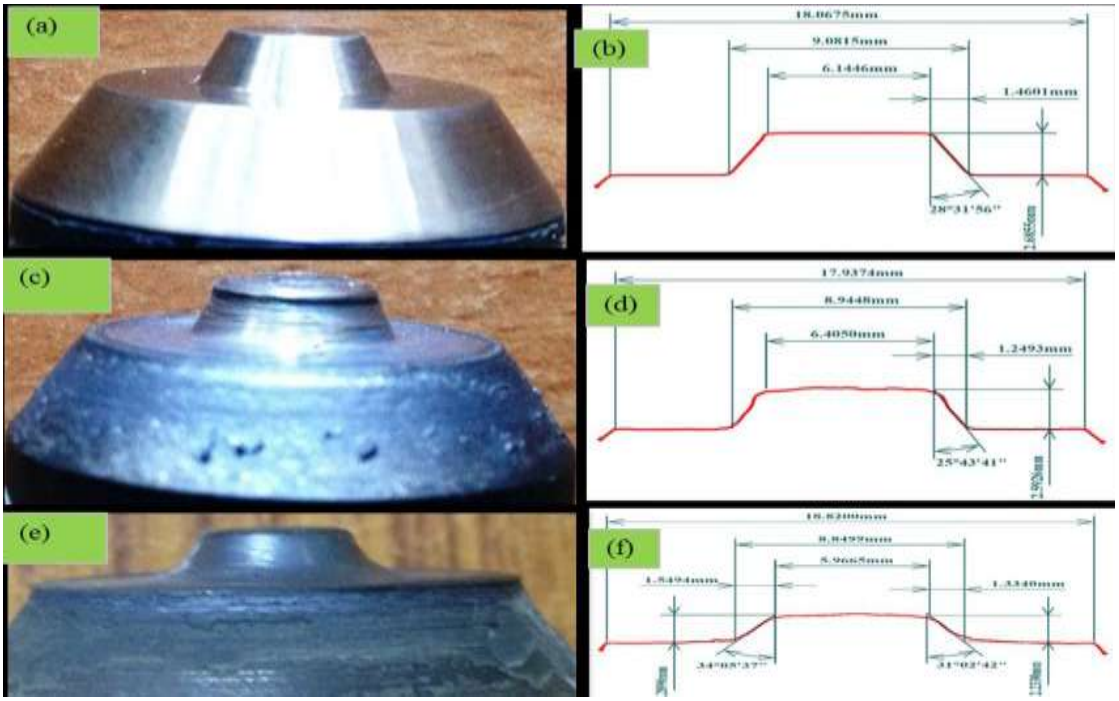

Fig-6: Tool pins and shoulder profiles before and after welds; (a) & (b) before welding, (c) & (d) after welding for tool T1, (e) & (f) after welding for tool T2 [22]

After welding for same length, considerable changes in tool profiles were observed for tool T2 as compared to tool T1, as tool T2 is degraded significantly as compared to tool T1. For tool T1, it was observed that pin length was found to be decreased with increase in pin diameter and pin tip is transformed to mushroom like pattern which can be seen from fig.6(c)&(d).The presence of lanthanum oxide particles in tool T1 offered better strength and toughness by preventing dislocation movements of W grains at elevated temperatures. Also recrystallization temperature of tool material is significantly higher than that of peak temperature reached during the process; there was less possibility of microstructural changes in tool material due to that respect. But the combined effect of decreased yield strength of tool material at high temperatures and severe process loads during process lead to geometrical changes of tool profile. Thus, the change in geometry of tool pin and shoulder was mainly due to severe plastic deformation as a result of the combined effect of compressive and torsional shear load experienced by tool at elevated temperatures. Though, subjected to slight geometrical changes (deformation), tool T1 has shown lesser mass loss indicating relatively low wear rate. In case of tool T2, pin length was drastically reduced with slight increase in shoulder diameter. The recrystallization temperature of tungsten heavy alloy is less as compared to tool T1. At this temperature, the alloying elements of tool, materials like Ni, Fe and Co would act as dislocation sites and undergo dislocation movement. Also, the presence of nickel in the tungsten matrix reduced recrystallization temperature and cause grain coarsening by Ostwald ripening phenomenon. Also process temperature resulted into decreased strength because of weakening of binder phases [23]. During FSW, the tungsten grains were severely deformed crossing threshold limit and micro voids formed as a result of difference in deformation between binder matrix and tungsten. Thus, at severe FSW environment, tool material was subjected to enhanced wear by attritionmechanism. Higher mass loss for tool T2 confirmed that tool degradation was mainly due to the tool wear mechanism.

The microhardness distribution across the weld zone for joints formed using tools T1 and T2 are shown in fig.7. In case of both the tools microhardness was significantly higher than that of base metal across the section of joint.

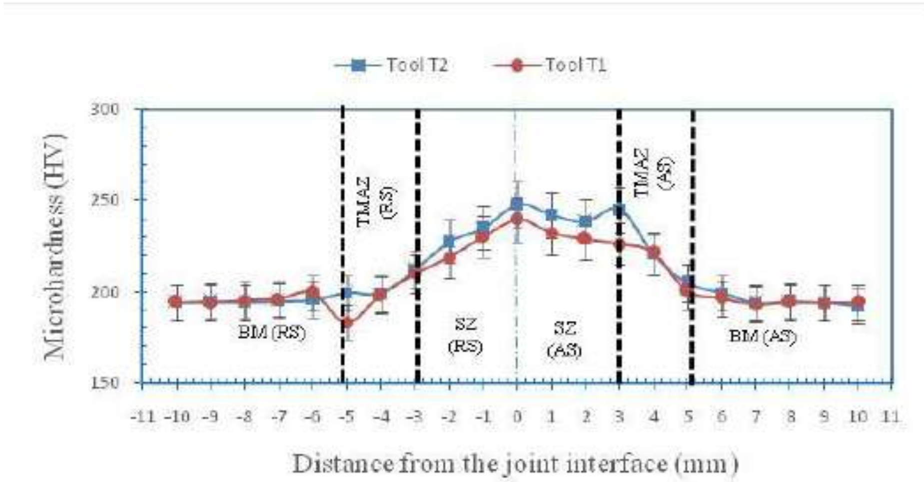

Fig. 7 Microhardness distribution of FS welded joints produced using tools T1 &T2.

The average microhardness across the joint for tool T2 was higher than that for tool T1.The peak value of microhardness for tool T2 was observed at stir zone and for tool T1 it was observed near interface of stir zone (SZ) and thermo-mechanically (TMAZ) affected zone. The increased stir zone microhardness in case of both the tools was mainly due to the highly refined and homogeneously packed grains at this zone. As tool T1 subjected to only minor changes in its geometry, resulted in better heat generation which causedthe relatively coarse grains in the stir zone and hence marginally lower microhardness than that of tool T2. The lower hardness in the weld zone for the joint produced using tool T1 observed at the interface of TMAZ and BM was due to the high strain rate plastic deformation followed by recovery of dislocations and lack of proper material coalescence. But for tool T2, this reduction in hardness is not observed because of distribution of tungsten wear debris in the weld zone. For tool T2, higher hardness than that at SZ was observed at the interface of SZ and TMAZ, which was probably due to increased distribution of tungsten wear debris in that region.

2.6 Future Scope

Evolution of cost effective method of fabrication of FSW joint can be explored for costly and strategic materials like super duplex stainless steels. Indigenizationof welding consumables and equipment can be taken up to further reduce the cost of welding. Intensive efforts are required in the area of non-destructive testing of weldment and post weld heat treatment especially to provide additional confidence of crack free weld using techniques like ultrasonic inspection and radiography.

3. Conclusions

FSW is a solid state joining process which eliminates the entire disadvantages of fusion welding. Characteristics of joint formed after welding were studied and it has been found that they were affected by various parameters like welding speed, rotational speed, shoulder diameter, and tool material etc. These parameters individually affect weld characteristics also the combined effect of these parameters was also studied.From review of investigations it has been found that, the size and shape of banded structure was changed with respect to the process parameters. This induced microstructural inhomogeneity and subsequently affected the failure location, tensile properties, degree of sensitization and impact toughness. At lower welding speed, larger shoulder diameter and higher rotational speed, a thicker and uneven ferrite bands with intermetallic phases was observed in the advancing side. This resulted in reduction of strength, toughness and sensitization resistance. This can be due to the decrease of chromium concentration in the austenitic matrix; since it is the strengthening element also it gives corrosion protection by the formation of thin tenacious layer of chromium oxide. The loss of toughness also depends on the resistance to grain boundary cracking and propagation due to the interface cavitation between the coarse carbides and austenitic matrix or within ferrite bands.

Also the tool degradation studies shown that the (99%) W- (1%) La2O3-Tungsten lanthanum oxide (T1) FSW tool isdegraded predominantly by plastic deformation and the tungsten heavy alloy tool (T2) isdegraded by abrasive wear.In both cases, no sign of sigma phase formation is observed in the SZ or any otherzones in the joint interface region.For both the tools, the yield strength of joints is significantly higher than that of thebase metal due to the increase in hardness across the joint.

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