International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 2 Issue 11, November - 2013

Friction Stir Welding/Processing Tool Materials and Selection

Kudzanayi Chiteka
Production engineering, Delhi Technological University, India

Abstract

Making a choice in selection of friction stir welding/processing (FSW/P) tool material has become an important task which determines the quality of the weld produced. The tool material selection depends on the tool material operational characteristics such as operational temperature, wear resistance and fracture toughness which therefore determine the type of materials which can be joined. In this research, several tool materials have been analysed and the materials which they could be used to join have also been outlined. Soft materials can be easily welded using tool steels while harder materials need harder tool materials such as carbide based materials and polycrystalline cubic boron nitride (PCBN).

1. Introduction

Friction stir welding (FSW) is a solid state welding process that does not involve the actual melting of the work material. The heat generated from the friction between the tool and the work material is enough to soften the work material at a temperature below the melting point of the base metal. The process of FSW involves the welding and processing of a wide range of materials from soft materials such as aluminium to hard materials such as titanium. In such a situation, the FSW tool is often subjected to severe stresses and high temperatures [1]. Zhang et al. [2] indicated that material characteristics can be critical for FSW. The tool material choice is dependent on the work-piece and the required tool life and also it depends on the user experience and preferences.

2. Tool material selection

As noted by Mishra and Ma [3], 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 circumstances. 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 to date and it was therefore concluded that further researches are required in tool material selection [3].

Rai et al. [1] established the characteristics that can be considered in the selection of tool material for FSW/P 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.

3. Desired FSW/P tool material characteristics

To produce a high quality FSW joint, it is a requirement that the tool material selection is done properly. According to Meilinger and Torok [4] and Zhang et al. [2], the characteristics that have to be considered in choosing the tool material for FSW/P include;

- Resistance to wear,
- No harmful reactions with the weld metal,
- Good strength, dimensional stability and creep resistance at ambient and elevated temperature,
- Good thermal fatigue strength to resist repeated thermal cycles,
- Good fracture toughness to resist the damage during plunging and dwelling,
- Low coefficient of thermal expansion, and
- Good machinability for the manufacture of complex features on the shoulder and probe.

4. Tool materials

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

4.1 Tool steels

Tool steel is one of the most commonly used tool materials in the welding/processing of aluminium copper and magnesium alloys and can weld up to 50 mm in these materials [4]. These materials are easily available and have good machinability and thermal fatigue resistance. Tool steels have a resistance 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. When welding using the butt joint configuration, harder work materials are put on the advancing side (AS) and thus the softer material on the retreating side (RS) and the tool is given a slight offset from the butt interface towards the softer material [1].

Several materials have been joined using tool steels as such; stainless steel (SS), high carbon high chromium steel (HCHCr), high speed steel (HSS), H13 and C40. Tool steels have been able to weld aluminium, copper, magnesium and mild steel as given in table1.

Table . Types of tool steels and materials joined.

	Materials Welded	Tool materials	References
1	AA5083-H111 Al alloy	HCHCr	[5]
2	Commercial grade Al-alloy 6 mm thick	SS310	[6]
3	AA5754 and C11000 copper 3.175 mm thick	H13	[7]
4	AA2011 and AA6063 alloys10 mm thick	HSS	[8]
5	AA6082 and AA2024 4 mm thick	C40	[9]
6	6061-T6 Al and AISI 1018 mild steel 6 mm thickness	H13	[10]

High carbon high chromium (HCHCr) tool steel has a remarkably high wear resistance among different tool steel grades. **H13** is characterised by shock and abrasion resistance combined with red hardness. It has a chromium composition of 5% and has high toughness. **High Chromium Stainless steel (SS)** has a very high corrosion resistance capability. Each alloy used in making specific tool steel has a special contribution to the characteristics of the tool steel obtained. However, if used in excessive amounts, undesirable effects will manifest in the tool steel. **HSS** and high alloy grade tool steel have a high wear resistant characteristic. The quality of tool steels depends on the heat treatment which they receive. To attain good results the following need to be done: Preheating, soaking (austenitising), quenching (martensitic transformation) and tempering. Fig.1 shows the microstructure of HSS.

Table . Chemical composition of tool steels.

Steel type	%C	%Mn	%Si	%Cr	%W	%Mo	%V	%Ni	References
HCHCr	1.5	0.5	0.3	12.0		0.9	0.9	-	[11]
AISI M2(HSS)	0.85	0.3	0.3	4.15	6.4	5.0	1.9	-	[11]
AISI M4(HSS)	1.4	0.3	0.3	4.15	6.4	5.0	1.9	-	[11]
H13	0.40	-	1.00	5.30	-	1.4	1.0	-	[12]
SS310	0.25	2	1.5	24-26	-	-	-	19-22	[13]
C40	0.37-0.44	0.5-0.8	0.4	0.4	-	0.1	-	0.4	[14]

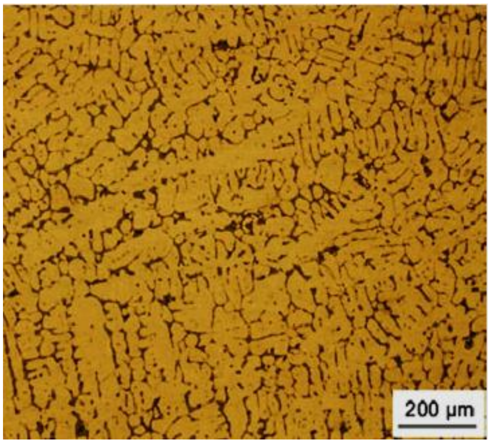

Figure . Microstructure of HSS [15].

4.1.1 Surface treatment

To prolong the operational life of tool steel, surface treatment is often a necessary requirement. These treatments improve on surface hardness, wear resistance and improve the frictional properties through reducing the coefficient of friction [11].

4.2 Carbide particle reinforced composites

Carbides are hard and wear resistant particles which are suspended in the matrix structure of alloy tool steels. Carbides form when some alloying elements such as vanadium, molybdenum, and chrome combine with carbon as the molten steel begins to solidify. Huge amount of carbides aids in wear resistance but they however reduce the toughness.

WC is often used in tools in form of cemented carbides mixed with metal binders such as Co, Fe and Ni. However, the fracture toughness and wear resistance of binderless WC cemented carbide is less than that of cemented carbides even though they have same hardness [16].

4.2.1 Tungsten Carbide - Cobalt materials (WC-Co)

According to Armstrong [17], the WC in WC-Co composite materials maintains the strength of the carbide particles at high temperatures. This composite has outstanding mechanical properties which makes it desirable in joining of hard materials. Liu et al. [18] reported that the addition of CrC_2 to WC-Co has an effect of reducing tool wear through reduction in oxidation of WC.

Kim [19] reported that WC-Co is generally classified into two grades. One of the grades is straight grades also referred to as unalloyed grades. These are pure WC-Co composites. For cutting tool grades, they contain between 3-13 wt% (weight percent) Co. Straight grades are the most wear resistant of the two grades. The other grade is known as alloyed grades. These have a composition of 3-12 wt% Co, 2-8 wt% TiC, 2-8 wt% TaC, and 1-5 wt% NbC. These are used on harder materials like steel.

Liu et al. [18] noticed that although WC-Co is a hard material, it can still wear out under certain welding conditions. In a study which they conducted a WC–Co tool was used in friction stir welding of a cast (AC4A Al–Si alloy matrix) aluminium metal-matric composite (AMC) composed of AC4AC30 vol% SiCp to examine the wear characteristics of the tool material. Although slight shoulder and pin wear were observed, the wear characteristics were appreciable. It was therefore noted that radial wear rate of the pin was influenced by the welding speed. The radial wear along the pin length was also found to be uneven with more wear close to the shoulder. In this experiment, the radial wear rate was defined as the varying pin diameter quantity per unit distance travelled by the pin.

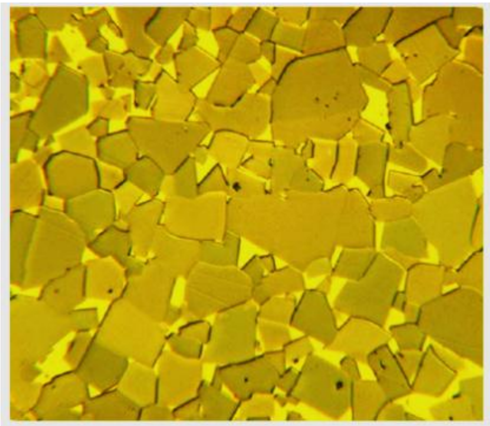

Figure . Optical micrograph of WC-Co composite. Dark yellow contrast represent Co phase [19].

Wear rate = varying quantity of pin diameter/travel distance [18].

If wear is represented by W, material quantity Q, and travel distance x, the wear rate may be expressed more mathematically as:

$$dW = \frac{dQ}{dx} \quad \text{(1)}$$

Jafarzadegan et al. [20] successfully joined 3 mm-thick plates of 304 austenitic stainless to plates of st37 steel using WC-Co tool.

4.2.2 Tungsten Carbide (WC)

WC-based tools increase the possibility of FSW/P 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. [1] indicated that there is little information concerning the chemical inertness of the material in relation to the material being joined. WC offer superior wear resistance for FSW/P at ambient temperature [2]. Materials joined using WC tool material are shown in table 3.

4.2.3 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 [21]. 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.

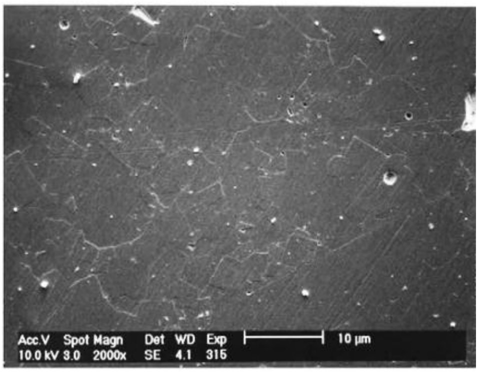

Figure . SEM micrographs of WC from 4.06 µm size powder sintered at 1800 °C [16].

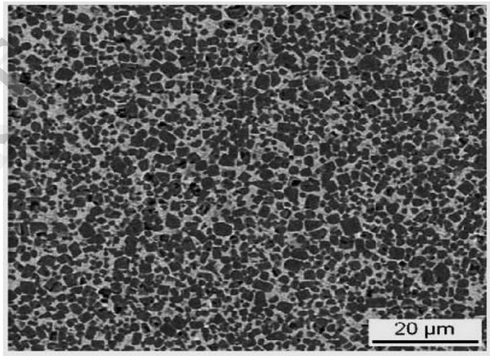

Figure . SEM micrographs of TiC–40 wt. % steel (TF4) [21]

Table . Materials joined by FSW using WC tool material.

	Materials Used	References
1	A3003-H112 Al alloy 15 mm thick & SUS304 (SS) 12 mm thick.	[22]
2	Al. alloy 1060 and titanium alloy Ti–6Al–4V plates 3 mm thick	[23]
3	Plates of SK4 high carbon steel alloy (0.95% C). 2 mm thick	[24]
4	Hyper-eutectoid steel (0.85mass% C, AISI-1080), 1.6 mm thick	[25]
5	SAF 2205 duplex stainless steel. 2mm thick	[26]
6	High carbon steel S70C (0.72 wt. % C). 1.6 mm thick	[27]
7	Carbon steels IF steel, S12C and S35C 1.6 mm thick plates	[28]

However, TiC has poor fracture toughness and it is also very expensive to manufacture [29].

On the other hand fine grained composites can be attained by using smaller carbide particles but the process is rather too expensive [29]. The microstructure of TiC is shown in fig. 4.

4.3 Nickel alloys and cobalt base alloys

Nickel and cobalt base superalloys have high strength, ductility, hardness stability and good creep and corrosion resistance. The strength of these alloys is derived from precipitates. As such, during operation their temperature should be kept below precipitation temperature which is between 600-800 ^{o}C [4]. Their use is, however, impeded by their poor machinability which is a hindrance to the production of complex features which include flutes and flats on tool profile [2]. These materials are often used in the FSW/P of copper alloys [4]. Zircaloy-4 nuclear grade material 3.1 mm thick has been joined using Co-based alloy tool [30].

4.4 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 1000 -1500 ^{o}C. This is made possible because many of these alloys are produced as single phase materials [2]. These materials are, however, very expensive, possess poor machinability and are brittle because they are processed using powder metallurgy methods [4]. Carbide materials are mostly desired for their wear resistance and reasonable fracture toughness.

Initially it was difficult to apply FSW/P to steel, stainless steel, nickel base alloys and Ti-alloys which are high melting temperature materials. This was because of tool material limitations. On the other hand, FSW/P tools made from refractory materials such as Tungsten, Molybdenum, Niobium, Hafnium, Rhenium, and Zirconium have high temperature properties but they however, lacked sufficient strength, hardness, and abrasion resistance. These elements would either alloy with the material being friction stir welded, or abrade and deposit tool material in the weld region after welding only a few centimetres. However, recent researches have made it possible to develop materials that can weld the previously considered unweldable materials.

4.5 Polycrystalline cubic boron nitride (PCBN)

It has been difficult to apply FSW/P to steels and other high temperature materials. This was because of lack of proper tool

Table . Tool materials and suitable weld metals

Tool Material	Suitable weld material
Tool steels	Al alloys, aluminium metal matrix composites (AMCs) and copper alloys
WC -Co	Aluminium alloys, mild steel
Ni-Alloys	Copper alloys
WC composite	Aluminium alloys, low alloy steel and magnesium alloys, Ti-alloys
W-alloys	Titanium alloys, stainless steel and copper alloys
PCBN	Copper alloys, stainless steels and nickel alloys

tool material that can resist the negative effects of high temperatures undergone during the process. The FSW technical handbook [31] 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/P 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/P of steels and Ti alloys.

Also, PCBN has a low coefficient of friction and hence it produces smooth weld surfaces [1]. 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

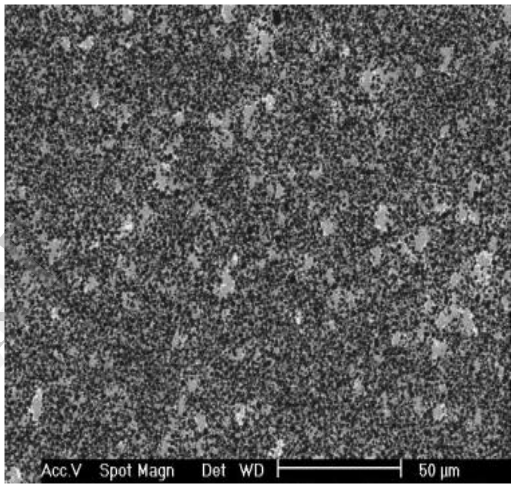

Figure . Microstructure of the G2 CBN-Al sintered materials (McKei, 2009) [32].

Table . Properties of Ceramics [9]

	Property	Value
1	Density	3.48 g/cm^3
2	Melting point	2700 ^{o}C
3	Fracture toughness	5 MPam$^{0.5}$
4	Knoop hardness	43 – 47 GPa
5	Young's modulus	600 -800 GPa
6	Thermal expansion	4.9 x10^{-6}K^{-1}
7	Thermal conductivity (20^{o}C)	150 -700 Wm^{-1}K^{-1}

PCBN is the second hardest material in the world. It is harder than the oxide, nitride and carbide ceramics. 1 - 10µm size of CBN particle are sintered with a variety of ceramic and metal phases applying ultra-high pressures and temperatures to get a solid, mass of PCBN [33]. PCBN can be applied on abrasive work pieces as well as materials of hardness exceeding 45 HRC. The properties of PCBN are shown in table 5.

4.6 Ceramic materials

Ceramics have been also used as FSW/P tool materials. This material is, however, too brittle as it normally fractures during the plunging phase [2]. 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 superalloys. 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 superalloys and alumina based ceramics are used on ferrous and non-ferrous materials. Table 5 shows the properties of ceramics.

5. Conclusion

It has been shown that in order to come up with good weld quality it is necessary to have knowledge of tool material selection. The type of material being welded as well as the weld parameters such as traverse speed and rotational speed as well as the material characteristics determines the best tool material that should be selected. The tool material selected should not be a source of contamination to the final joint. This normally happens if the tool material is not hard enough to offer sufficient wear resistance to the materials being joined/processed. In general, soft materials can be joined with relatively harder tool materials while hard materials also need very hard tool materials for successful joints to be made.

References

[1] R. Rai, A. De, H. K. D. H. Bhadeshia and T. DebRoy, Review: friction stir welding tools, *Science and Technology of Welding and Joining*, (2011) VOL16 NO4 325.

[2] Y. N. Zhang, X. Cao, S. Larose and P. Wanjara, Review of tools for friction stir welding and processing, *Canadian Metallurgical Quarterly*, (2012) VOL 51 NO 3.

[3] R.S. Mishra, Z.Y. Ma, Friction stir welding and processing, *Materials Science and Engineering*, R 50 (2005) 1–78.

[4] Akos Meilinger and Imre Torok, the importance of friction stir welding tool, *Production Processes and Systems*, vol. 6. (2013) No. 1. pp. 25-34.

[5] R. Palanivel and P. Koshy Mathews, Prediction and optimization of process parameter of friction stir welded AA5083-

H111 aluminum alloy using response surface methodology, *J. Cent. South Univ*. (2012) 19: 1−8.
[6] Biswajit Parida, M Mohapatra, Pankaj Biswas, N R Mandal, Study of Mechanical and Micro-structural Properties of Friction Stir Welded Al-Alloy, *International Journal of Emerging Technology and Advanced Engineering*, (2012).
[7] Esther T. Akinlabi and Stephen A. Akinlabi, Microstructural Characterizations of Dissimilar Friction Stir Welds, *Proceedings of the World Congress on Engineering* (2012) Volume III.
[8] L. Karthikeyan, M. Puviyarasan, S. Sharath Kumar and B. Balamugundan, experimental studies on friction stir welding of AA2011 and AA6063 aluminium alloys, *International Journal of Advanced Engineering Technology*, IJAET/Vol.III/ Issue IV/Oct.-Dec. (2012) 144-145.
[9] P. Cavaliere, A. De Santis, F. Panella, A. Squillace, Effect of welding parameters on mechanical and microstructural properties of dissimilar AA6082–AA2024 joints produced by friction stir welding, *Materials and Design* 30 (2009) 609–616.
[10] W H Jiang and R Kovacevic, Feasibility study of friction stir welding of 6061-T6 Aluminium alloy with AISI 1018 steel, *Proc. Institution of Mechanical Engineers, J. Engineering Manufacture* (1999) Vol. 218 Part B.
[11] Nick Tarkany, balancing wear strength and toughness, *Stamping Journal*, (2000).
[12] Tata steels, *Hot Work Tool Steel – AISI H13*, www.tatasteelnz.com.
[13] Atlas Steels Australia, *Stainless Steel - Grade 310 (UNS S31000)*, http://www.azom.com/article.aspx?ArticleID=966.
[14] Henan BEBON international co. ltd, *EN10083 C40 steel plate high carbon steel*, http://www.bebonchina.com.
[15] Zhou Xuefeng, Fang Feng and Jiang Jianjing, Solidification microstructure of M2 high speed steel by different casting technologies, CHINA FOUNDRY, Vol.8 No.3
[16] Seung I. Cha, Soon H. Hong, Microstructures of binderless tungsten carbides sintered by spark plasma sintering process, *Materials Science and Engineering* A356 (2003) 381 /389.
[17] Ronald W. Armstrong, The Hardness and Strength Properties of WC-Co Composites, *Materials* 2011, 4, 1287-1308; doi: 10.3390/ma4071287.
[18] H.J. Liu, J.C. Feng, H. Fujii, K. Nogi, Wear characteristics of a WC–Co tool in friction stir welding of AC4AC30 vol%SiCp composite, *International Journal of Machine Tools & Manufacture* 45 (2005) 1635–1639.
[19] Chang-Soo Kim, *Microstructural-Mechanical Property Relationships in WC-Co composites*, Ph. D. Thesis, Carnegie Mellon University, Pittsburgh, PA 15213, USA.
[20] M. Jafarzadegan, A. Abdollah-zadeh, A.H. Feng, T. Saeid, J. Shen and H. Assadi, Microstructure and Mechanical Properties of a Dissimilar Friction Stir Weld between Austenitic Stainless Steel and Low Carbon Steel, *J. Mater. Sci. Technol.*, (2013) 29(4), 367-372.

[21] Irina Hussainova, effect of microstructure on the erosive wear of titanium carbide-based cermets, *Wear* 255 (2003) 121–128.

[22] Tomo Ogura, Yuichi Saito, Taichi Nishida, Hidehito Nishida, Takumi Yoshida, Noriko Omichi, Mitsuo Fujimoto and Akio Hirose, Partitioning evaluation of mechanical properties and the interfacial microstructure in a friction stir welded aluminum alloy/stainless steel lap joint, *Scripta Materialia* 66 (2012) 531–534.

[23] Yanni Wei, Jinglong Li, Jiangtao Xiong, Fu Huang, Fusheng Zhang and Syed Hamid Raza, Joining aluminum to titanium alloy by friction stir lap welding with cutting pin, *Materials Characterization* 71 (2012) 1–5.

[24] S.A. Khodir, Y. Morisada, R. Ueji and H. Fujii, Microstructures and mechanical properties evolution during friction stir welding of SK4 high carbon steel alloy, *Materials Science & Engineering* A 558 (2012) 572–578.

[25] Y.D. Chung, H. Fujii, R. Ueji and N. Tsuji, Friction stir welding of high carbon steel with excellent toughness and ductility, *Scripta Materialia* 63 (2010) 223–226.

[26] T. Saeid, A. Abdollah-zadeh, H. Assadi and F. Malek Ghaini, Effect of friction stir welding speed on the microstructure and mechanical properties of a duplex stainless steel, *Materials Science and Engineering*, A 496 (2008) 262–268.

[27] Ling Cui, Hidetoshi Fujii, Nobuhiro Tsuji and Kiyoshi Nogi, Friction stir welding of a high carbon steel, *Scripta Materialia* 56 (2007) 637–640.

[28] Hidetoshi Fujii, Ueji Rintaro, Cui Ring, Nakata Kazuhiro and Kiyoshi Nogi, Friction stir welding of ultrafine grained IF and carbon steels, *Transactions of JWRI*, Vol. 35 (2006), No. 1.

[29] Industrial materials for the future, *Project Fact Sheet*, (2001).

[30] Yutaka S. Sato, Yoshito Nagahama, Sergey Mironov, Hiroyuki Kokawa, Seung Hwan C. Park and Satoshi Hirano, Microstructural studies of friction stir welded Zircaloy-4, *Scripta Materialia* 67 (2012) 241–244.

[31] FSW Handbook, ESAB AB, *Welding Automation* SE-695 81 LAXA (no date).

[32] Amanda Lynne McKie, *Mechanical Properties of cBN-Al Composite Materials Dependence on Grain Size of cBN and Binder Content*, University of the Witwatersrand, Johannesburg, (2009).

[33] E6 Advanced Materials, www.e6.com.