Recent Developments and Research Progress on Friction Stir Welding of Titanium Alloys: An Overview

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Abstract. Titanium and its alloys are joined by various welding processes. However, fusion welding of titanium alloys resulted solidification problems like porosity, segregation and columnar grains. The problems occurred in conventional welding processes can be resolved using a solid state welding i.e. friction stir welding. Aluminium and Magnesium alloys were welded by friction stir welding. However alloys used for high temperature applications such as titanium alloys and steels are arduous to weld using friction stir welding process because of tool limitations. Present paper summarises the studies on joining of Titanium alloys using friction stir welding with different tool materials. Selection of tool material and effect of welding conditions on mechanical and microstructure properties of weldments were also reported. Major advantage with friction stir welding is, we can control the welding temperature above or below β-transus temperature by optimizing the process parameters. Stir zone in below beta transus condition consists of bi-modal microstructure and microstructure in above β-transus condition has large prior β-grains and α/β laths present in the grain. Welding experiments conducted below β-transus condition has better mechanical properties than welding at above β-transus condition. Hardness and tensile properties of weldments are correlated with the stir zone microstructure.

1. Introduction
Titanium and its alloys demand for various industrial applications and, are extensively used for chemical, aeronautical, aerospace, and nuclear applications due to the challenging of their exceptional corrosion resistance and high specific strength [1-3]. Out of all titanium alloys Ti-6Al-4V is the extensively used two phase titanium alloy for aero-engines, various biomedical surgical instruments and parts or campaigns which has high in corrosion and strength, and chemical and oil reprocessing plants appliances[4].

The continuous demand for advancing the industrial applications of Ti alloys is a most important and challenging process owing to mechanical, metallurgical and other needs of these alloys. In general, titanium alloys are subjected to atmospheric contamination at elevated temperatures due to the
easily absorption of oxygen, hydrogen & nitrogen and are resulting in joint embrittlement. Moreover, due to the high melting temperatures during welding affected in residual stress formation and large deformation in the joints [5,6]. Titanium and its alloys were joined using fusion welding processes [7-11]. Large thermal cycle during welding by fusion welding processes leads to problems like distortion of weld joints, oxidation of weld surface and sputtering. However, there are some obvious limitations associated with conventional joining processes of Ti-6Al-4V, such as brittle coarse microstructure, epitaxial growth and coarse β grains, and a significant distortion with a high residual stress [12]. In this regard solid state joining methods like diffusion bonding [13], friction welding [14-16], friction stir welding [17], and explosive welding [18] are contemplated to conquer these issues which are related to materials melting. However, solid state welding techniques are not able to produce a quality joints in case of dissimilar combinations of titanium to stainless steel, aluminium, magnesium, etc. A new technique of using inter layers of aluminium [19, 20], silver, copper [21] and nickel [22,23], has been developed to overwhelm the problems of dissimilar joining. Friction stir welding is the best process in order to astound the problems to produce a complex joint. Friction stir welding was emerged at The Welding Institute in 1990s [24] Principle of friction stir welding is a tool is rotated and is progressively embarked into the weld joint of the sheets to be joined Friction stir welding has been used for industrial applications because of numerous benefits and was used for joining of aluminium alloys [25-29], magnesium alloys [30-32] and copper alloys [33-34].

Present paper deals with the research progress on friction stir welding of titanium and Ti-6Al-4V alloy. Tools used for joining of Titanium alloys are reported. Influence of process conditions on defect formation, mechanical properties and microstructures of weldments were also reported.

2. Research progress on FSW Titanium alloys

Tool material and its design

The friction stir welding tools used for fabrication of various materials and metals, such as steels and titanium and its alloys should have superior strength at elevated working high temperature environments to withstand the loads during friction stir welding. Tool material should also have good wear resistance. Tool wear will not only reduce the lifetime of the tool but also probably affect the material flow and mechanical properties of the welds. Processing of tools for friction stir welding is difficult. The tools used for FSW of titanium alloys include W-Mo, W-Re, W-1% La₂O₃, cobalt based alloys and molybdenum alloy tools [35-53]. Tools used for FSW of titanium alloys were presented in figure 1 and 2, and different tool shapes in figure 3. Rai et al. [54] reported an excellent review on tools used for friction stir welding. They have mentioned various tools used for joining of steels and titanium alloys selection of tool material, tool geometry and pin profiles. Preparation of tungsten-rhenium alloy tools is strenuous because of high cost. However, other tungsten based alloys i.e. Densimet [55] is machined with low cost. W-La₂O₃ alloy is also has low cost as Densimet and can be used for working temperature range of W-Re alloy.

Wang et al. [41] have worked on joining of Ti-6Al-4V sheets by FSW with tungsten based alloy tools. Tool wear during welding was also reported. They reported that tool degradation was observed in the W-1.1% La₂O₃ tool due to plastic deformation and it will diminished with increasing the tool pin diameter. Extensive study on this revealed that a reaction stir zone was shaped on the outer edges of tungsten carbide tool owing to decarburization. Sivaji and Reddy [56] worked on friction stir welding of alloy Ti-6Al-4V using W-Mo alloy tool. They reported that the tungsten inclusions were present in the stir zone due to tool wear. Polycrystalline cubic boron nitride (PCBN) tool which is considered as a tool for cutting of steels and titanium alloys [57-58], has shown the feasibility as the FSW tool for various steels and sound joints can be obtained [59-61]. Zhang et al. [62] have been conducted a preliminary study on FSW of pure titanium using PCBN tool, and microstructure and property investigations showed that PCBN has the potential as the tool of FSW for pure titanium, although tool wear was observed in the weld. They reported tool wear of PCBN during FSW of pure titanium using EMPA & EDS and they inferred that boron nitride (BN) might have reacted with
titanium. Wu et al. [50] described the influence of tool wear on joint properties of Ti-6Al-4V alloy using friction stir processed with PCBN tool. They reported that at higher rotation speeds of 800 rpm and 1200 rpm, and the greatest tool wear occurred at the tool plunge point with a tool rotation of 800 & 1200 rpm. The greatest tool wear occurred at the location of 7 mm from the tool plunge point with 400 rpm. Sivaji and

![Figure 1 Cemented carbide tool (a) Before welding (b) Tool wear after welding [40].](image1)

![Figure 2 W-Re tool showing the pin shape and shoulder [41].](image2)

![Figure 3(a-d) Tools used for various joint thicknesses [37].](image3)

Reddy [51] worked on FSW of Ti-6Al-4V alloy using PCBN tool. Edwards and Ramulu [63] have reported the shape of tool pin and its effect on heat generation. Microstructural analysis Ti-6Al-4V sheets were joined using FSW with varying welding parameters. The major advantage with the FSW is controlling of heat input during welding by optimizing process parameters. Friction stir welding was performed by several researchers in above and below β-transus conditions. Liu et al. [64] have welded Ti-6Al-4V sheet using 400 rpm tool rotation speed and welding speeds of 25-100 mm/min. Stir zone has bimodal microstructure. Stir zone consists of a bimodal microstructure Zou et al. [65] have studied the influence of FSW tool rotational speed on stir zone mechanical and microstructure properties of alloy Ti-6Al-4V weldments. Weld zone obtained with the 400 rpm speed has achieved a bimodal microstructure, whereas at 500 or 600 rpm sped; the weld zone has lamellar microstructure. The formation of α colony size and prior β grain size in the weld zone increased due to the increase in rotational speed. Influence of welding temperature on the mechanical properties and microstructural
characteristics of Ti-6Al-4V joint has been presented by Kitamura et al. [66]. Temperature at various zones during welding was measured using thermocouples. They have reported that the cooling rate was in need of welding speed and as the increase in weld metal cooling rate, the lamellar α β sizes starts to decreased when the temperature of the welding reaches beyond the β-transus temperature. Stir zone consists of equiaxed α grains when welding temperature was conducted within the β transus temperature.

![Diagram](image)

**Figure 4** Influence of β transus temperature and cooling rate on morphologies of friction stir welded Ti-6Al-4V [28]

![Cross sections of welds showing typical defects](image)

**Figure 5** Cross sections of welds showing typical defects [35].

The influence of process parameters on microstructure of friction-stir welding of alloy Ti-6Al-4V is shown in figure 4. Buffa et al. [39] and Esmaily et al. [68] studied that the tunnel defect & inclusions has been found in the stir zone because of deficient heat input. Jianqing et al. [67] identified the welding parameters effect on peak temperature. They reported that high peak temperature was observed when welding is performed at higher rotational speed and also the minimal traverse speed.
Lower rotation rate and/or higher speed of welding have exhibited with the very fine prior β grains and α colonies in smaller size. Buffa et al. [69] implemented an FEM model and simulation for FSW and validated the results with experimental observations. Material flow pattern during FSW of Ti-6Al-4V was reported for the first time by Edwards and Ramulu [42]. The formation of material flow patterns through FSW were experimentally observed using a new technique i.e. inserting a refractory powder into the joint. Refractory material was traced using radiography technique and/or metallography technique. They also...

Figure 6(a) Macrostructure of the stir zone, (b) stir zone (c) pole figure from the α and β phases [35]

Figure 7 (a) macrostructure of weld zone and microstructure of (b) stir zone (c) stir zone after stress relieving treatment (d) base material [72].
Reported that high and low heat inputs resulted in the formation of defects. Weld cross sections showing defects were shown in figure 5. Sungook Yoon et al. [70] studied the influence of as received microstructure on Ti-6Al-4V joint by FSW reported that microstructure is varied from top to bottom of stir zone. Microstructural variation of stir zone shows that owing to the phase transformation or plastic deformation. The key phenomenon of the formation of recrystallization is the in the microstructure characteristics evaluation nearer to bottom of the stir zone. Mironov et al. [71] studied the grain morphology of friction stir welded joint in β phase. Stir zone consists of priorβ grains with α/β lamellae present within the grain, is illustrated in figure 6.

Friction stir welding of Ti and its alloys has the potential for fabricating welds via mechanical properties and microstructures and are easier to make comparison with other commercially available material than outmoded conventional arc welding methods. Edward et al. [72], have found the close relation between the microstructural formation and mechanical properties such as fatigue cracks with his extensive studies on friction joining of alloy Ti-6Al-4V. Figure 7 illustrates the joint nugget macrostructure and various zones of the microstructures. The macrograph of the joint nugget exhibits that, it is not completely penetrated in the root of the weld. This is due to the slight modifications of the specimens before welds. All the specimens used for testing was machined on both sides to eliminate tool marks and lack of penetration of welds. The macrograph was clear from the micro defects except the lack of penetration. The further observations of the microstructures observations showed the small size of heat affected zone formation close to the stir zone. It is known fact that thermal conductivity of the materials has significant effect on HAZ formation; in general HAZ formation is smaller and very less distinct in Ti FSW joints compared to Al FSW joints. In addition to this, in the present study, the specimens were experienced to machining operation before welding such mill annealing effect of the base metal. Due to this effect, specimen reaches temperature of β transus of the material in a short period of time (20s). The micrographs were clearly shown the different weld zones formation across the nugget. Macrostructure shows that the no evidence of thermo-mechanically affected zone adjacent to the stir zone. Whereas, a presence of several width of TMAZ can be seen from the microstructures evaluations under higher magnification but this was not the significant to identify as effecting factor for mechanical properties. Mill annealed microstructure was transformed to acicular structure with coarser β grain. After PWHT, the weld microstructure showed signs of recovery.

The fabrication of high strength alloys using friction stir welding are more challenging due to the tool wear problems, it should be high strength and wear resistant than the joining specimens. However, these kind of issue very few in FSW of Al alloys because of the proper selection of tool design and tool material selection. In case of FSW of steel, Titanium and other hard alloys not easy to join them using conventional tool materials, it needs special materials which cause more production cost and manufacturing problems. In recent studies it is observed that the tool wear problems and weld metal contamination followed by the degradation of mechanical properties. Tool materials like nickel base and
W-Re alloys used for FSW of materials used for elevated temperature applications via titanium alloys and steels, are consumable. In order to avoid these issues and enhance the materials thermo plasticization for which need to be weld and also reducing of wear of the tool, various studies have developed new methods of heating on top plate of the sheet aided friction stir welding for welding of materials which have high-melting temperatures. Several heating methods were used by different researchers such as electrical current aided method, GTAW aided friction stir welding and laser assisted with FSW was applied for different alloys. Most recently, Ji et al. [73] have reported welding and its properties under back heating assisted FSW (BHAFSW) of Ti-6Al-4V alloy to avoid the problems of tool wear. The output of the welds cross-sections are revealed the tearing defects formation at different rotating speeds. However, at a tool rotation speed of 200 rpm smaller tearing defects are observed with various welding speeds 100 rpm, 120 rpm & 150 rpm. The results of the alloy Ti-6Al-4V thermal conductivity show lower and it is owing to much higher in temperature at the upper surface of the joint compared to the bottom surface. Back heating assisted FSW diminishes the temperature gradient laterally the thickness of the weld, which is more advantageous to condense the stress under tension of the joint. Due to this the defects caused by tearing are completely eliminated from the friction stir welded specimens. It is also observed that the welds after FSW exhibit material adhesion, which was seen on the tool surface. While removing tool material adhesion, some of elements will also be removed. However, evaluation of tool wear using weight loss method is inexact. In addition, the measuring of tool wear of material, EDS analysis was used and it is found to be most effective to estimate the wear mechanism of the tool. Figure 8 clearly indicates the zone affected shoulder and its EDS analysis of the where some of W and Re elements were detected from the lap joints. Compared with conventional FSW, BHAFSW joint notice abundant lower amount in elements of W and Re in SZ. It is owing to the developed the alloy Ti-6Al-4V of thermo plasticization by using BHAFSW technique.

Figure 8 EDS analysis at stir zone top zones of (a) friction stir welding and (b) back heating assisted FSW joints [73].
Materials used for aerospace application could be joined using friction stir welding. It is more advantageous to welding of hollow constituents in large size which subsidizes in the direction of production of light weight and aircrafts with higher efficiency. Furthermore, this process was used for surface modification and microstructural changes without joint formation, is called as friction processing (FSP). Friction stir processing can be applied to required sections of components for enhancing the mechanical properties. This new technique has promoted for developing tool materials with high softening temperature. Defect free weld joints were produced with high joint efficiency. However, it is difficult to find the fatigue properties and fatigue crack initiation and growth. Even the studies on fatigue properties are few details are available it is more interesting to find the relation between microstructure and fatigue properties. The recent studies done by Milton et al. [38], the influence of mechanical and microstructural properties on propagation behaviour of fatigue cracks on FSW titanium alloys. It is also noticed the residual stress formation also had been influenced fatigue properties of the welds. Previous studies reported the analogues approach was used for the welds to associate the fatigue stress of the welds with that of stress annealed specimens and found insignificant difference, and fatigue strength was enhanced due to fine grain microstructure in the processed region [74]. The base metal and the weld joint residual stresses were restrained using X-ray diffraction technique by applying sin2ψ method. Figure 9 shows the macro and microstructures of the joints; base metal microstructure has affected by mill annealed microstructure and predominantly has the elongated alpha grains with size of 20 µm x 5 µm and inter-granular β microstructure. The distinctive curvy aspect were seen on the another side of weld zone as advancing side at arrange of 1-4 mm depth of from top to bottom of the weld. It is also found that the microstructure consists of lamellae microstructure. The microstructural formation influenced the fatigue crack direction contour was modernized over and done with reflection of ΔKeq where the normal in SZ and interfacial zones.

Figure 9 (a) weld cross section microstructure of (b) base metal (c) stir zone on the rectangle side (d) macrostructure of stir zone (e) microstructure at the centre of stir zone [74].
promote higher fatigue crack paths higher compared to tortuous cracks observed at substrate and heat affected zones microstructures.

As mentioned in earlier section, tool wear problems are more significant in the weld microstructure formation and mechanical properties. Especially for the titanium alloys tool selection and its properties after welding are more important. Most suitably used tool materials are polycrystalline cubic boron nitride (PcBN) was used to cut steels and titanium alloys and same material thought to be feasible to use it for FSW process. The welds obtained using of these tool materials results in defect free welds although the tool wear was observed in the weld. It has more challenges for FSW of titanium alloys because of

![Figure 10 (a) BN core shell structure in the “tail band” with an inserted SAD pattern of BN and nanometer TiB\textsubscript{2} particles, and (b) α-Ti layer. [75].](image)

Figure 10 (a) BN core shell structure in the “tail band” with an inserted SAD pattern of BN and nanometer TiB\textsubscript{2} particles, and (b) α-Ti layer. [75].

its higher strength and high weld temperature and at that temperature poor plasticity. Along with mechanical wear, chemical wear occurrence also found and the formation of rich chromium borides through the reaction of the work pieces and FSWed PcBN tool. As shown in figure 8, the PcBN tool wear during friction stir welding of titanium using EPMA and EDS inferred that the BN caused to have reaction with titanium. However, it is not clear about the effect of mechanical properties and nature of the wear products mechanisms. Till today there is no significant research done on tool wear effects on weld metal deterioration properties of the welds. Wu \textit{et al.}[39], studied the detailed study on tool wear problems and also its effects on tensile strength and other properties of the FSW Ti alloys. They have conducted the detailed study on microstructures of the weld nugget using higher characterization techniques. The detailed microstructural observations exhibit the three types of microstructures in the SZ. The first type was a Widmanstatten structure in the “onion rings” microstructure. The second type of microstructure was in the dark bands of the onion rings region where large quantities of rod-shaped white particles (50-300 nm in width and 0.2-2 mm in length) were observed in a Widmanstatten matrix [75]. The compositions of the black particles indicate the BN phase, suggesting that they were tool wear debris. The higher magnified image shows such a core shell structure contained three layers, the BN core, second layer consists of ~20 nm spherical particles, and third layer consisting of rod shaped particles. These rod-shaped particles exhibited a clear trend of being swept into the matrix. The third type of microstructure came from the dark band, which looked like the tail of the “onion ring” region. TEM observations of the dark bands in the onion rings region and the tail band region revealed the existence of several tens to hundreds of nanometres-sized particles with various shapes including rod, hexagonal morphologies. The formed morphologies of
shaped particles were composed of the same elements and crystal structure, and could be identified as the same phase by selected-area diffraction (SAD). Figure 10 shows the typical TEM image of the first type of core shell structure. The core identified as BN phase by SAD, second layer was identified as TiB$_2$ and the third layer were TiB. In the α-Ti layer, N element detected by EDS analysis and suggesting that N intended to dissolve into α-Ti to become an α-Ti (N) layer [75].

**Mechanical properties**
Zhang *et al.* [76] have evaluated the mechanical properties weld joints. They reported that the average hardness distribution value of the stir zone (SZ) lowers with increasing tool rotational speed. The heat affected zone has the minimum value of hardness for each joint and the minimum value of hardness lowering with increasing tool rotation speed. Tensile test results show the each and every welded specimen have very low strength and ductility compared base metal and the mechanical properties of the welds decreasing with increase of FSWed tool rotation speed. Ramulu *et al.* [77] studied tensile properties of welds in different conditions i.e. as welded, as welded+ stress relieved and as welded+ super plastic formed. Welded samples have more yield & tensile strength than the base metal. However welds exhibit less elongation compared to base metal. Weld joints after stress relieving treatment resulted a little increase in strength with same elongation. Mechanical properties of welds prepared with a constant rotation speed with varying traverse speeds were evaluated by Liu *et al.* [78]. Weld has lower hardness compared to substrate in all conditions and hardness of lowest values was observed in the stir zone. Stir zone hardness is increased with increasing welding speed. Stir zone involvements dynamic recrystallization encouraged through the friction heat generated by tool rotation and plastic deformation executed via pin tool. Liu *et al.*[78] also reported that the weld joints achieved lower tensile strength and ductility in comparison to base metal and mechanical properties were enhancing with the increase of welding speed. Tensile property results exhibited that all the joints were failure at lower hardness region of weld. As we know that, the strength of the metallic materials is directly proportional to its micro hardness values, hence the joint strength lowering can be described by the decrease of micro-hardness in the welds. Degree of recrystallization is softening in the SZ decreasing through the increase in welding speeds, hence the mechanical properties of the welds enhancing with the influence of welding speed. Zhou *et al.* [79] reported that weld zone has a hardness value of minimum over the base metal and it starts decreasing with the increase of tool rotation speed. The decrease in hardness described at higher tool rotational speeds was explained with upper level heat input which aids to the microstructure coarsening. They reported that the transverse tensile property results exhibited that the welds have less elongation and strength than the base metal [80-84]. The tensile stresses of the welds were declined with increasing tool rotation speed.

**Modelling and simulation**
Numerical Model is an important process which will be helpful for most of the industrial applications in terms of reducing the cost of the material, selection of a suitable tool material and to evaluate the properties using various process parameters. Numerical analysis has been a useful technique to predict the thermal profiles during welding. Schmidt *et al.* [85] and Chao *et al.* [86] used two approaches, First model is based on the thermal profile and second approach was on finite element thermo-mechanical model. The heat in the thermal model is produced by the friction amongst tool shoulder &specimens and heat is also generated by the plastic deformation of the work pieces. Kamp *et al.* [87] and Chen C M & Kovacevic et al. [88] have represented finite element thermo mechanical model to evaluate the strain and stress distribution through FSW. Chiumenti *et al.* [89] used ALE approach to produce the model for the area surrounding the pin and Eulerian approach was opted for the rest of the sheet material. Buffa et al. [90-91] have implemented a numerical method for FSW of Al alloys and developed a customized model for titanium alloys based on preliminary results. They also reported the distribution of phases in the weld zone. Pasta and Reynolds et al. [92] have used numerical simulation to identify the effect of residual stress on the fatigue crack propagation of the weld joint. Buffa *et al.* [91] presented the characterization of the weld joints using experiments and numerical simulation.
They have also reported the integrative effect of strain and temperature for the transformation of as received microstructure to β phase structure. During cooling of the weld the β phase is transformed into α+β microstructure. The mechanism of the FSWed process is illustrated in figure 7. Edwards et al. [93] have carried out a hybrid experimental approach and numerical methods findings to know the concert of the FSWed and FSW+super-plastically formed titanium weld joints. Model developed by Edwards et al. has given excellent results between experimentally observed and Model of stress-strain behaviour of weld joint.

3. Conclusions

From the literature review, there is a scope for development of tool materials which have high strength, wear resistance and cost effective. Most of the research studies on friction stir welding of titanium alloys are available only on development of tool materials, and very few studies are done on characterization of the weldments which is most important to understand the weldability of titanium alloys. Based on this study, the following conclusions are drawn:

1. Friction stir welding was performed using tungsten based alloy tools, cobalt based tools, and molybdenum based tools and polycrystalline cubic boron nitride tools.
2. The titanium alloy of Ti-6Al-4V is a two phase (α+β) alloy. The microstructure formation during welding can be controlled by controlling the heat input.
3. Stir zone in below beta transus condition consists of bi-modal microstructure and in above β-transus condition has large prior β-grains and α/β laths present in the grain. Weld zone conducted below β-transus condition has better mechanical properties than welding at above β-transus condition.

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