Friction Stir Welding of Copper Alloys by PTA Hardfaced Chromium Carbide Tools

A.Baskaran[1], K.Shanmugam[2] and V. Balasubramanian[3]
Assistant Professor[1], Associate Professor[2] and Professor[3]
Department of Manufacturing Engineering, Annamalai University, Annamalainagar- 608002, Tamil Nadu
Email: bas_au2006@yahoo.co.in[1]

ABSTRACT

In the present work an attempt was made to develop high temperature wear resistant hardfaced tools for friction stir welding (FSW) of commercial grade copper alloys. Hardfacing was applied on mild steel rod using chromium carbide forming powder by plasma transferred arc (PTA) hardfacing process. Commercially available tool materials like high carbon steel (HCS), high speed steel (HSS) and super high speed steel (SHSS) were also used to friction stir weld copper alloy for comparison purpose. From this investigation, it is found that the PTA hardfaced tool yielded defect free joints without tool wear compared to other tools. The optimum level of heat generation, formation of finer grains and higher hardness of stir zone are main reasons for the superior tensile properties of the joints fabricated by PTA hardfaced tungsten carbide tools.

Keywords : Plasma transferred arc hardfacing, Friction Stir Welding, Copper alloy, Tensile properties, Microstructure.

1.0 INTRODUCTION

Copper is one of the important engineering materials, widely used in the manufacturing industries because it has excellent electrical and thermal conductivity and suits well for manufacturing of electrical components. However, joining of copper by traditional welding processes is a challenge since the weld joint is seriously affected by the porosity and oxide formation [1]. Due to high thermal conductivity, the copper alloys require high heat input for welding and this causes change in base metal properties resulting in poor weld joint strength. Many research works [2, 3] were carried out to improve the mechanical and metallurgical properties of the conventional fusion welded copper joints. But it is very difficult to reduce the problems of conventional fusion welding processes such as spatter, shrinkage, distortion and porosity [4].

Friction stir welding (FSW) is a kind of solid-state joining technique, which was invented at The Welding Institute (TWI) of UK in 1991 and was originally applied to Aluminium alloys. With the rapid development of this technique and the application of high strength and durable rotational tools, the use of FSW has been expanded to many other materials including Magnesium, Copper, Titanium, Steels and Nickel alloys etc. [5]. The defect-free FSW joints displayed excellent mechanical properties when compared to conventional fusion welded joints. FSW process was demonstrated to avoid severe distortions and generated lower residual stresses compared to the traditional welding processes [6, 7]. The main obstacle to use FSW process to weld higher melting point materials is the development of tool materials capable of surviving the high temperatures and forces generated during welding. Considerable advances have been made, mainly through improved materials selection and tool design. One of the major challenges in expanding the application of FSW process to copper alloy is the lack of suitable conventional tool materials with high temperatures resistance. To be effective, tool materials must resist physical and chemical wear, possess sufficient mechanical strength at elevated temperatures, and effectively dissipate the heat carried to the tool during the welding process [8, 9].

Weld hardfacing techniques are employed mainly to extend or improve the service life of engineering components either by rebuilding or by fabricating in such a way to produce a composite wall section to combat wear, erosion and corrosion. Surface properties and quality depend upon the selected alloys and deposition processes [10]. Nowadays chemical and fertilizer plants, nuclear, steam power plants space, aircraft components, and in numerous industries employ weld hardfacing processes [11]. One of the hardfacing methods used for these purposes is plasma transferred arc (PTA) hardfacing process. The PTA hardfaced deposits exhibit enormous potential because of lower production cost and a higher productivity as well as easy operation and no need for any special surface treatment compared to thermal sprayed coatings [12, 13]. This method stands out for its high quality, metallurgical bonded with substrate and low diluted coatings. Moreover these hardfacing also exhibit high homogeneity, low oxide content, and low concentrations of other unwanted inclusions [14].

In this investigation an attempt was made to develop PTA hardfaced tool by depositing chromium carbide forming powder on mild steel rod. Thus developed PTA hardfaced tool was used to friction stir weld 6 mm thick rolled plates of commercial grade copper alloy. Further commercially available tools made of high carbon steel (HCS), high speed steel (HSS) and super high speed steel (SHSS) were also used to friction stir weld copper alloy. The performance of these tools (conventional and PTA hardfaced) was compared, analyzed and presented in this paper.

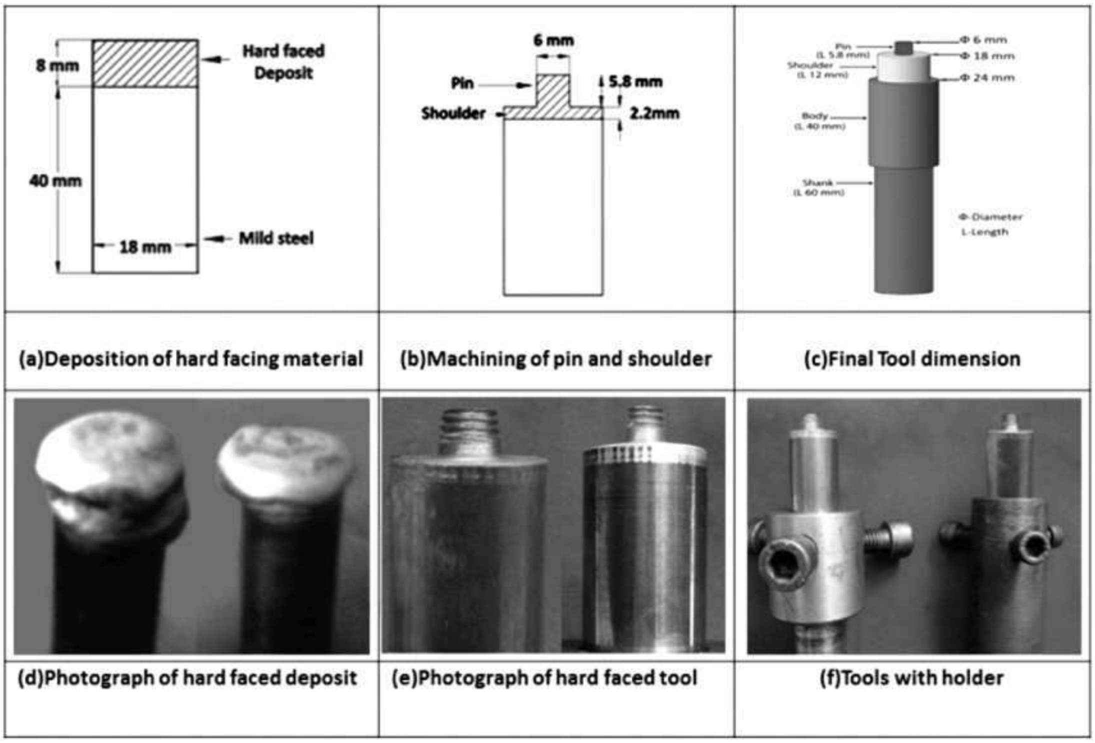


Fig. 1 : Schematic representation of hardfaced tool fabrication

2.0 EXPERIMENTAL PROCEDURE

Table 1 : Chemical Composition (wt%) of base metal

Fe	S	Bi	Ag	Pb	Sb	Cu
0.005	0.005	0.001	0.005	0.005	0.002	Balance

Copper plates of 6 mm thickness were used as base material in this investigation. The chemical composition and mechanical properties of the base metal are presented in **Table 1** and **2**, respectively. The commercially available mild steel rod was used as substrate for the deposition of the hardfacing material. The chemical composition of hardfacing powder and conventional tool material are presented in **Table 3**. The procedure used to fabricate the tool by PTA hardfacing method is shown in **Fig. 1**. Chromium carbide forming powder was used to deposit hardfaced layer onto the mild steel rod by PTA process. A self-fluxing powder NiCrBSi was also added to increase the coating adhesion and to avoid the temperature mismatch between the particle and substrate. Hardfacing was produced using optimized process parameters with powder composition consisting of 60 mass percent (%) Cr_3C_2 and 40 mass percent (%) NiCrBSi. Argon gas was used as plasma gas, shielding gas as well as powder transporting gas. PTA hardfacing parameters are shown in **Table 4**. After deposition, the tool was machined by the help of diamond wheel followed by hard turning to obtain the pin and top surface of the shoulder as shown in **Fig. 1e**.

The FSW parameters and tool dimensions used to fabricate the joints using HCS, HSS, SHSS and PTA hardfaced tools PCC (weld) are presented in **Table 5**. An indigenously designed and developed CNC controlled friction stir welding machine was used in position control mode to fabricate the FSW joints.

The joint configuration, tensile specimen dimensions, photographs of joints and tensile specimens are shown in (**Fig. 2**). The unnotched and notched tensile specimens were prepared as per the ASTM E8 M-04 guidelines [15]. Unnotched smooth tensile specimens (**Fig. 2c**) were machined to evaluate the transverse tensile properties of the joints such as yield strength, tensile strength and elongation.

Table 2 : Mechanical properties of base metal

0.2% Yield strength (MPa)	Tensile strength (MPa)	Notch tensile strength (MPa)	Notch strength ratio	Hardness @0.5N load (HV)	Elongation in 50 mm gauge length (%)
280	350	420	1.20	130	30

Table 3 : Chemical composition (wt. %) of tool materials

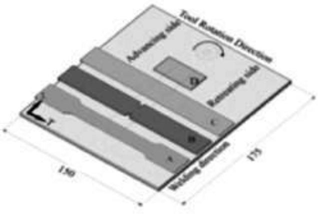
Tool Used	C	Cr	Fe	Mn	Mo	Si	V	W	Co	Ni	S	B
HCS	1.50	12.0	84.0	0.50	0.80	0.30	0.90	-	-	-	-	-
HSS	0.75	4.2	-	-	5.0	-	2.0	6.0	-	-	-	-
SHSS	0.8	4.0	-	-	5.0	-	2.0	6.0	5.0	-	-	-
PCC(weld)	4.8	Bal	0.10	-	0.15	0.04	-	-	11.0	1.90	0.03	0.5

Table 4 : Parameters used for PTA hardfacing

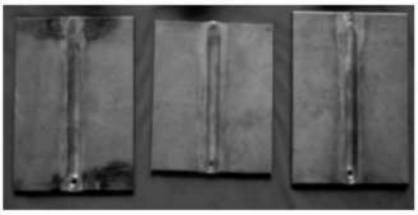
Transferred arc current (Amps)	160
Voltage (Volts)	22
Travel speed (mm/min)	170
Powder feed rate (gms/min)	30
Torch oscillation frequency (cycles/min)	42
Standoff distance (mm)	10

Table 5 : FSW Process Parameters and Tool dimensions used in this investigation

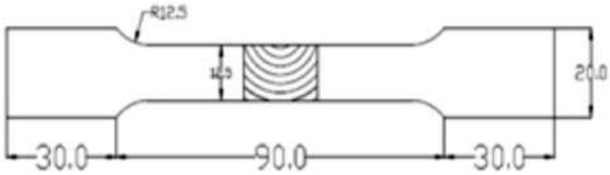
Joint configuration, (mm)	150 x 150 x 6
Tool rotational speed, N (rpm)	1200
Tool travel speed, S (mm/min)	25
Axial force, F (kN)	9
Tool inclination angle (?)	2?
Pin length, L (mm)	5.8
Tool shoulder diameter, D (mm)	18
Pin diameter, d (mm)	6
Pin profile	Taper threaded
Tool material	HSS, SHSS & PCC (weld)



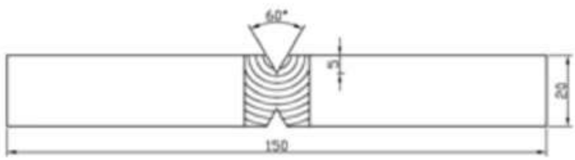
(a) Joint configurations



(b) Photographs of fabricated joints

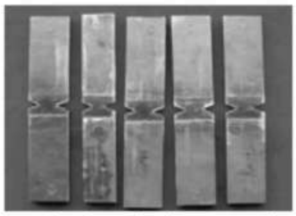


(c) Dimension of unnotched tensile specimen

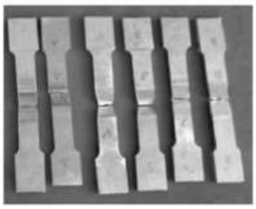


(d) Dimension of notched tensile specimen

(e) Photograph of unnotched specimen-before test



(f) Photograph of notched specimen-before test



(g) Photograph of unnotched specimen - after test

(h) Photograph of notched specimen - after test

Fig.2 : Fabrication of joints and tensile specimen

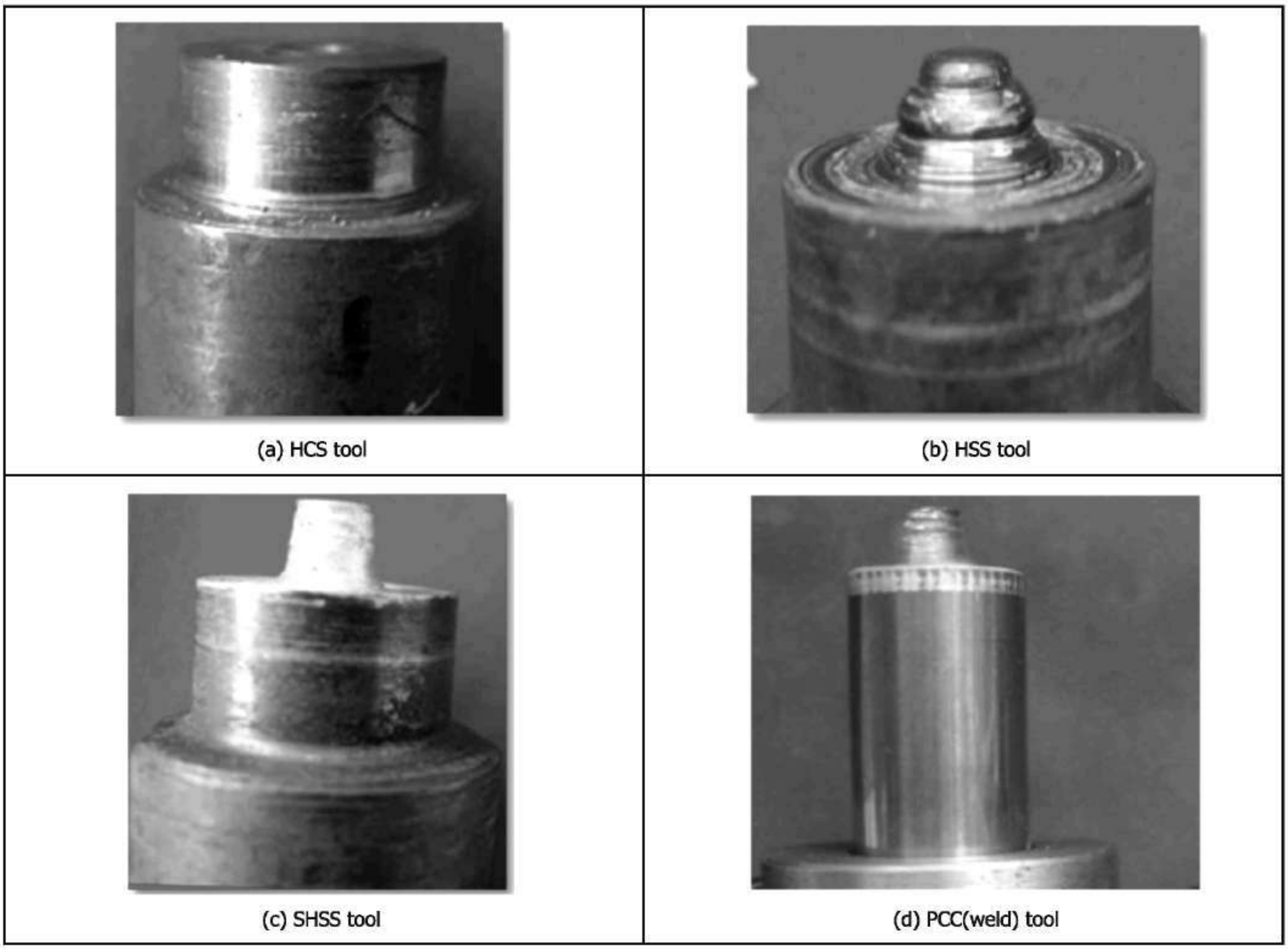
Notched tensile specimens (**Fig. 2d**) were prepared to evaluate notch tensile strength and notch strength ratio (notched tensile strength/un-notched tensile strength) of the joints. Tensile testing was carried out using 100kN, electro mechanical controlled universal testing machine with a loading rate of 1.5 KN/mm. Photographes of tensile specimens are displayed in **Fig. 2 (e-h)**.

Vickers micro hardness testing machine was used to measure the hardness at the stir zone and tool material with 0.5 N load and dwell time 15 s. Micro structural examination was carried out using an optical microscope incorporated with an image analysing software. The specimens for metallographic examination were sectioned to the required size from the joint comprising stir zone, Thermo mechanical affected zone (TMAZ), heat affected zone (HAZ) and base metal regions, and polished using different grades of emery papers. Final polishing was done using a diamond compound (1 μm particle size) in the disc polishing machine. The specimens were etchedwith a solution of 15 ml hydrochloric acid, 100 ml distilled water and 2.5 g iron chloride was used to reveal the microstructure of the welded joints. Average grain diameter of the weld nugget region was measured by applying the Heyn's line intercept method.

3.0 RESULTS

3.1 Tool Performance

The photographs of tools after friction stir welding 1m length of copper alloys of 6mm thick plates are shown in **Fig. 3**. During plunging stage itself the HCS tool pin failure occurred (**Fig. 3a**) and there was no welding taken place. Hence the joint fabricated using HCS tool was not analyzed for further



(a) HCS tool

(b) HSS tool

(c) SHSS tool

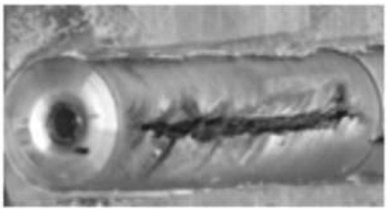
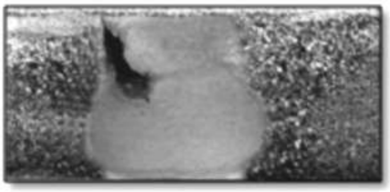
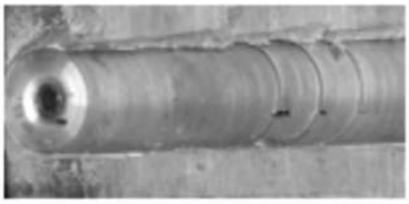
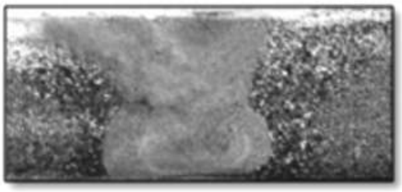
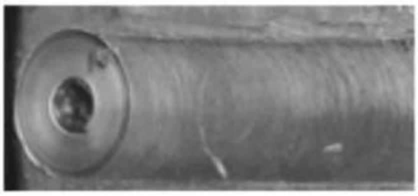
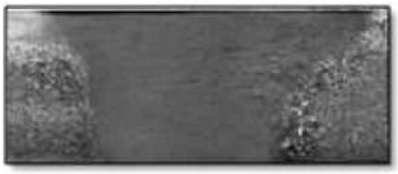
(d) PCC(weld) tool

Fig. 3 : Appearance of the tools after FSW of copper

investigations. However the HSS tool was able to complete the welding but defect was observed on the top surface of the weld and the tool was worn out excessively (**Fig. 3b**).Thread pin profile was completely worn out in SHSS tool (**Fig. 4c**). No defect was observed in weld top surface while using PTA hardfaced tool and the tool dimensions were not affected during welding (**Fig. 3d**).

3.2 Macrostructure Analysis

Fig. 4 shows the macrograph of the friction stir welded joints fabricated with HSS, SHSS, and PCC (weld) tools. Usually, friction stir welded joints are free from solidification related defects since there is no melting takes place during welding and the metals are joined in solid state itself due to the heat generated by the friction and flow of metal by the stirring action. However, FSW joints are prone to other defects like pin hole, tunnel defect, piping defect, surface defect, groove defect, Zig-Zag line and cracks,etc [16], due to improper flow of metal and insufficient consolidation of metal in the FSP (weld nugget) region. All the joints fabricated were examined at low magnification (10X) using stereo zoom macroscope to reveal the quality of weld nugget region. The joint welded using HSS tool showed a surface crack along the weld. The cross-sectional macrograph reveals that the crack is located well beneath the top surface and extended to half of the plate thickness in advancing side hence the joint made by HSS was not analyzed further. The joint made by SHSS and PCC (weld) tools are free from macro level defects in the top surface as well as in cross-section. Hence these two joints were taken for further analysis.

Tool used	Top surface of Weld	Cross Sectional macrograph AS RS	Observation
HSS			Surface defect
SHSS			Defect free
PCC (Weld)			Defect free

3.3 Transverse tensile properties

Table 6 : Tensile properties of FSW joints

Tool	0.2% Yield strength (MPa)	Tensile strength (MPa)	Elongation in 50 mm gauge length (%)	Notch Tensile strength (MPa)	Notch Strength ratio (NSR)	Joint efficiency (%)	Location of failure
SHSS	190	230	20	240	1.042	66	SZ
PCC (Weld)	230	280	22	320	1.142	80	TMAZ-AS

The transverse tensile properties such as yield strength, tensile strength, percentage of elongation, notch tensile strength, and notch strength ratio of the FSW joints made by SHSS and PCC (weld) tools were evaluated. In each condition, three specimens were tested, and the averages of the results are presented in **Table 6**. The tensile strength of the joints welded by SHSS and PCC (weld) tool are 230 MPa and 280 MPa respectively and Higher strain tolerance is observed in the joint made by PCC (weld) tool (**Fig.5**). The elongation of the un-welded parent metal is 30 %, and the elongation of SHSS and PCC (weld) joints are 20% and 22%, respectively. Another notch tensile parameter, NSR, is found to be greater than unity (>1) for both the joints. The NSR is 1.2 for un welded parent metal, but it is 1.042 and1.142 for the FSW joints made by SHSS and PCC (weld) tools respectively. Joint efficiency is the ratio between tensile strength of welded joint and tensile strength of the unwelded parent metal. The joint efficiency of the joint made by SHSS tool is approximately 66% and the efficiency of the joint made by PCC (weld) tool is 80 %. Of the two joints, the joints made by PCC (weld) tool exhibited 15% higher joint efficiency.

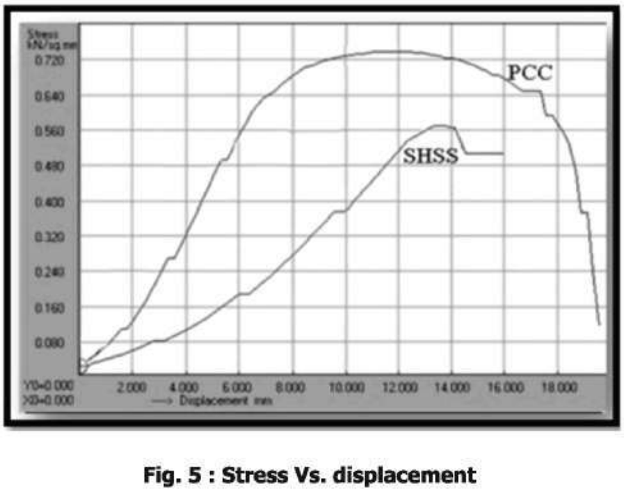
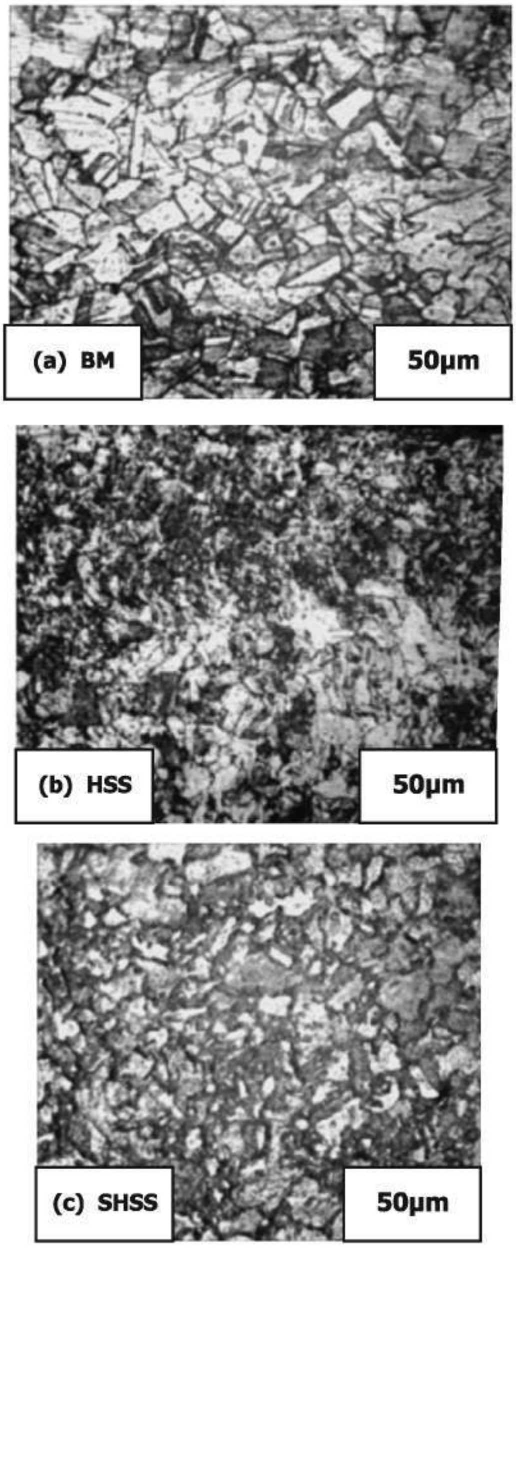


Fig. 5 : Stress Vs. displacement

3.4 Microstructure



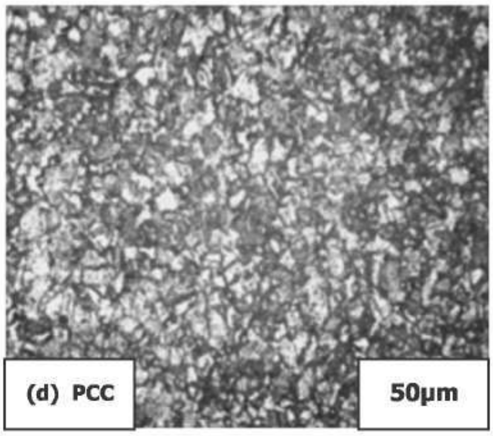


Fig. 6 : Optical micrographs of Stir zone

All the tensile specimens failed in the stir zone (**Fig.2 g & h**) and hence the optical micrographs taken at the stir zone are displayed in **Fig. 6** for comparison purpose. The base metal **Fig 6 (a)** contains coarse grains of 65.1 μm average grain diameter .The stir zone of joint made by HSS tool shows partially deformed grains (**Fig.6b**) with the grain size of 54.5μm and this may due to in sufficient heat generation. Thestir zone joint made by SHSS tool shows dynamic recrystallized grain (**Fig.6c**) with average grain diameter of 15.3 μm. The stir zone made by PCC (weld) tool shows the finer grains (**Fig.6d**) with average grain diameter of 5.6 μm.

3.5 Micro hardness

Hardness of the stirzone of FSW joints and tool materials (before welding) were measured at 5 different locations and the average is presented in **Table 7** for comparison purposes. Hardness of PCC (weld) tool is higher due to the presence of Chromiumcarbide. Hardness of the stir zone of the joint made by PCC (weld) tool is higher than the stir zone of the joint made by SHSS tool. This is mainly due to the presence of finer grains in stir zone.

Table 7 Hardness of Tool Materials and Stir zone

Joint made using	Hardness of Tool material ($HV_{0.5}$)	Hardness of Stir Zone ($HV_{0.5}$)
HSS	430	65
SHSS	640	100
PCC (weld)	860	110

4.0 DISCUSSION

In FSW, the tool hardness is more sensitive than other parameters particularly; heat generation due to friction is mainly dependent on tool material hardness. The tool material hardness will decide the coefficient of friction μ. If μ is higher, then friction between tool and base metal will be greater and the resultant heat generation will be higher. If μ is lower, then friction will be less and the resultant heat generation will be lower [17]. The heat generation due to friction $d\dot{e}f$ in FSW is given by the equation [2]

$$d\dot{e}f = \delta(\omega r - U \sin \Theta)\mu\, p\, dA \qquad (2)$$

Where, d is the extent of slip, μis the friction coefficient and p is the local pressure applied by the tool on the elemental area dA.

From the equation it is known that the heat generation is a direct function of co efficient of friction (μ). The higher coefficient of friction in the PCC (weld) tool is attributed to the higher hardness value measured in the tool (860 HV) and similar proportions was observed in SHSS tool (640 HV). The tool with higher hardness will have less deformation capabilities [18] and hence PCC (weld) tool experienced no wear loss.

The high thermal conductivity of copper alloy requires higher heat input for welding in comparison with other materials, resulting in quite low welding speeds. The required heat input is supplied by the PCC (weld) tool to make a defect free joint than the SHSS tool due to the better tool properties such as hardness, high coefficient of friction, less deformation and less wear rate.

While using SHSS tool, the joint was completed but threaded pin profile was completely worn out. SHSS tool indicate that the area between the shoulder diameter and pin diameter is reduced which in turn reduced the material flow from the leading to trailing edge. Insufficient frictional heat hinders the viscoplastic material flow. Also high flow stresses in the material can cause the tool to fail and tool material entrapped in stir zone.

While using PCC (weld) tool for friction stir welding, the base metal which is plastically stirred under the action of the rotating tool, undergo severe plastic deformation and the coarse elongated grains are fragmented into fine, equiaxed grains, and coarse strengthening precipitates are fractured into very fine uniformly distributed particles in the friction stir processed zone.

5.0 CONCLUSIONS

In this investigation, an attempt was made to develop low cost and high wear resistance tool material using PTA hardfacing technique to friction stir weld copperalloy. From this investigation, the following important conclusions are derived:

(i) Of the four tools investigated, HCS tool failed during plunging stage itself; HSS tool produced surface defect on the welded joint and the pin underwent excessive deformation; SHSS tool able to weld without defect but the threaded pin profile was worn out completely; PCC (weld) tool (Plasma transferred arc hardfaced Chromium carbide tool) was able to withstand the high temperatures and forces during FSW of copper alloys and yielded defect free joint.

(ii) The joint fabricated using PCC (weld) tool yielded higher tensile strength (280 MPa) and showed higher ductility (22%) and exhibited higher joint efficiency (80%) compared to the joint made by SHSS tool. This is mainly due to the formation of finer grains (5.6μm) in the stir zone as result of effective stirring of plasticized metal around the pin and under the shoulder. Presence of finer grains also increased the hardness of stir zone.

ACKNOWLEDGEMENT

Authors are grateful to Centre for Materials Joining & Research (CEMAJOR) Department of Manufacturing Engineering, Annamalai University for extending all the necessary facilities to carry out this investigation.

REFERENCES

[1] Hwang, Y. M; Fan, P. L; Lin, C.H. (2010) Experimental study on friction stir welding of copper metals, 'Mater Science and Eng ' vol. 527, 5723–5727

[2] Lorraina, O; Favierb, V; Zahrounic, H; Lawrjaniecd, D. (2010) Understanding the material flow path of friction stir welding process using unthreaded tools, 'Jourl of Mater Proce Tech' vol. 210, 603–609

[3] Lee, W. B; Jung, S. B. (2004) The joint properties of copper by friction stir welding, 'Mater Letters' vol. 58, 1041– 1046

[4] Steuwer, A; Barnes, S. J; Altenkirch, J; Johnson, R; Withers, P. J. (2011) Friction stir welding of HSLA-65 steel part ii. The influence of weld speed and tool material on the residual stress distribution and tool wear the minerals, Metals & Materials Society and ASM International,

[5] Sun, Y. F; Fujii, H. (2011) The effect of SiC particles on the microstructure and mechanical properties of friction stir welded pure copper joints, Mater Sci and Eng vol. 528, 5470–5475

[6] Hamiltona, C; Dymekb, D; Blicharskib, M. (2008) A model of material flow during friction stir welding, Mater charact vol. 59, 1206 – 1214

[7] Cavalierea, P; Nobilea, R; Panellaa, F; Squillaceb, W. (2006) Mechanical and microstructural behaviour of 2024–7075 aluminium alloy sheets joined by friction stir welding, 'International Journal of Machine Tools & Manufacture' vol.46, 588–594

[8] Packer, S; Nelson, T; Sorensen, C. D; Steel, R; Matsunaga, M. (2004) Tool and equipment requirements for friction stir welding ferrous and other high melting temperature alloys. In: 4th Intl FSW symp.,

[9] Ouyang, J. H; Mei, H; Valant, M; Kovacevic, R: Application of laser-based additive manufacturing to production of tools for friction stir welding.

[10] Balasubramanian, V; Varahamoorthy, R; Ramachandran. C. S; Muralidharan, C. (2009) Selection of welding process for hardfacing on carbon steels based on quantitative and qualitative factors, 'Int Jour of Adv Manuf Tech' vol. 40, 887–897

[11] Srimath, N; Murugan, N. (2011) Prediction and Optimisation of Weld Bead Geometry of Plasma Transferred Arc Hardfaced Valve Seat Rings, 'Euro Jour of Sci Rese' vol. 51, No.2, 285-298

[12] Flores, J. F; Neville, A. N; Kapur, A; Gnanavelu. (2009) Wear vol. 267, 213

[13] Katsich, C; Badisch, E. (2011) 'Surface Coating Technology' vol. 206, 1062

[14] Eitvydasgruzdys; Šarūnasmeškinis : (2011) Influence of Plasma Transferred Arc Process Parameters on Structure and Mechanical Properties of Wear Resistive NiCrBSi-WC/Co Coatings, 'Materials Science' vol.17, No.2, 1392

[15] ASTM E8 M-04. Standard test method for tension testing of metallic materials.

[16] Rajakumar, S; Muralidharan, C; Balasubramanian, V. (2011) Influence of friction stir welding process and tool parameters on strength properties of AA7075-T6 aluminium alloy joints. Materials and Design 32 535–549

[17] Elangovan, K; Balasubramanian, V; Valliappan, M. (2008) Influences of tool pin profile and axial force on the formation of friction stir processing zone in AA6061 aluminium alloy Int J Adv Manuf Technol 38: 285–295

[18] Nandan, R; Deb Roy, T; Bhadeshia, H. K. (2008) Recent advances in friction stir welding–process, weldment structure and properties. Progress in Mater Sci 53: 980–1023