IJAPIE-2016-04-203,Vol 1(2), 17-21

INTERNATIONAL JOURNAL OF ADVANCED PRODUCTION AND INDUSTRIAL ENGINEERING

(A Blind Peer Reviewed Journal)

Selection of Tool Material and Pin Geometry for Friction Stir Welding: A Review

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Abstarct : *The selection of tool material depends on the operational characteristics such as temperature, wear resistance and fracture toughness which determine the type of materials that can be joined. In this research, paper several tool materials along with pin geometry have been studied and a review has been presented.*

Keywords : *Tool Material, Friction Stir welding, Pin geometry, operational characteristics*

I. INTRODUCTION

Invented and later patented by The Welding Institute (TWI) in 1991 [1], Friction Stir Welding (FSW) is the solid state joining process which is considered to be unconventional in nature as the material does not melt during the process. Friction stir welding is a continuous, self-induced process involving a rotating tool which is non-consumable in nature and made up of harder material than the base metal. A variety of aluminium alloys with good mechanical properties and defect free welds have been made. When alloys are friction stir welded, phase transformations that occur during the cool down of the weld are of a solid state type in which a rotating tool moves along the joint interface, generating heat and resulting in a re-circulating flow of plasticized material near the tool surface [2].

The working principle of Friction Stir Welding process is shown in Figure 1. The FSW technique was initially developed for Al-alloys but it also has great potential for welding of Mg-, Cu-, Ti-, Al-alloy matrix composites, lead, stainless steels, Thermoplastics and different material combinations, mainly those which have identical melting temperatures and similar behaviour such as hot workability.

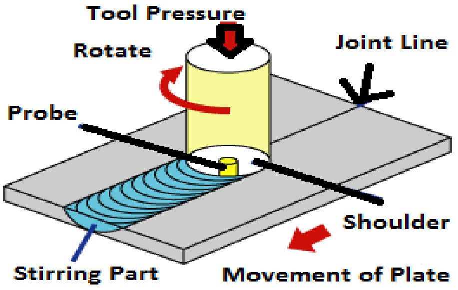

Figure 1: Friction Stir Welding Process

II. TOOL MATERIAL SEALECTION

Tool material is one of the important factors in the diagnosis of the suitability of a tool for a particular application. Welding is carried out around 70–90% of the material melting point so it is important that the tool material should have sufficient strength, hardness and wear resistance at this temperature otherwise the tool can twist and break. During the welding process the tool will reach temperatures in the range of 500 degree Celsius at tool tip depending on the type of material being welded. The tool material must have good hardness, toughness and wear resistant properties at elevated temperatures. A tool that comprises of outstanding high temperature strength, high temperature toughness and high temperature wear resistance is Tungsten carbide (WC) tool [3]. As noted by Mishra and Ma [4], in the FSW of aluminium alloys, the wear of the tool is not as much. As such, tool materials such as tool steels can be used. However, in the FSW of high melting point materials such as steel and titanium, as well as materials that can wear out such as metal matrix composites (MMCs), tool wear has been noted to be a serious issue in such cases. It was also noted that tool material selection is considered to be important in FSW of steel, titanium and composites. However, systematic researches focused on tool material selection have not been undertaken till date and it was further concluded that further research is required in tool material selection [4].

Rai et al. [5] established the characteristics that can be considered in the selection of tool material for FSW processes. They asserted that the properties of the weld metal and quality required influence the tool material to be used. The microstructure of the weld produced can be influenced by the interaction with the eroded tool material. The strength of the work material determines the stresses induced to the tool. Tool material properties influence the heat generation in the tool and thus the temperatures attained. Such properties like thermal conductivity are then important in tool material selection to attain particular properties in the final joint. Thermal stresses experienced in a tool are dependent on the coefficient of thermal expansion. Tool material selection may also be based on hardness, ductility and reactivity of the work materials.

Desired Tool Material Characteristics

To produce a high quality FSW joint, it is required that the tool material selection is done in a proper manner. According to Meilinger and Torok [6] and Zhang et al. [7], the characteristics that have to be considered in choosing the tool material for FSW include:-

- Wear Resistant
- Non reactive with the weld metal
- Sufficient strength, dimensionally stable and creep resistant at different temperatures
- Good thermal fatigue strength
- Resist the damage during plunging and dwelling hence it should have good fracture toughness
- Low coefficient of thermal expansion and good machinability for the manufacturing of the shoulder and probe

III. TOOL MATERIALS

There are several tool materials that have been used in the FSW process. These materials include but are not limited to; tool steels, high speed steel (HSS), Ni- alloys, metal carbides and ceramics.

A. Tool Steels

Tool steel is one of the most commonly used tool material in the welding/processing of aluminium, copper and magnesium alloys and can weld up to 50 mm in these materials [8]. These materials are easily available, have good machinability and thermal fatigue resistance. Tool steels are resistant to damage from abrasion and deformation in the FSW of aluminium alloys and other low melting temperature materials. Tool steels can be used to weld both similar and dissimilar welds as lapped joints or as butt joints.

Table 1: Types of Tool Steels & Materials Joined

S. NO	Materials Welded	Tool Material	References
1.	AA5083-H1111 Al Alloy	HCHCr	[9]
2.	Commercial grade Al-Alloy	SS310	[10]
3.	AA5754 & C11000 copper	H13	[11]
4.	AA2011 & A6063 alloy	HSS	[12]
5.	AA6082 & AA2024	C40	[13]
6.	6061-T6 Al & AISI 1018 mild steel	H13	[14]

Where HCHCr is High Carbon High Chromium, SS is Stainless Steel, HSS is High Speed Steel and C denotes Carbon.

B. Tungsten Carbide (WC)

WC-based tools increase the possibility of FSW of steels and titanium alloys. WC has excellent toughness and its hardness is about 1650 HV. This material has also been proved to be insensitive to sudden changes in temperature and loading during welding trial. However, Rai et al. [5] indicated that there is little information concerning the chemical inertness of the material in relation to the material being joined. WC offers superior wear resistance for FSW at ambient temperature [7].

Table 2: Properties of Tungsten Carbide

Properties	**Values**	**Units**
Density	14.9	gm/cubic cm
Hardness	91	Rockwell Hardness
Melting point	2870	Degree Celsius
Thermal Conductivity	110	Watts Per Meter Kelvin

C. Titanium Carbide

Titanium carbide (TiC) is well known for its hardness, chemical inertness, respectable strength, high-temperature stability and low density. TiC is an inert material which implies it does not react with the weld material [15]. This in itself is an advantage in terms of weld quality. Conventionally produced TiC has insufficient fracture toughness due to the process used which involves synthesis through the use of carbon black at high temperatures resulting in reduction of titanium dioxide. Large carbide particles are formed due to the high temperatures involved in the process and can cause the failure of TiC-based cemented carbides.

Table 3: Properties of Titanium Carbide

Properties	**Values**	**Units**
Density	4.93	gm/cubic cm
Hardness	2470	kg/mm/mm
Melting Point	3160	Degree Celsius
Thermal Conductivity	330	Watts Per Meter Kelvin

D. Refractory Metals

Refractory materials which include Tungsten (W), Molybdenum (Mo), Niobium (Nb) and Tantalum (Ta) are desired for their capability to withstand very high temperatures up to between 1000ºC – 1500ºC. This is made possible because many of these alloys are produced as single phase materials [7]. These materials are, however, very expensive, possess poor machinability and are brittle because they are processed using powder metallurgy methods [6]. Carbide materials are mostly desired for their wear resistance.

Table 4: Properties of Niobium (A PCBN)

Properties	Values	Units
Density	8.57	gm/cubic cm
Vickers Hardness	1320	Mega Pascal
Melting Point	2477	Degree Celsius
Thermal Conductivity	52	Watts Per Meter Kelvin

E. Polycrystalline Cubic Boron Nitride (PCBN)

It has been difficult to apply FSW to steels and other high temperature materials. This was because of lack of proper tool material that can resist the negative effects of high temperatures undergone during the process. The FSW technical handbook [16] outlined that the resistance to wear is very critical because no traces of the tool material should be left in the joint. Among the most promising tool materials that can fulfil these requirements is PCBN. Although PCBN was originally meant for machining of tool steels, it is now also being used as FSW tool material due to its high mechanical and thermal performance. Its high strength and hardness at elevated temperature as well as its high temperature stability, PCBN is desired in the FSW of steels and Ti alloys. Also, PCBN has a low coefficient of friction and hence it produces smooth weld surfaces [5]. This material has the capability to avoid the development of hot spots on tools due to its high thermal conductivity. The use of PCBN is, however, inhibited by its high cost of manufacturing. It is known that PCBN is the second hardest material in the world.

F. Ceramic Materials

Ceramics have been also used as FSW tool materials. This material is, however, too brittle as it normally fractures during the plunging phase [7]. Ceramic cutting tools are harder and more heat resistant than carbides but they are somewhat more brittle. These materials are well suited for machining of hard steels and super alloys. There are two types of ceramic cutting tools which are the alumina-based and the silicon nitride-based ceramics. Silicon based ceramics are normally used on super alloys and alumina based ceramics are used on ferrous and non-ferrous materials.

Table 5: Properties of Ceramic Materials

Properties	Values	Units
Density	Low	-
Hardness	Very Hard	-
Melting Point	1000-1600	Degree Celsius
Thermal Conductivity	3-200	Watts Per Meter Kelvin

IV. TOOL PIN GEOMETRY

Friction stirring pins produce deformational and frictional heating to the joint surfaces. The pin is designed to disrupt the faying, or contacting surfaces of the work piece, shear material in front of the tool, and move material behind the tool. In addition, the depth of deformation and tool travel speed are governed by the pin design.

The shape of the tool pin influences the flow of plasticized material and affects weld properties. The axial force on the workpiece material and the flow of material near the tool are affected by the tool pin profile. The length of tool pin depends on the thickness of base plates.

A. Cylindrical Pin

A round end to the pin tool reduces the tool wear upon plunging and improves the quality of the weld root directly underneath the bottom of the pin. The best dome radius was specified as 75% of the pin diameter. It was claimed that as the dome radius decreased, a higher probability of poor-quality weld was encountered, especially directly below the pin. In flat bottom cylindrical pin the friction velocity of a rotating cylinder increases from zero at the centre of the cylinder to a maximum value at the edge of the cylinder [17].

Figure 2: Cylindrical Tool Pin

B. Conical Pin

Cylindrical pins were found to be sufficient for aluminium plate up to 12mm thick, but researchers wanted to friction stir weld thicker plates at faster travel speeds. A simple modification of a cylindrical pin is a truncated cone. A triangular or ‘trifluted’ tool pin increases the material flow compared with a cylindrical pin [18]. The axial force on the workpiece material and the flow of material near the tool are affected by the orientation of threads on the pin surface [19].

Figure 3: Conical Tool Pin

C. Square Pin

Elangovan et al [20] studied five tool profiles – straight cylindrical, threaded cylindrical, tapered cylindrical, square and triangular – for the welding of AA 6061 aluminium alloy and found that the square pin profiled tools produced defect free welds for all the axial forces used.

Figure 4: Square Tool Pin

D. Tri Flute Pin

It contains three flutes cut in to the helical ridge. The flutes reduce the displaced volume of a cylindrical pin by approximately 70% and supply additional deformation at the weld line in addition it increases the tool travel speed. It can be used advantageously to weld thick-section aluminium alloys.

Figure 5: Tri Flute Tool Pin

Table 6: Comparison b/w Various Tool Materials and Tool Pin Geometries

Tool Material	**Tool Pin Geometry**	**Workpiece Material**	**Positive Aspects**
Tool Steels	All types of Pins	Almost all Aluminium alloys	Good machinability and thermal fatigue resistance
Tungsten Carbide	Conical Pin and Square Pin	Titanium Alloys	Good toughness and insensitive to sudden changes in temp.
PCBN	Square and Tri Flute Pin	Steels and Ti Alloys	High mechanical and thermal performance
Ceramic Materials	Tri Flute Pin	Super Alloys, Ferrous and Non Ferrous Materials	Harder and more heat resistant than carbides

V. CONCLUSIONS

In this paper, critical reviews on the selection of tool material and tool pin geometry for friction stir welding were carried out successfully. The following conclusions were therefore made:

1. The tool material selected should not create impurity to the final joint. This problem happens if the tool material is not hard enough to offer sufficient wear resistance to the materials being joined.
2. Tool Steels are preferably used to obtain welds between similar and dissimilar aluminium alloys of reasonable strength.
3. PCBN and tungsten based alloys are favorable materials for the FSW of high strength materials. High strength, hardness and high temperature stability of PCBN allow much smaller wear compared with other tools.
4. Tungsten based alloys, although not as hard and wear resistant, are more affordable options and have been used to weld steels and titanium alloys in a limited scale.
5. Cost effective and long life tools are available for the FSW of aluminium and other soft alloys. They are needed but not currently available for the commercial application of FSW to high strength materials.
6. The welding will not be successful if the pin length is equal to the base material thickness. The pin can touch the support plate or it can cause material congestion so the shoulder doesn't touch the surface and doesn't create heat.
7. For cost effective tool and to reduce tool wear, cylindrical tool pin may be used.
8. In order to produce defect free weld, square tool pin may be preferred.
9. Conical tool pin was preferred because it has a long standing shape and fewer imperfections appear than in case of use of unusual pin geometries. The simple pin shape is also not favorable because it cannot produce enough heat input on the whole thickness of aluminium alloys. The solution was little used pin geometry, the staged shape.
10. In general, soft materials can be joined with relatively harder tool materials while hard materials need very hard tool materials to successfully join them.

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