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A REVIEW ON FRICTION STIR WELDING OF TITANIUM ALLOYS

C.M. VIVEK[a1], S.P. MANIKANDAN[b] AND J. KESAVAN[c]

[abc]Department of mechanical engineering, Periyar Maniammai University, Thanjavur, Tamilnadu, India.

ABSTRACT

A solid state joining process Friction stir welding is one of the proven approaches in metal joining. Titanium is considered as material opted for all mechanical and bio transplants applications. Joining of materials with high strength by friction stir welding (FSW) is complicated due to severe tool wear and change in the shape/size of the tool. This review paper focus on the FSW process in titanium alloys highlighting its tool design, welding parameters, weld strength etc.

KEYWORDS: Friction Stir Welding, Tool Design, Weld Strength, Titanium

FSW is a solid state joining process, most widely used in aluminum and its alloys to enhance the weld strength. FSW has significant importance over other welding techniques such as low concentration of defects, improved mechanical properties, regardless of position it operates (horizontal or vertical) and reduction in machining after welding. FSW was majorly used in low melting temperature materials like aluminum. The selection of tool materials and welding parameters has broader range to work with. In recent years FSW is being widely attempted in high melting temperature materials such as steel, nickel and titanium alloys [Mishra, 2005, Nandan, 2008 and Threadgill, 2009]. For these materials lot of attention is needed for selecting the FSW tool design, tool rotation, traverse speed, tool depth, plunge depth etc.

MATERIAL SELECTION

Titanium is an allotropic metal that exhibits high specific strength, mechanical properties, excellent corrosion resistance and concurrent weight. Due to their excellent properties, titanium is widely applied in the fields of aerospace, automotive, shipbuilding, railways, medical transplants etc [Boyer, 1996, Polmear, 1996, Majumdar, 1997 and Fuji, 1995]. Titanium has hexagonal close packed crystal structure (HCP) with limited number of independent slips which can't accommodate arbitrary plastic strain [Lienert, 2007 and Lee, 2005]. On alloying titanium with elements like aluminum, tin, vanadium, molybdenum, chromium, copper, zirconium, silicon either crystal can be stabilized, forming alpha, beta and mixed alpha beta titanium. These three types of titanium have its own advantages and limitations but mixed alpha beta is considered as metallurgicaly balanced due to presence of both alpha and beta stabilizers. These mixed alpha and beta have range of applications especially Ti-6Al-4V titanium alloy is extensively used in various applications. Pure titanium and alloys of titanium with alpha stabilizing elements maintain the crystal structure HCP and they are called alpha titanium grades. These grades don't exhibit ductile –brittle transformation and hence finds its applications in cryogenic temperature. The beta titanium alloys contains beta stabilizing element and small amount of alpha stabilizers which allow second level phase strengthening. The major alloying element is considered to be very biocompatible, which brings beta titanium alloys to have applications related to medical transplants .These possess good fabricability. But total worldwide output of titanium mill products includes only a few percent of beta titanium alloys by weight [Palanuwech, 2003]. Welding of titanium alloys are done by traditional fusion welding techniques like gas tungsten arc welding (GTAW), Gas metal arc welding (GMAW), plasma arc welding, Laser beam welding etc [Lathabai. 2001]. These techniques have several difficulties due to high material reactivity with oxygen, hydrogen, nitrogen with consequent embrittlement of the joint. The below are the summary of recent works in titanium based alloys using FSW.

FSW IN DISSIMILAR MATERIALS

Dissimilar welding using FSW possess more challenge than similar welding due to selection of materials which exhibit characteristics like melting point, plastic deformation etc.FSW is done on commercially pure titanium with ADC12 cast aluminum alloy using WC-Co tool. Three welding speeds are selected as 60, 90, 120 mm/min. Maximum failure load of 9.39 KN is achieved at 90mm/min. Defects arise at 60mm/min due to insufficient flow of Ti which cause inhomogeneous distribution. At 120 mm/min due to lower heat input and low reaction time for Ti and Al, decrease in tensile strength is observed [Chen, 2009]. The modified butt joint configuration is employed into the FSW of Ti-6Al-4V alloy to Al-6Mg alloy with a special pin plunge setup. The results reveal that the joint mechanical tensile strength can reach more than 92 % of the parent aluminum alloy strength [Li, 2014]. Lap joint of TC1 Ti alloy and LF6 Al alloys dissimilar materials were subjected to FSW. With the

[1]Corresponding author

increase of welding speed or decrease of tool rotation the amount of titanium alloy particles stirred into stir zone by the force of tool pin decreases continuously. Uneven distribution of micro hardness is observed in the lap joint and hardness of stir zone is 4 times higher than that of LF6Al base material which is due to the formation of TiAl intermetallic compound in stir zone [Yu-hua, 2012]. The effects of alloying elements on the microstructure of dissimilar butt joints of Mg-Zn-Zr alloy (ZK60) and titanium by using FSW. Zn and Zr are alloying elements of Mg-Zn-Zr alloy improves the tensile strength of titanium and magnesium joints by forming the thin reaction layer at point of interface during FSW. FSW carried out in dissimilar pure magnesium and titanium reveals lower tensile strength than that of magnesium alloy [Aonumaa, 2012]. The dissimilar lap joining of commercially pure titanium plate and structural steel plate using FSW with tool of different probe lengths (0.8 to 1.2mm) reveals sound joint in 0.9 and 1.0 mm only. This is due to the formation of non intermixed type interface compound of FeTi intermetallic compound of β-Ti phase and intermixed interface respectively. Intermetallic compound phases FeTi and Fe2Ti were observed in Tem. Over heating is found to be reason for deterioration of sound joints while using probe length of 1.1 and 1.2 mm [Gao, 2015]. Al 1060 and Ti-6Al-4V plates were lap jointed by FSW with a tungsten carbide cutting pin of rotary burr to cutoff titanium plate while welding. High strength lap joints were successfully obtained in this case which is due to titanium scrapings distributed in aluminum near the interface. It is also observed that ultimate fracture happen in aluminum metal that underwent thermal cycle provided by shoulder using FSW [Weia, 2012]. FSW (butt joint) was attempted in Ti-6Al-4V and aluminum alloy AA2024-T3 with tool pin center shifted towards aluminum. The strength of joint reached about 73 % of AA2024-T3 base material strength. It was also assumed that one material was clutched to other at least locally. It is also recorded that future research might be to increase the number and size of these clutched areas by optimization of welding parameters [Dressler, 2009]. Weldability of duralumin (2024-T3 and 7075-T651) and pure titanium/ titanium alloy Ti-6Al-4V using FSW has been investigated. It has been reported that Ti-2024 joint were higher in tensile strength compared to other combinations. An intermetallic compound TiAl3 forms in the Ti-6Al-4V aluminum alloy joint which affects the tensile strength [Aonuma]. Tungsten inert gas welding (TIG) or Gas tungsten arc welding (GTAW) assisted Hybrid FSW has been to join Al6061-T6 aluminum alloy and Ti-6Al-4V titanium alloy. The effects of GTAW as an preheating source on mechanical and micro structural properties for HFSW welds. Due to these preheating techniques smooth material flow is observed which causes sound joint. It is also recorded that the ultimate tensile strength is 91% of aluminum alloy base material and elongation in HSFW is two time over than elongation in FSW [Bang, 2013].

FSW OF SIMILAR TITANIUM METALS

Grain structure evolution during FSW of commercial purity α – titanium with Mo based alloy tool has been studied using optical microscopy and electron back scattered diffraction (EBSD). The grain structure evolution was shown to be a complex process driven mainly by the texture induced grain convergence, but also involving the geometrical effects of strain and limited discontinuous recrystallization. The development of the deformation induced grain boundaries in the stir zone was demonstrated to be influenced by texture evolution [Mironov, 2009].TC4 titanium alloy was friction stir welded using W-Re pin tool. The micro structural observation made in the stir zone revealed equiaxed recrystallized α phase, transformed β phase and fine lamellar α + β. The stir zone was considered to be weakest part of joint and fracture surface reveals a typical plastic fracture characteristic [Jie, 2010]. Development of given structure during high temperature β phase field during FSW of Ti-6Al-4V alloy has been studied. EBDS analysis confirms that β to α phase transformation during the cooling cycle of FSW was governed by Burger's orientation relationship. It also indicates that material flow in the β phase field resulted from a simple shear deformation arising from the {110} <111> slips [Mironov, 2008]. FSW is carried out in Ti-6Al-4V by adding 0.3 and 0.5 wt% of hydrogen (HYDROGENATION). This results in widening the welding parameters like rotation speed and traverse speed. It improves weld appearance, tool life and also reduces flash significantly. The microstructure in as received material Ti-6Al-4V consists of primary α and transformed β. Titanium alloys have a high affinity for hydrogen. It is demonstrated as temporary alloying element during FSW and then removed through a subsequent post weld dehydrogenation process [San-Martin, 1987 and McQuillan, 1951]. FSW with hydrogen in titanium Ti-6Al-4V alloy reveals a microstructure of acicular martensite in as weldeded structure which is related to reduction of critical cooling for martensite transformation. After post weld dehydrogenation process, martensite gets transformed into α + β which is fine equiaxed microstructure in weld zone. The addition of hydrogen is very effective in reducing softening temperature, thereby improving hot workability of titanium alloys and flow stress [Zhou, 2010 and Zhou, 2011]. An Finite element method (FEM) for FSW of Ti-6Al-4V titanium alloy has been developed to predict the phase volume fraction in typical weld zones and compared with the experimental procedures. The model result reveals that with increase in rotational speed of the tool from 300 to 700 rpm, the microstructure changes from α phase to α + β phase in the stir zone. It is also stated that the final phase volume distributions are in good agreement with experimental observations [Buffa, 2013]. Tool wear characterization has been studied by weight loss method, pin profile photographic technique and microscopic observations during FSW of titanium alloy Ti-6Al-4V the tool materials taken for study are W-La2O3, CY16 grade WC-Co and WC411 grade WC-Co tools. It is reported that tool deformation is observed in W-La2O3 with small conical pin which can be overcome by increasing the size of conical pin. Fracture was observed in CY16 grade WC-Co tool with 8% wt Co. No fracture or deformation is observed in WC411 grade WC-Co tool with 115 wt Co [Wang, 2014]

SCOPE FOR FUTURE WORK

From the above stated literatures it is clear that FSW is carried out in similar metals and in dissimilar metals. It is extensively carried out in aluminium, titanium alloys steels and magnesium. In titanium FSW is concentrated much in pure titanium and alpha beta titanium. Hence there exists a scope to carry out extensive research in following areas.

1. Hydrogenation during FSW of two dissimilar materials with titanium as one metal can be done and micro structural examinations (optical microscopy, SEM, EDSD studies), mechanical properties of weld zones tool wear mechanism can be studied.

2. Effect of hydrogenation in mechanical properties of stir zone after carrying out FSW in similar titanium alloys mixed α β titanium can be carried out.

3. Beta titanium is widely considered as biocompatible and hence used in medical transplants. However it is noted that beta titanium are welded using various techniques but not FSW. Hence if FSW is tried in beta titanium new tool design parameters can be evolved the resulting micro structural changes can be studied.

4. FSW can be carried in dissimilar materials with titanium as one material and with tool pin center shifted more towards the second metal, so as to increase the number and size of these second material clutched to titanium. Optimization of welding parameters can made using various well established techniques based on the volume of clutched areas.

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