# A Review on Friction Stir Welding of Steels

Girish N Wattamwar[1], Rahul V Bhakare[2], Vikramsingh B Vakte[3]

## Abstract

In recent years it has made significant progress in friction stir welding of steels since unfavourable phase transformations occurred in welds due to the melting of the parent and filler metals in fusion welding can be eliminated. The main advantage of FSW overtraditional fusion welding is the reduction in the heat-affected zone (HAZ), and the joints exhibit excellent mechanical and corrosion resistance properties. This article reviews the progress in the relevant issues such as the FSW tool mate- rials and tool profiles for joining steels, microstructure and mechanical properties of steels joints, special problems in joining dissimilar steels. Moreover, in-situ heating sources was used to overcome the main limitations in FSW of hard metals and their alloys, i.e., tool damages and insufficient heat generation. Different in-situ heating sources like laser, induction heat, gas tungsten arc welding assisted FSW for various types of steels are introduced in this review. On the basis of the up-to-date status, some problems that need further investigation are put forward.

**Keywords:** Friction stir welding, Steels, Microstructure, Mechanical testing, Hybrid weldingFriction Stir Welding (FSW) is the most promising solid-state metals joining method introduced in this era.

## 1 Introduction

A friction stir welding (FSW)[1–5] tool is obviously a critical component to the success of the process. The tool typically consists of a rotating round shoulder and a threaded cylindrical pin that heats the workpiece, mostly by friction, and moves the softened alloy around it to form the joint. Since there is no bulk melting of the workpiece, the common problems of fusion welding such as the solidification and liquation cracking, poro- sity and the loss of volatile alloying elements are avoided in FSW. These advantages are the main reasons for its widespread commercial success for the welding of aluminium and other soft alloys. However, the FSW tool is subjected to severe stress and high temperatures particularly for the welding of hard alloys such as steels and titanium alloys and the commercial application of FSW to these alloys is now limited by the high cost and short life of FSW tools.The feature of joining metals in the semisolids state helps this FSW method to join metals with different melting points like aluminium and copper. Nowadays, FSW has become one of the prevailing joining processes of alu- minium alloys in the industry [3–5]. While considering hard metals like steel, FSW still does not accomplish the same feasibility in aluminium alloys [6, 7].

The limita- tions of friction stir welding on steels are as follows: (a)

a very high durable tool is required for welding steels, (b) the temperature produced by the tool pin and shoulder will not be sufficient to plasticize the metals, (c) welding speed cannot be attained as good as on aluminium alloys due to the high hardness of steels, (d) tool damage rate is very high, and (e) high flow stress is maintained by the hot steels while conducting FSW process, and which causes high contact stress and severe tool degradations [8]. Tool material like commercial pure Tungsten (Cp-W) or Polycrystalline Cubic Boron Nitride (PCBN) tools can survive these problems. Still, it increases the weld-ing cost by eight times or even more while comparing to fusion welding.a very high durable tool is required for welding steels, (b) the temperature produced by the tool pin and shoulder will not be sufficient to plasticize the metals, (c) welding speed cannot be attained as good as on aluminium alloys due to the high hardness of steels, (d) tool damage rate is very high, and (e) high flow stress is maintained by the hot steels while conducting FSW process, and which causes high contact stress and severe tool degradations [8]. Tool material like commercial pure Tungsten (Cp-W) or Polycrystalline Cubic Boron Nitride (PCBN) tools can survive these problems. Still, it increases the weld-ing cost by eight times or even more while comparing to fusion welding.

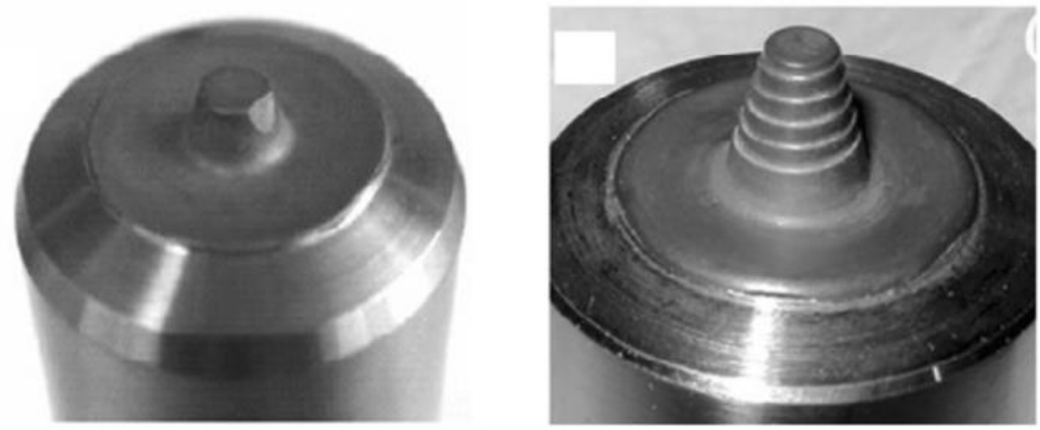
Although the FSW tools for steel are expensive, fric- tion stir welding of steel has numerous advantages com-pared to conventional fusion welding methods. Some of them are as follows: (a) the heat-affected zone created by fusion welding is large, and this eventually decreases the strength and quality of the weld, (b) fusion welding requires a filler metal to join the base metals, where FSW

defects,fusion welding requires shielding gas which will pollute theused nowadays are silicon nitride, tungsten carbide, tung- sten lanthanide, and tungsten carbide cobalt alloy [24, 25].

### 1.1 Synthetic Material as an FSW Tool

The Polycrystalline Cubic Boron Nitride (PCBN) is one of the best Carbon Boron Nitride tools commonly used for friction stir welding, machining and cutting opera- tions. By utilizing a sintering or frottage method, the PCBN can be fabricated [29–31]. For this sintering pro- cess, high temperature and pressure are necessary, along with binder phases. The binder phase includes metals like nickel and copper and ceramics like aluminium oxide, titanium carbide, and titanium nitride [32–35]. Figure 2 shows the properties of PCBN.

PCBN provides high hardness, and diamond is the only hard material available which offers more hardness than PCBN. Comparing with diamond, PCBN can withstand very high temperatures. PCBN also resists thermal shock, chemical wear and offers high toughness [36–39]. Due to these abilities, PCBN tools were accepted mainly for machining areas, including friction stir welding. Numer-ous researches are conducted on PCBN tools.



(a) (b)

**Figure** Examples of tool profiles: **a** Tapered PCBN tool, **b** Convex scrolled shoulder + step spiral pin tool [62]

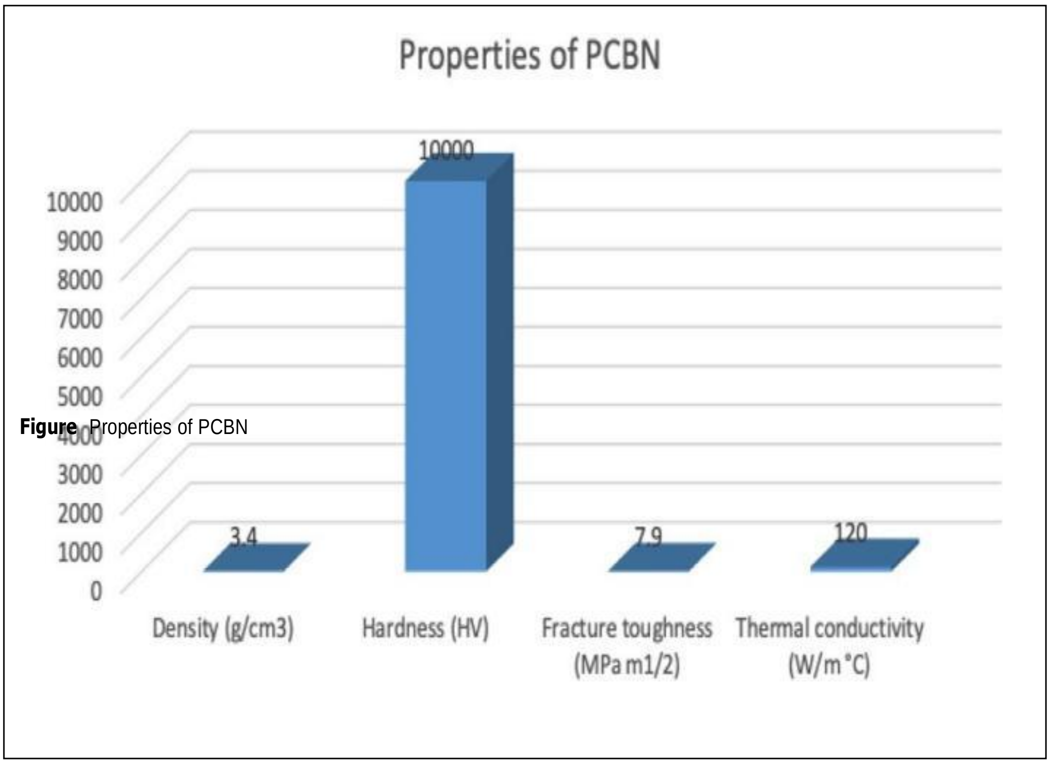



**Figure** Properties of PCBN

concentrates on the pin and shoulder profiles and how it affects the weld's mechanical properties [40].

The studies show that PCBN can successfully imple- ment for alloy steels and stainless steels, like austenitic stainless steel, ferritic stainless steel, martensitic stain- less steel, and duplex stainless steel. Comparing with the refractory metals FSW tools, PCBN provides a much better joint with uniform microstructures [41, 42]. Many researchers took PCBN-tungsten alloys tools to weld less hard steel alloys with a thickness of up to 12 mm. While using the same alloys, deformations were still happening to these tools [43]. Nowadays, superalloys tools are pri-marily considered. The superalloys mainly used for FSW are cobalt or nickel-based ones [44–46].

Moreover, these are not sustainable remedies for pre- venting the fracture of tools, improving joints' strength, and making the steel welding process cheaper. The cur-rent research shows that the better option is to adopt a hybrid welding technique. By utilizing such methods, conventional tools can weld hard alloys, such as the tung- sten carbide tool for AISI 410 stainless steel plates [47].

### 1.2 Tool Profile

The tool profile or tool geometry critically influences the weld quality and the tool wear rate. The tool pro- file helps the FSW process in the followings ways: (a) to generate accurate temperature in welding, (b) to create the same axial force to the weld region, (c) to achieve good welding speed, and (d) to gain proper metal flow in the stir zone and to gain homogenous grain structure [48, 49]. The stir zone's plastic deformation rate also depends on the tool profile, not on the tool rotation rate and welding speed. The significant factors that need to consider before design a tool are (a) the thickness of the base plate, (b) the kind of base metal, whether it is a soft or hard metal, and (c) the tool material [50]. While designing a tool, the vital factors that need to consider are the pin diameter & profile and the shoulder diam- eter & profile. The shoulder profile plays a crucial role in FSW. The area needs to heat, and the heat generated for welding depends on the shoulder profile and diam- eter [51–53]. With increasing the shoulder diameter, the heating area will also get increased. The unwanted increment in the shoulder size leads to an increase in the heat-affected zone [54].

Ultrahigh carbon steel with a thickness of 2.3 mm was welded successfully with the aid of a tapered PCBN tool (shoulder diameter 12 mm, and pin length 2 mm, diameter at the top 4 mm and bottom 5.8 mm) [55, 56]. The results have shown that the fine grain structure was visible in the thermomechanical affected zone due to continuous dynamic recrystallization. An NSSC 270 super austenitic stainless steel with a thickness of 6 mm

was welded by using a convex scrolled shoulder + step spiral pin tool at a tool rotation speed of 400 and 800 r/ min [57–60]. At 400 r/min, the strength and ductility of the joint were similar to the base metal, while more intermetallic phases were formed at 800 r/min, which resulted in weak joint strength. Figure 3 shows the tapered PCBN tool and the convex scrolled shoulder + step spiral pin tool.

A SAF 2507 grade super duplex stainless steel of thickness 1.5 mm was butt welded by PCBN tool with a concave shoulder (diameter 25 mm) and tapered pin (length 3.8 mm) [61–63]. The results show that the joint possesses the same strength as the base metal, and the specimen was broken at the retreating side near the thermomechanical affected zone and retreating side [64, 65]. An AISI 304L stainless steel of thickness 3.4 mm was welded using a tungsten alloy tool with a con- cave shoulder profile (shoulder diameter 10.2 mm) and a cylindrical pin profile (pin length of 2.3 mm) [66–68]. The result shows that a joint efficiency attained ranges from 80% to 98%, and the ultimate tensile strength is near to the base metal. After successful welding, tool wear is found at the pin tip and shoulder edg.

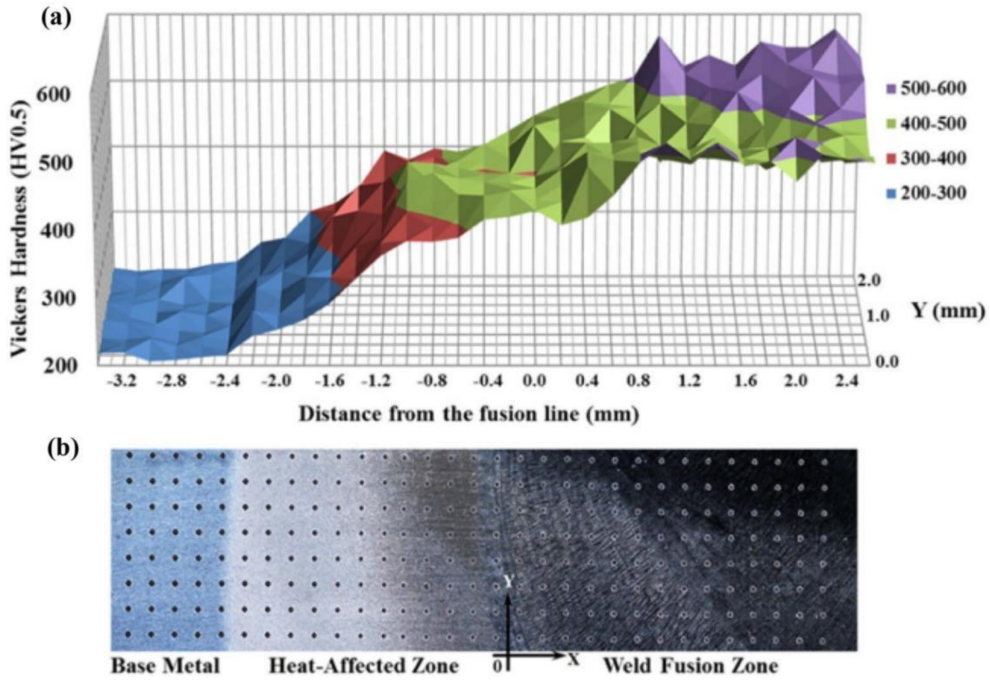



**Figure** Vickers microhardness map: **a** microhardness distribution, **b** microhardness indentations [79]

kinds of wear are mostly happening to the tungsten alloy tools due to their inability to withstand large axial force in welding [69, 70].

An AISI 410 martensitic stainless steel plate of thick- ness 3 mm was successfully welded by induction assisted FSW. The tool used was tungsten carbide (25 mm shoul- der diameter, 2.6 mm pin length and 5 mm pin diameter, hexagonal pin profile) [71, 72]. The strength gained was close to the base metal that is 462 MPa, and the speci- men exhibited a much higher corrosion rate of 2.79757 mm/year, which is better than the corrosion rate of base metal. The in-situ heating helped the tool propagate and stir well in the stir zone and achieved a homogeneous fine grain structure than the base metal [73]. An S45C steel plate was successfully welded by using laser-assisted FSW. The tool used for this welding was a tipped tung- sten cobalt alloy tool. The main advantage shown in this process was the high welding speed, 800 mm/min. In the conventional FSW method, it was about 400 mm/min [74, 75]. This method made a tensile strength of joint close to the base metals, and the specimen failure has happened in the base metal area.

## 2 Microstructure and Mechanical Properties

### 2.1 Mechanical Properties

The prime aim of a metal joining is to achieve excellent mechanical properties like tensile strength and hard- ness. Nowadays, a lot of research has been conducted to enhance the joints' mechanical properties [76–78]. Many studies show that most friction stir welded steel joints achieve mechanical properties close to the base metals.

The friction stir welding on modified 9Cr–1Mo–V–Nb steel was done successfully, and the microhardness dis- tribution across the weldment cross-section was studied. The weld zone possessed a different range of microhard- ness from the heat-affected zone to the stir zone due to varied heat generated in each area [79]. The weld is shown the peak microhardness of 503 HV0.5. The for- mation of fresh martensite resulted in this microhard- ness. Relatively lower microhardness was found in the tempered region. Due to the tempering effect, the micro- hardness found was 482 HV0.5. Because of the mar- tensitic substructure, the heat-affected zone shown a microhardness of 417 HV0.5 [80, 81]. Figure 4 shows the Vickers microhardness map at the cross-section of fric- tion stir welded P91 steel joint.

An austenitic stainless steel grade AISI 410 was suc- cessfully welded by using the tungsten lanthanum oxide tool. The influence of the tool tilt angle was studied. When a tool tile angle of 1.5°, with the parameter combi- nation of tool rotation speed 600 r/min, welding speed 45 mm/min, and axial load 11 kN, was used, the best results were achieved. The tool tilt angle enhanced the weld's plasticization so that a uniform microstructure through- out the weld was obtained [82–85]. The yield strength of the weld joint was 605 MPa, which means the weld jointan achieve a strength of 96% of the base metal. An aver- age microhardness attained in the stir zone was 230±5 HV, and this microhardness value is higher than the thermo-mechanically affected zone.

DP700 high strength steel was butt welded with two constant parameters and one varying parameter. The tool rotation speed was constant at 800 r/min and tool tile angle at 3°, while the welding speed varied from 100 mm/ min, 150 mm/min, and 200 mm/min [86, 87]. A param- eter combination of 800 r/min tool rotation speed, 150 mm/min welding speed and 3° tool tilt angle provided the best results. The mechanical properties like tensile strength and microhardness were studied. The stir zone had an average microhardness of 395 HV, while the base

metal had a microhardness of 275+3 HV. The improved

microhardness gained in the stir zone is due to the cool-ing rate and grain refinement. Under the same param- eter combination, the tensile strength of the joint was 687 MPa, which means the weld joint offers 91.7% morestrength than the base metal.

FSW welded a steel plate of IS 2062, and a mechani- cal test like microhardness was carried out. The average microhardness found in the base metal and stir zone was 143 VN and 182 VN at 200 g load. The increase in the stir zone's microhardness was due to the grain refinement and cooling rate [88–91]. The result has also shown that grain refinement helped to increase the tensile strength of the joint.

## 2.2 Microstructure Evaluation

The weld structure analysis helps to study and under- stand the material flow and microstructure formation. By evaluating these things, the weld defects can be eas- ily found out. The grain structure evolution during weld-ing can be examined by comparing the grain structureof welded specimens with that of the parent metal. The grain's homogeneity in the weld area can be determined[92–95].

Currently, many types of research are conducted in theFSW of steels. The results show that many factors affect the microstructure formation in friction stir welding of steels. Some of the significant parameters affecting the microstructures are (a) tool rotation speed, (b) weld-ing speed, (c) axial force, (d) tool profile, and (e) tool tilt angle. The common thing related to these parameters is the amount of heat generated by these process param- eters, while welding significantly affects microstructure evolution [96, 97]. The material flow in the stir zone pre-dominantly depends on the tool and its profile. The toolshoulder influences the top layer material movements, while the pin profile and tip control material movementsat the intermediate and lower portions [98–101]. Figure 5 shows the tool influencing areas during FSW.

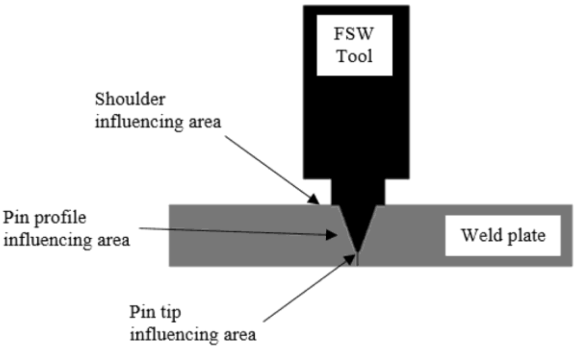



**Figure** Tool influencing areas in FSW

A butt joint was configured using DP 700 grade stain- less steel. The microstructure evaluation showed that the stir zone's grain structure was transformed into a single-phase austenite structure at a 100 mm/min weld- ing speed. The temperature generated at this time was 885 °C [102–104]. Increasing the welding speed to 150 mm/min and 200 mm/min, a dual-phase ferrite-austen- ite area was found in the bottom regain. The top and the middle portion remained the same single phase aus- tenite structure. The temperatures generated in welding at 150 mm/min and 200 mm/min were 813 °C and 731
°C, respectively [105]. The study has shown that the high welding speed led to the formation of a fine-grain structure with high hardness in the weld region. The correlation of temperature and welding speed in the microstructure change in DP 700 stainless steel friction stir welding was addressed well.

An AISI 316L stainless steel was welded successfully using the FSW method, and a nearly fine grain struc- ture was found in the stir zone. The same grain struc- ture was visible in the hot working process of AISI 316L stainless steels, and this is due to the low stack- ing fault energy of the austenitic steels [106–108]. The results showed that the weldment had a higher strain rate than the base metal's critical strain rate due to the displacement density across the grain boundaries and the strain-free nucleated grains.

Figure 6 presents the macrographs of the weld zone made at three different tool tilt angles. There are mainly four zones visible in a friction stir weld specimen, i.e., the base metal (BM), heat affected zone (HAZ), thermo-mechanically affected zone (TMAZ), and the stir zone (NZ) [109, 110]. In Figure 6, very small or no HAZ is visible, revealing that the heat generated during welding was optimum. The tool shoulder diameter on the joint surface and the tool pin diameter towards the plate's bottom was roughly the same as the stir zone's volumetric size.

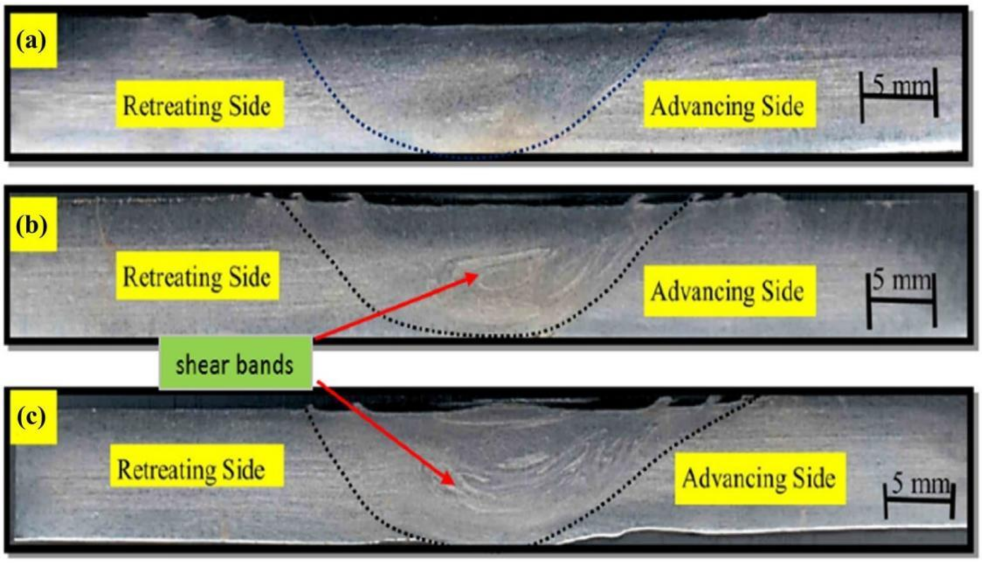



**Figure** Macrographs of FSW welds: **a** 0° tilt angle, **b** 1.5° tilt angle, **c** 3° tilt angle [110]

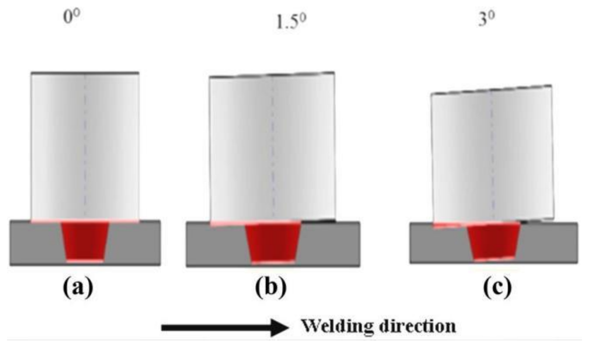



**Figure** Schematic representation of dynamic stir zone: **a** 0° tilt angle, **b** 1.5° tilt angle, **c** 3° tilt angle [110]

Figure 7 is a schematic diagram illustrating the dynamic stir zone volume for three different tool tilt angles. When the tool tilt angle is increased, the stir zone's dynamic volume is raised a little [111–114]. Under three levels of tool tilt angle 0°, 1.5° and 3°, the dynamic volume is 104.64 $mm^3$, 116.24 $mm^3$ and 127.84 $mm^3$, respectively.

It is visible that at 0° tool tile angle, the stir zone's vol- ume and the tool shoulder diameter are similar due to perfect contact between the tool shoulder and the weld surface [115–117]. Hence, the physical contact changes when it comes to 1.5° and the 3° tool tilt angle, and the dynamic stir zone also increases. The shear band for- mation in the weld zone can be explained by the rise in the stir zone's dynamic volume, where the formation of the nugget zone with an incline top flow arm is more comprehensive when moving towards the advanc- ing side [118, 119]. This shear band is very narrow and defect-free. One of the disadvantages of this shear band is that they are inelastic and does not undergo deforma-tion at a high strain rate.

Figure 8 shows the AISI 316L stainless steel and fric- tion stir weld joint's micrograph at three different tool tilt angles. It indicates that the tool tilt angle signifi- cantly affects forming microstructure and material flow in the weld zone. A temperature of 865 °C was attained by the 3° tool tilt angle, which is sufficient to produce a sound joint in AISI 316L stainless steel. The heat- affected zone generated was significantly less [120– 122]. Moreover, a fine grain structure was achieved. A temperature of 968 °C was developed by 0° tilt angle, and the increase in heat led to the rise in the heat- affected zone and some coarse grain structure in the stir zone. While adopting a tool tilt angle of more than 3°, the tool cannot produce sufficient heat and results in poor joint strength [123].

The optical microscope also reveals that due to the strong dynamic recrystallization in the stir zone by different tool tilt angles of 0°, 1.5°, and 3° resulted in the formation of grains of size 8±3 mm, 5±2 mm

and 6±2 mm, respectively. Due to the discontinu-

ous dynamic recrystallization process, approximately equiaxed refined grains were visible in the stir zone. Similar recrystallization was observed in all medium to low stacking fault energy materials like AISI 316L [124–126].

(three and twenty-four hours) weight-loss method with the aid of 0.5 M H2SO4 showed that the stir zone improved corrosion resistance property due to refined grain formation [239]. The in-situ heating increased the welding speed, lowered clamping force, and reduced tool wear.

The induction assisted friction stir welded AISI 410 stainless steel shows that the tool's travelling speed is much higher than conventional FSW [240–243]. The microstructure revealed that a fine homogeneous

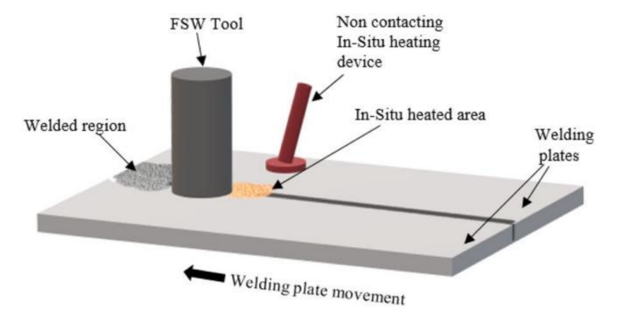


**Figure** Hybrid FSW process

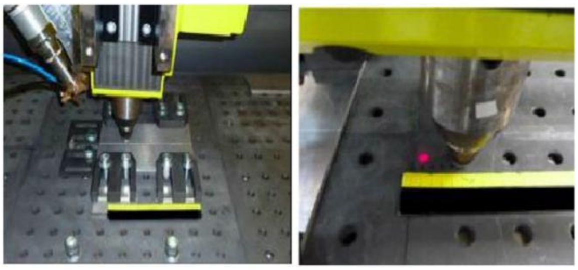


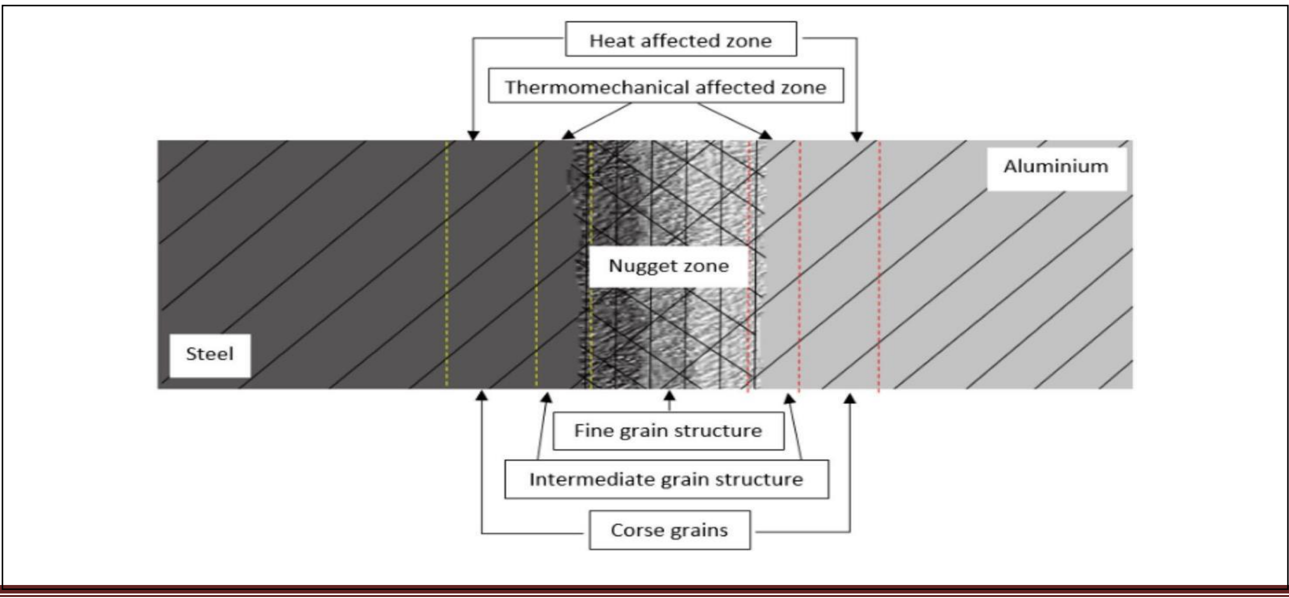
**Figure** Laser-assisted friction stir welding [235]

martensitic grain structure was found in the stir zone. The formation of an exemplary microstructure enhanced joint strength of 467 MPa.

**Gas Tungsten Arc Welding Assisted FSW**

AZ31B magnesium alloy and SS400 mild steel were suc- cessfully joined using gas tungsten arc-friction stir weld-ing [244]. In this joining process, the preheating focuseson the SS400 mild steel because magnesium alloy has a lesser melting point than mild steel. Comparing standard friction stir welded joints and gas tungsten arc assisted friction stir welded (GTA-FSWW) joints was done. Theresults show that the GTA-FSW joints have superior strength than the usual friction stir welded joints. The tensile strength gained was 91% of the strength of mag-nesium alloy AZ31B, that is 237 MPa, which is higher than the strength gained by conventional friction stir welding, which is 226 MPa, which is the 77% strength of the AZ31B magnesium alloy [245, 246]. The enhanced plastic flow enhances the tensile strength, and the limited annealing happened on the AZ31B magnesium alloy bythe in-situ heating of GTA-FSW. Moreover, the maxi- mum welding speed achieved by the GTA-FSW is 72 mm/min, while the counterpart conventional friction stir welding achieved only 55 mm/min welding speed. Fig- ure 34 shows the optical microscope images of the dis- tinct regions of friction stir welded and GTA-FS weldedjoints.

A fine equiaxed grain structure is visible in the micro- structure of the base metal (A) in the magnesium alloy,



as shown in Figure 34(a). The heat-affected zone and the thermomechanical affected zone in the magnesium alloy the mechanical stirring and the frictional heat generated by the tool. Similarly, a refined grain structure is found in the stir zone (C) due to plastic deformation, and the weld nugget (D) shows a bimetal interface of magnesium alloy and mild steel. The bottom region provides a non-mixed structure [247]. While examining the lower and upper area of the nugget zone of mild steel (E) exhibits uniform size and shape. Moreover, the microstructure in the TMAZ and HAZ of the mild steel (F) shows a more or less similar grain structure to the base metal.

Figure 34(b) shows the microstructure of GTA-FSW joints. Due to the in-situ heating, the average grain size of magnesium alloys become 16.4 μm and which is slightly coarser than the FSW joint (B). The stir zone (C) shows

**Figure** Induction assisted friction stir welding setup [237]

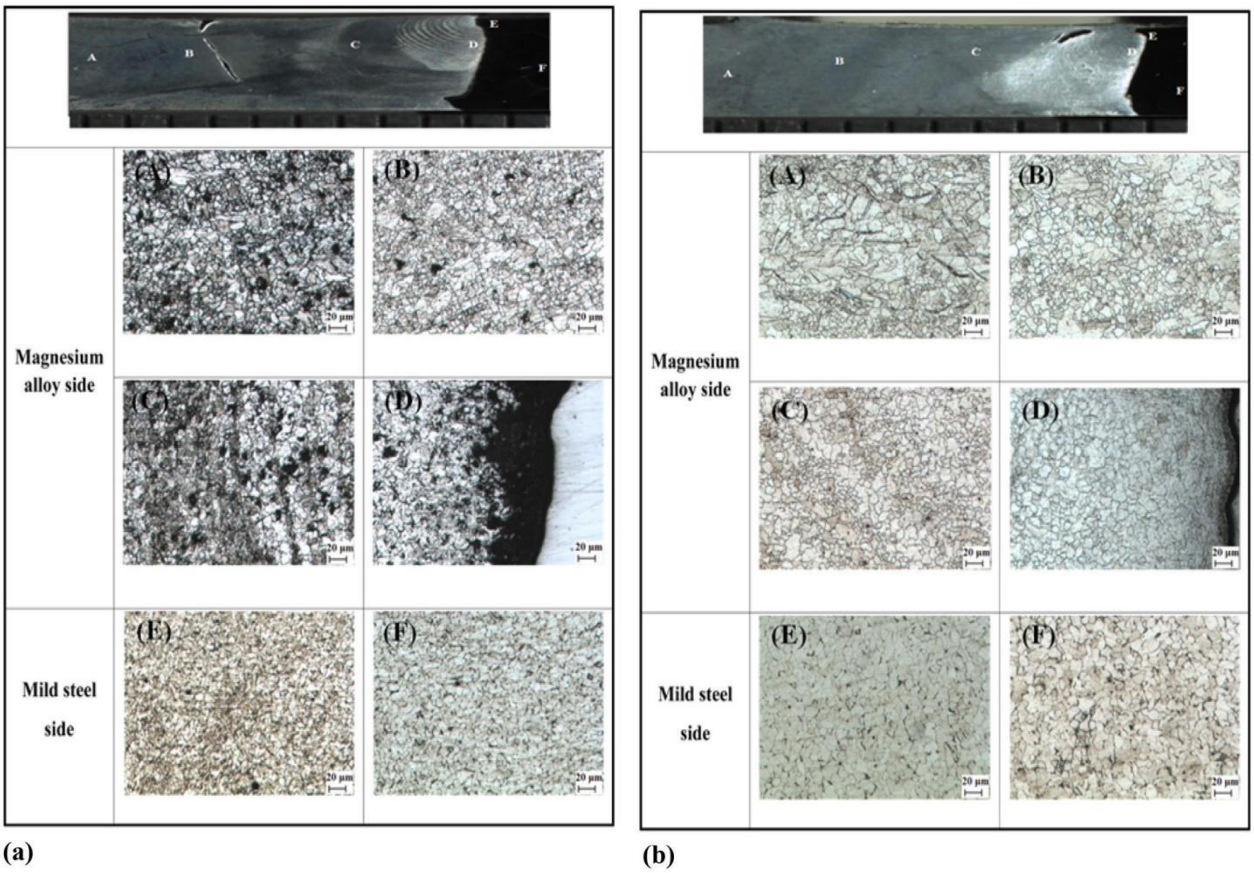



**Figure 34** Optical microstructure of the distinct regions of the weldments **a** shows the microstructure of the FSW and **b** shows the microstructure of the GTA-FSW [245]

(B) also exhibits a comparatively similar grain structure. The grain size in the HAZ is 12.4 μm, where the grain size in the base metal is around 8.2 μm, which means the HAZ has a slightly coarser grain structure. While in the TMAZ region (B), the size of the grains found was 7.1 μm, which is an almost fine grain structure due toa fine recrystallized grain structure due to the severe plastic deformation. Moreover, the weld nugget (D) at the interface of magnesium alloy and mild steel exhibits completely refined grains with a sound weld structure. Comparing the average grain size of the upper side (10.8 μm) with the lower side (14.4 μm) of the nugget zone, the upper portion has a fine grain structure (E) due to the work hardening that happened due to the tool stir- ring and the in-situ heating by GTAW during joining. In contrast, the grain structure in the HAZ and TMAZ in the mild steel region (F) was slightly coarser than FSW joints due to the in-situ heat input. In contrast, this research shows that a good joint with better strength can be achieved by using GTA-FSW joining method.

## 5 Summary and Future Work

Friction stir welding of steels reached a certain height recently. Many types of research have been conducted to find better combinations like tool material, tool profile, welding speed, tool rotation speed, axial force, and tool tilt angles. This research shows that better steel joints can be fabricated by using friction stir welding [248]. While considering the structure changes, the primary factor affecting heat generation is welding and cooling rate. A fine-grain structure can be achieved in the weld region by controlling the heat generation and cooling rate after welding [249]. This method will enhance the tensile as well as the toughness of the joints. While comparing with the conventional fusion welding techniques, this fric- tion stir welding has many advantages. The pollution that occurs while friction stir welding is nearly nil; porosity and hydrogen embrittlement should not happen while using FSW. Moreover, the heat-affected zone is com- paratively less, and the mechanical and corrosive proper- ties of the joints are far better than fusion-welded joints [250]. The paramount aim of this research is to identify the benefits and limitations of FSW while applying the same method to join different grades of steel.

Comparing with fusion welding methods, this FSW method has many advantages like higher mechanical properties, corrosion resistance property, lesser heat- affected zone, and FSW does not require any filler metals or special environments to join steel [251]. FSW showed a substantial saving in power consumption. The power consumed in fusion welding was four times or higher than FSW for fabricating similar joints. Also, FSW exhib- its better microhardness in the weld zone compared to fusion welding. Moreover, the HAZ in FSW was narrower than that in fusion welding. Nevertheless, the fusion welding process produces higher amounts of harmful gases such as carbon monoxide and carbon dioxide to the surroundings (2.7 ppm and 346 ppm, respectively). At the same time, the FSW is a green method, which does not produce any harmful gases. [252, 253].

The review on the friction stir welding on steel shows that more research is needed to conduct simi- lar and dissimilar steels and other alloys using hybrid and conventional FSW to reduce the joining costs and enrich the commercialization of friction stir welding inall-metal joining areas. The above review shows that most researchers concentrate on enhancing the strength of the joints, and a few are concentrated on the economic fea- sibility of the research. Numerous researches were con- ducted on similar stainless steel joints using PCBN like expensive tools; still, the strength gained was inadequate [254]. Using such tools are not recommendable due to its high expense. In dissimilar metal joining, the microstruc- ture generated in the bimetal region is satisfactory, and the strength gained is insufficient to adopt this method to industry [255]. While laser-assisted FSW and induc- tion heated FSW is widely used for welding steel and its alloys. One of the limitations of IA-FSW is that it can only use for ferromagnetic materials, while ultrasonic vibration-assisted friction stir welding can be adopted for any metals. High strength metals require high heat input to increase the metal flow to obtain a good joint. This volumetric material flow can be enhanced by clubbing an ultrasonic vibration unit with the friction stir welding unit. The significant advantage of ultrasonic vibration- assisted friction stir welding (UVAFSW) is that this ultra- sonic vibration is directly given to the tool itself, so there is no energy loss. But since no evident research is under- taken on ultrasonic vibration-assisted FSW for steel andits alloys, this research area requires more attention.

While considering metal matrix composites (MMC), these MMC's are poorly explored using friction stir welding. Dissimilar MMC joining by friction stir weld- ing is still in the nascent stage. These limitations canbe addressed by using hybrid friction stir welding and advance FSW tools. Still, enough researches are con- ducted on the cryogenic post-weld treatments for fric- tion stir weld specimens. The study on pre and post-weld treatments' effect on steels is a prerequisite in friction stir welding research. The impact of different profiled bobbin tools on steel friction stir welding needs more studies. These are the current research voids found in the friction stir welding of steels, which are required to address well.

References

[1] Y S Sato, H Kokawa, H T Fujii, et al. Mechanical properties and micro- structure of dissimilar friction stir welds of 11Cr-Ferritic/Martensitic steel to 316 stainless steel. Metallurgical and Materials Transactions A: Physical Metallurgy and Materials Science, 2015, 46(12): 5789–5800.

[2] M Hajian, A Abdollah-zadeh, S S Rezaei-Nejad, et al. Microstructure and mechanical properties of friction stir processed AISI 316L stainless steel. Materials and Design, 2015, 67: 82–94.

[3] V Msomi, S Mabuwa. Analysis of material positioning towards micro- structure of the friction stir processed AA1050/AA6082 dissimilar joint. Advances in Industrial and Manufacturing Engineering, 2020, 1: 100002.

[4] X Xu, X Ren, H Hou, et al. Effects of cryogenic and annealing treatment on microstructure and properties of friction stir welded TA15 joints. Materials Science and Engineering A, 2021, 804: 140750.

[5] Y Hu, H Liu, D Li. Contribution of ultrasonic to microstructure and mechanical properties of tilt probe penetrating friction stir welded joint. Journal of Materials Science and Technology, 2021, 85: 205–217.

[6] V Karami, B M Dariani, R Hashemi. Investigation of forming limit curves and mechanical properties of 316 stainless steel/St37 steel tailor- welded blanks produced by tungsten inert gas and friction stir welding method. CIRP Journal of Manufacturing Science and Technology, 2021, 32: 437–446.

[7] R Padmanaban, V Balusamy, V R aira Vignesh. Effect of friction stir weld- ing process parameters on the tensile strength of dissimilar aluminum alloy AA2024-T3 and AA7075-T6 joints. Materialwissenschaft Und Werkst- offtechnik, 2020, 51(1): 17–27.

[8] D G Mohan, S Gopi. Influence of In-situ induction heated friction stir welding on tensile, microhardness, corrosion resistance and microstruc- tural properties of martensitic steel. Engineering Research Express,