Welding International 2005 **19** (12) 929–933
Selected from Journal of the Japan Welding Society 2005 **74** *(3) 14–17; Reference JJ/05/3/14; Translation 3519*

Friction stir welding of copper and copper alloys

doi:10.1533/wint.2005.3519

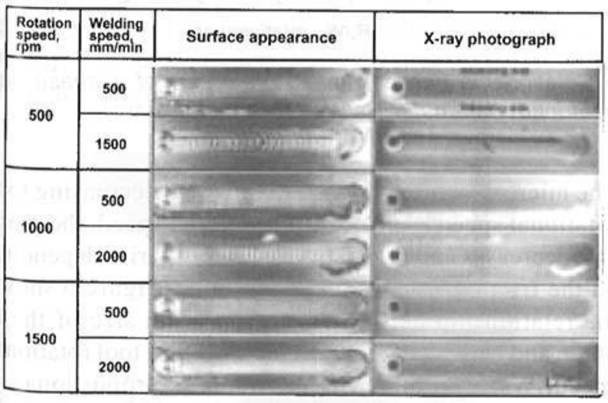
K NAKATA
Joining and Welding Research Institute, Osaka University

Introduction

Copper, through having good thermal conductivity and a relatively high melting point, generally requires preheating treatment to maintain satisfactory penetration during arc welding, ranking as a hard-to-weld material. Like aluminium and magnesium, however, copper is basically a soft metal and can therefore be relatively easily joined by friction stir welding. Available FSW research has focused on fabrication of copper (oxygen-free copper) containment canisters for nuclear waste,[1–6] fabrication of copper backing plates for sputtering devices by FSW seal welding,[7,8] and some other applications,[9] whereas FSW research on copper alloys has thus far been little documented.[10,11] Related research topics include studies of Al alloy to Cu alloy dissimilar joints[12,13] as well as – although not quite the same as friction stir welding – friction stir processing of Ni–Al bronze for casting structure modification[14–16] and friction stir processing of a Cu–Mn alloy for surface modification purposes.[17]

Among available research relating to the joining properties of friction stir welded copper and copper alloys, studies targeted at some specific product applications have accordingly progressed most, whereas any fundamental systematic research on friction stir welding of aluminium alloys has been little reported.

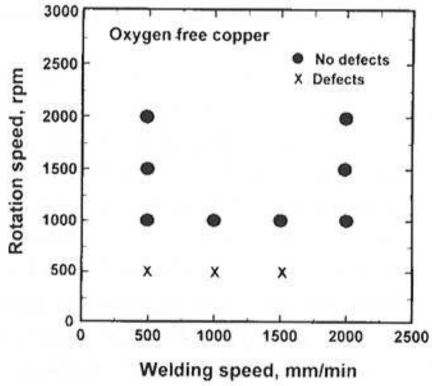
This article profiles the friction stir weldability of copper and copper alloys based on the author's own research.



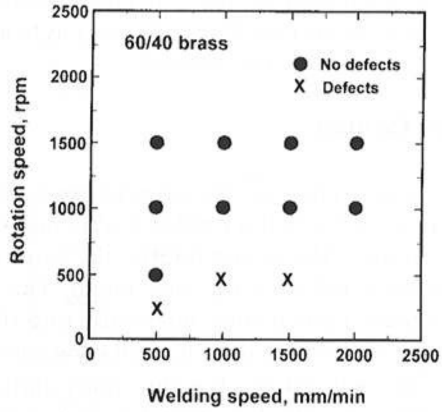
1 *Weld surface appearances and corresponding X-ray photographs during friction stir welding of 2 mm thick 60Cu/40Zn brass sheets with variation in tool rotational speed and welding speed (shoulder diameter: 15 mm, pin diameter: 5 mm). Arrow indicates groove-like weld defect.*

Welding parameters

Figure 1 shows the weld surface appearances and corresponding X-ray photographs during friction stir welding of 2 mm thick 60Cu/40Zn brass sheets with variation in the tool rotational speed and welding speed as typical friction stir welding parameters. The arrow marked in one X-ray photograph indicates a groove-like weld defect. Figure 2**a** and **b** respectively show the range of acceptable friction stir welding conditions necessary to achieve good-quality joints without defects during friction stir welding of oxygen-free copper and 60Cu/40Zn brass at a sheet thickness of 2 mm, shoulder



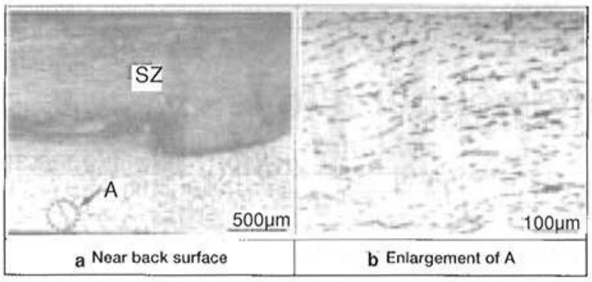
a Oxygen-free copper



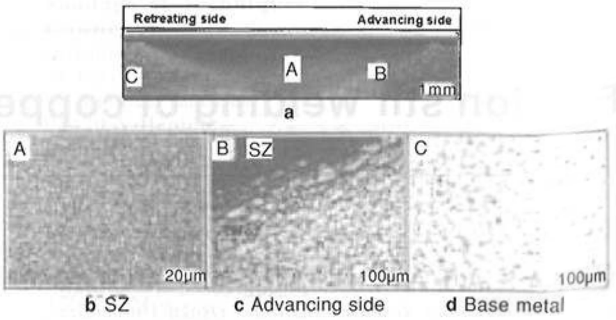
b 60Cu/40Zn brass

2 *Range of acceptable friction stir welding conditions necessary to achieve good-quality joints without defects during friction stir welding of oxygen-free copper and 60Cu/40Zn brass at sheet thickness of 2 mm (shoulder diameter: 15 mm, pin diameter: 5 mm).*

doi:10.1533/wint.2005.3519



3 *Kissing bond defect found on root face on plate back (60Cu/40Zn brass, 1000 rpm, 2000 mm/min).*



4 *Cross-sectional macrostructure (**a**) and microstructures of stirred zone (**b**), TMAZ (**c**) and base metal (**d**) in 2 mm thick 60Cu/40Zn brass friction stir welded joints (shoulder diameter: 15 mm, pin diameter: 5 mm).*

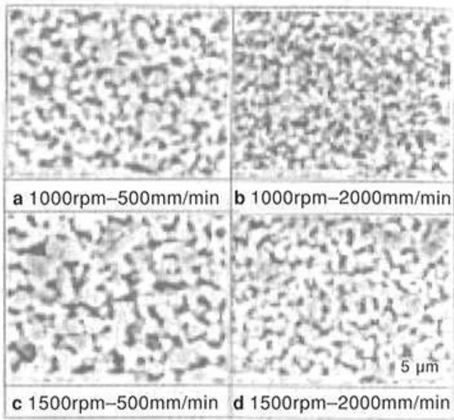
diameter of 15 mm, and pin diameter of 5 mm. The tool material used here is SKD61. Both materials show much the same results, having a relatively wide range of acceptable friction stir welding conditions.

With an increasing sheet thickness, however, the range of acceptable friction stir welding conditions rapidly narrows, being restricted to the low welding speed range. The acceptable range largely depends on factors such as the tool material and shape, the power of the friction stir welder, the applied pressure, and system rigidity. The results of the author's own research, however, suggest that this range extends up to around 400 mm/min for 3 mm thick high-strength brass, being around 50 mm/min for 5 mm thick oxygen-free copper. The joining temperature is also reported to attain 700–750 °C,[5,6] it being necessary to seek optimization of the tool shape and material.

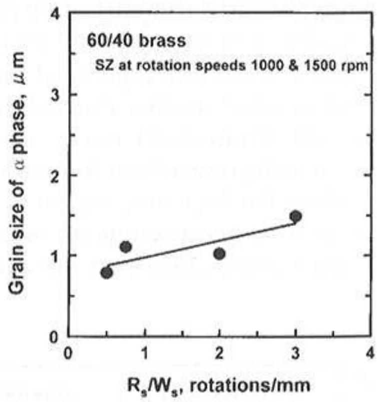
Welding defects generally occur under low rotational speed, high welding speed conditions. Defects typical of friction stir welding include groove-like defects on the weld surface (arrow in Fig. 1), tunnel-like cavities inside welds, and kissing bonds in the root zone. Kissing bond defects are particularly difficult to detect even by visual inspection and NDT. In the high welding speed range above 1000 mm/min, kissing bonds readily occur, being detectable by microstructural observations, as shown in Fig. 3. Materials with a high thermal conductivity such as copper are particularly susceptible to kissing bond defects. To prevent their occurrence, it is necessary to ensure precise control of the pin end position and satisfactory heat input control in such a way as to achieve adequate plastic flow on the pin end.

Structures formed

Figure 4 shows a cross-sectional macrostructure and microstructures of 2 mm thick 60Cu/40Zn brass friction stir welded joints. Macrostructurally, the joint can be clearly discriminated from the base metal. The stirred zone (SZ) shows a much finer microstructure than the base metal, the microstructure being well known to sustain fine equiaxing induced by dynamic recrystallization. Between both zones, the base metal incorporates what is known as a thermomechanically affected zone (TMAZ) involving elongation of the base metal structure. Figure 5 shows enlarged SEM micrographs of the stirred zone. Most is α phase material, with β phase being preferentially corroded by etching and thereafter becoming void-like.

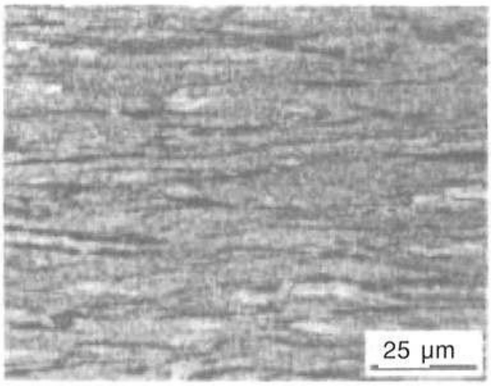


5 *Microstructural changes in 60Cu/40Zn brass stirred zone due to friction stir welding conditions.*

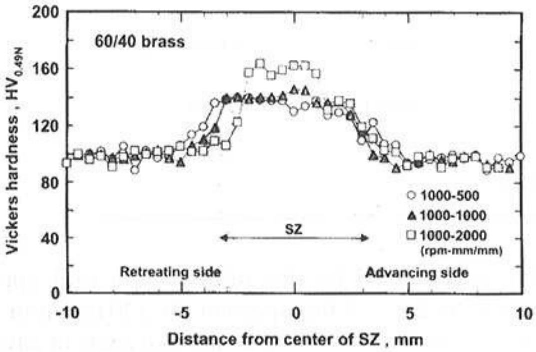


6 *Relationship between mean grain size of α phase and heat input parameter Rs/Ws (60Cu/40Zn brass).*

The microstructures suggest that, with a decreasing tool rotational speed and increasing welding speed, the grain size decreases and the grain size largely varies depending on the friction stir welding conditions. Figure 6 shows the relationship between the mean grain size of the α phase and heat input parameter Rs/Ws (Rs: tool rotational speed, Ws: welding speed),[18] which is proportional to the quantity of heat generated per unit weld length. Both parameters show a proportional relationship. With a smaller Rs/Ws, i.e. with a decreasing heat input, the grain size also decreases. Figure 7, however, shows that, when the heat input is inadequate, the stirred zone sustains



7 *Striated structure found in stirred zone under low heat input conditions (1000 rpm, 2000 mm/min, 60Cu/40Zn brass).*

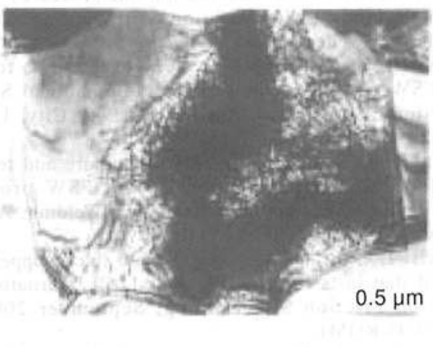


8 *Hardness distribution over cross-section of friction stir welded joints (60Cu/40Zn brass).*

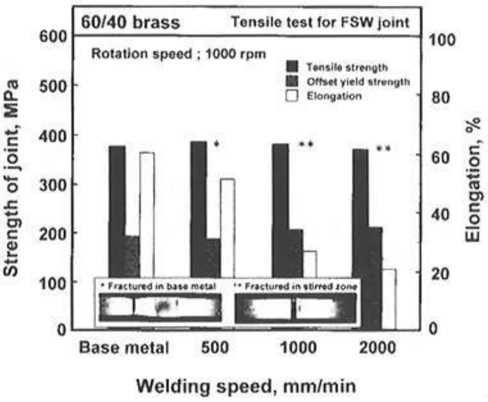
the same striated structure as the TMAZ together with a heightened risk of welding defects occurring.

Joint strength

Figure 8 shows the hardness distribution over the cross-section of 60Cu/40Zn brass friction stir welded joints. The stirred zone and TMAZ show a much greater hardness than the base metal (around HV 100), which becomes more pronounced with a faster welding speed. Figure 9 shows a TEM micrograph of the stirred zone, giving an example of the α phase being affected by numerous dislocations. This aspect warrants further detailed research in future to determine the precise nature of the response alongside the α phase behaviour. Oxygen-free



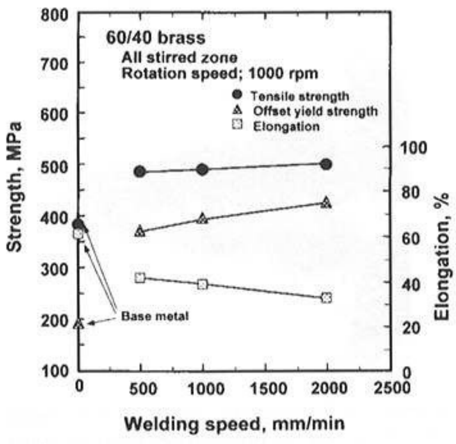
9 *TEM micrograph of α phase in stirred zone (60Cu/40Zn brass, 1000 rpm, 500 mm/min).*



10 *Tensile test results of 60Cu/40Zn brass as friction stir welded joints.*

copper, however, shows a lower hardness than the base metal as rolled material, although smaller changes can be obtained through suitable selection of welding conditions.

Figure 10 compares the base metal tensile test results with those of 60Cu/40Zn brass friction stir welded joints produced with variation in the welding speed at a constant tool rotational speed of 1000 rpm within a range of typical friction stir welding conditions. At a welding speed of 500 mm/min, fracture occurs in the base metal. In keeping with the hardness distribution shown in Fig. 8, the stirred zone and TMAZ have a higher strength than the base metal. At welding speeds of 1000 and 2000 mm/min, however, fracture occurs in the stirred zone, being due to the presence of kissing bonds (Fig. 3) acting as fracture initiators. To investigate the stirred zone strength in more detail, small-sized tensile specimens were sampled exclusively from the stirred zone. Figure 11 presents the corresponding tensile test results. The stirred zone has a higher tensile strength and offset yield strength than the base metal, with particularly the offset yield strength being around two-fold greater. In keeping with the hardness distribution, both values tend to increase with a faster welding speed. The elongation, however, tends to decrease slightly. Oxygen-free copper also shows much the same trend as the hardness response, whereas its stirred zone strength is lower than that of the base metal (rolled material).



11 *Tensile test results exclusively of 60Cu/40Zn brass stirred zone.*

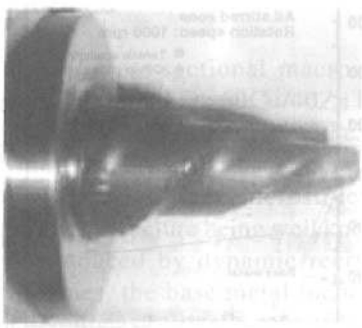
Table 1 Tool materials suitable for friction stir welding of various copper materials (author's own elaboration based on data in Ref. 11)

Tool materials	Copper materials			
	Oxygen-free copper (OFC)	Phosphorus-deoxidised copper	Al bronze (CuAl5Zn5Sn)	Cupronickel (CuNi25)
Tool steel (H13) Uddeholm QRO90SUPREME)	Good	Good	Poor	Impossible
Ni-base heat-resisting alloys (IN738LC, IN939, IN738LCmod)	Excellent	Excellent	Possible	Impossible
HIPed TiC–NiMo (TiC/Ni/Mo = 3/2/1)	Impossible	Impossible	Impossible	Impossible
Sintered TiC–NiW (TiC/Ni/W = 2/1/1)	Impossible	Impossible	Impossible	Impossible
Tungsten	Good	Good	Poor	Impossible
Polycrystalline boron nitride* (PCBN)	Good	Good	Good	Good

*Through being extremely brittle, this material requires special tool settings.

Tools

Through the oxygen-free copper and brass discussed in this article having a relatively low high-temperature strength, they have even been joined with tools produced from tool steel. During friction stir welding of copper alloys, such as Al bronze, phosphor bronze, cupronickel, etc, however, the pin at the tool end may readily fracture, making joining difficult. K. Savolainen *et al*[11] have tested a variety of tool materials for joining of copper alloys. Table 1 is based on the results obtained by these authors. PCBN ceramic tools can be applied for all copper materials, although they are adversely brittle and require special settings for proper use. L. Cederqvist[5] has successfully developed a friction stir welding system consisting of a high-power friction stir welder and specially shaped tool (with a Ni-base superalloy Nimonic 105 pin and sintered tungsten alloy shoulder) for friction stir welding of ultra-thick oxygen-free copper with a plate thickness of 50 mm, as shown in Fig. 12. The friction stir welding conditions reported by the author are a tool applied pressure of 90 kN, welding speed of 80–120 mm/min, tool rotational speed of 350–450 rpm, and tool angle of advance of 3–4°.



12 *Appearance of friction stir welding tool used for tool welding of ultra-thick oxygen-free copper with a plate thickness of 50 mm (Ref. 5) (pin material: Ni-base superalloy Nimonic 105, shoulder material: sintered tungsten alloy).*

Conclusions

Important tasks to be addressed in future include the development of tools suitable for copper alloy applications. Presently available tools may offer acceptable correspondences for oxygen-free copper and tough-pitch copper as relatively low-strength high-purity grades, although the development of tools tailored to copper alloy applications must be investigated from the combined perspective of material and shape. This may require much the same correspondences as for titanium alloys and steel.

References

1 Andersson C-G and Andrews R E: 'Fabrication of containment canisters for nuclear waste by friction stir welding'. 1st International Symposium on Friction Stir Welding, June 1999, Thousand Oaks, CA, USA (CD-ROM).
2 Andersson C-G *et al*: 'A comparison of copper canister fabrication by electron beam and friction stir processes'. 2nd International Symposium on Friction Stir Welding, June 2000, Gothenburg, Sweden.
3 Cederqvist L and Andrews R E: 'A weld that lasts for 100 000 years: FSW of copper canisters'. 4th International Symposium on Friction Stir Welding, April 2003, Park City, Utah, USA (CD-ROM).
4 Kallgren T and Sandström R: 'Microstructure and temperature dependence in copper welded by the FSW process'. 4th International Symposium on Friction Stir Welding, April 2003, Park City, Utah, USA (CD-ROM).
5 Cederqvist L *et al*: 'FSW to seal 50 mm thick copper canisters – a weld that lasts for 100 000 years'. 5th International Symposium on Friction Stir Welding, September 2004, Metz, France (CD-ROM).
6 Kallgren T *et al*: 'Finite element modelling of friction stir welding on copper canisters'. 5th International Symposium on Friction Stir Welding, September 2004, Metz, France (CD-

ROM).
7 Okamoto K *et al*: 'Fabrication of backing plates of copper alloy by friction stir welding'. 3rd International Symposium on Friction Stir Welding, September 2001, Kobe, Japan.
8 'Hitachi wrought copper: Present status of high-performance, high-precision joining of copper by friction stir welding'. *Welding Technique* 2001 **49** (9) 108–111.
9 Bang K-S *et al*: 'Study on weldability of Cu (OFC) by friction stir welding'. Proc International Welding/Joining Conf, Korea 2002, October 28–30, 2002, Gyeongju, Korea, 522–527.
10 Park H S *et al*: 'Microstructures and mechanical properties of friction stir welds of 60%Cu–40%Zn copper alloy'. *Mat Sci Engng A* 2004 (371) 160–169.
11 Savolainen K *et al*: 'Friction stir weldability of copper alloys'. 5th International Symposium on Friction Stir Welding, September 2004, Metz, France (CD-ROM).
12 Murr L E *et al*: 'Interaction vortices and related microstructural features in the friction stir welding of dissimilar metals'. *Materials Research Innovations* 1998 **2** (3) 150–163.
13 Murr L E *et al*: 'Microstructures in friction stir welded metals'. *J Materials Processing and Manufacturing Science* 1998 **7** (2) 145–161.
14 Mahoney M W *et al*: 'Microstructural modification and resultant properties of friction stir processed cast NiAl bronze'. *Materials Science Forum* 2003 426–432, 2843–2848.
15 Oishi K *et al*: 'The influence of friction stir processing on microstructure and properties of a cast nickel–aluminium bronze material'. *Materials Science Forum* 2003 426–432, 2885–2890.
16 Palko W A *et al*: 'Investigation of use of friction stir processing to repair and locally enhance the properties of large NiAl bronze propellers'. *Materials Science Forum* 2003 426–432, 2909–2914.
17 Lynch S P *et al*: 'Friction stir processing of a high-damping MN–Cu alloy used for marine propellers'. *Materials Science Forum* 2003 426–432, 2903–2908.
18 Nakata K *et al*: 'Weldability of high-strength aluminium alloys by friction stir welding'. *ISIJ (Iron and Steel Institute of Japan) International* 2000 **40** S15–S19.