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# THE EFFECT OF VARYING PROCESS PARAMETERS ON THE MICROHARDNESS AND MICROSTRUCTURE OF CU-STEEL AND Al-$Al_2O_3$ FRICTION JOINTS

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**Abstract.** Varying the rotational speed and forging pressures during friction welding affect the joint properties differently. C11000 copper to AISI 1030 mild steel (Cu-steel), and 6061 aluminum to alumina (Al-$Al_2O_3$) friction joints were fabricated on a direct drive friction welding machine. Microhardness traverses across the joint showed lower copper hardness, and higher steel hardness compared to the parent material, when 900 rpm rotational speed as used. This trend is reversed when the rotational speed is increased to 1800 rpm. Grain structure distortation was confined to an area of $< 0.5$ mm from the joint interface. Microhardness traverses across the Al-$Al_2O_3$ joint could not yield much information due to the influence of porosity on the microhardness readings. The results indicate that microhardness test is not appropriate for the characterization of Al-$Al_2O_3$ friction joints.

*Keywords:* Friction welding, copper, steel, aluminum, alumina, microhardness

**Abstrak.** Perbezaan dalam kelajuan putaran serta tekanan tempaan semasa kimpalan geseran mempengaruhi sifat-sifat sambungan yang terhasil. Sambungan geseran tembaga C11000 dan keluli lembut AISI 1030 (Cu-keluli) serta aluminium 6061 dan alumina (Al-$Al_2O_3$) disediakan dengan menggunakan mesin kimpalan geseran pacuan terus. Kekerasan mikro merentasi sambungan menunjukkan kekerasan tembaga yang lebih rendah dan kekerasan keluli yang lebih tinggi berbanding kekerasan bahan induk apabila kelajuan putaran 900 rpm digunakan. Pada kelajuan putaran 1800 rpm, keputusan yang sebaliknya diperolehi. Ubahbentuk ira terhad pada kawasan $< 0.5$ mm daripada garis sambungan. Kekerasan mikro merentasi sambungan untuk sambungan Al-$Al_2O_3$ tidak dapat memberi keputusan yang jelas disebabkan kesan liang terhadap kekerasan mikro yang diukur. Keputusan ini menunjukkan ujian kekerasan mikro tidak sesuai untuk pencirian sambungan Al-$Al_2O_3$.

*Kata kunci:* Kimpalan geseran, tembaga, keluli, aluminium, alumina, kekerasan mikro

## 1.0 INTRODUCTION

Friction welding can join metals to ceramics. Metals are not easily joined to ceramics [1] because of differences in the thermal expansion coefficient [2], the high stiffness

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of ceramics [3], as well as the lack of wettability of ceramic surfaces by commonly used molten metals [4]. These difficulties frequently lead to residual stress problems when higher joining temperatures are used, thus limiting the use of fusion welding processes in favor of solid state processes. Although there has been limited success in the fusion welding of metals to ceramics [5], the majority of processes commonly used for joining metals to ceramics have been limited to solid state processes such as brazing [6], or friction welding [7,8] since solid state processes do not face the same problem as fusion welding processes [9,10].

However, in comparison with a large amount of research on brazing processes and the development of new braze compositions [11], friction welding has been almost ignored as a process for joining metals to ceramics [12]. In view of the widespread application of friction welding as a process for joining metals, it might be helpful to study the friction welding of metals, as well as metals to ceramics, in order to take advantage of the large body of knowledge available. For friction welding to be accepted as a viable alternative to existing metal to ceramic joining processes, practical aspects such as the effect of varying process parameters on the properties of the joint have to be evaluated [13]. However, any such approach would have to use techniques applicable to both metals and ceramics, in order to properly characterise the joint.

Varying the rotational speeds and forging pressures might have different effects upon the mechanical properties of friction joints. Increasing rotational speed might lead to greater frictional heat at the interface, consequently leading to softening of the material [14], a greater extent of recrystallization [15,16], or even increased intermetallic formation [17]. Increasing the forging pressures have been found to cause an increase on the mechanical properties of the material adjacent to the joint [18]. Additionally, depending upon the type of materials joined, or more accurately the mechanical and physical properties involved, different ranges of rotational speeds and/or forging pressures produce different effects upon the quality of the joint [19]. Therefore, appropriate rotational speeds and/or forging pressures must be used in order to minimise any detrimental effects and produce joints of good quality.

## 2.0 EXPERIMENTAL

Friction joints were fabricated between C11000 copper and AISI1030 steel rods with a diameter of 9 mm on a modified lathe machine (APA TUM-35). 6061 aluminum rods were also joined to slip cast alumina rods on the same machine using different process parameters. Table 1 gives the chemical composition of the metals used as revealed by using x-ray fluorenscence (XRF) technique.

For the Cu-steel joints, rotational speeds were varied from 900, 1250 to 1800 rpm when forging pressures were maintained at 90 MPa. Rotational speeds were then maintained at 1250 rpm while forging pressures were varied from 70, 90 to 110

**Table 1** Chemical composition of the metals used as revealed by XRF

| Sample | Content (wt%) | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | C | Si | P | S | Cr | Mn | Ni | Al | Cu | Fe | Mg | Zn | rem. |
| Steel | 0.30 | 0.22 | 0.02 | 0.02 | 0.12 | 0.78 | 0.10 | - | 0.44 | 98 | - | - | <0.01 |
| Copper | - | - | - | - | - | - | - | - | 100.00 | - | - | - | <0.01 |
| Aluminum | - | 0.59 | - | - | - | 0.09 | 0.01 | 97.97 | 0.25 | 0.22 | 0.85 | 0.03 | <0.01 |

MPa. The Al-$Al_2O_3$ joints were prepared using rotational speeds varying from 900, 1250 to 1800 rpm, while forging pressures were maintained at 40 MPa.

Completed joints were sectioned perpendicular to the joint, mounted in epoxy and polished by using 400, 600, and 1200 grit SiC papers respectively. Knoop microhardness traverses test were performed across the joint interface. Measurements were taken 0.5 mm apart until a point 3.5 mm from the joint interface. A load of 0.1 kgf was used for the metal part of the joints. Due to the high hardness of alumina, a load of 0.3 kgf was used.

Samples for microstructural examination were given a final polishing using 0.5 μm alumina. Steel samples were etched by swabbing with 5% nital while the copper was swabbed with a solution of 25 ml $NH_4OH$, 50 ml $H_2O_2$ (3%), and 25 ml deionized water. The etching solution was selected based on its reaction to etch the selected metal without etching the joined metal too severely. The original microstructures of the metals used are shown in Figure 1. The change in grain size across the joint interface was evaluated using a 3 circle method. Due to the very different properties of alumina and aluminum, the Al-$Al_2O_3$ joints were not etched. A commonly used HF-based etchant for the alumina would attack the Al too severely, thus destroying any microstructure of interest near the joint line. Similarly, the Al part of the joint would not survive a thermal etch cycle carried out in excess of 1400°C.

## 3.0 RESULTS AND DISCUSSION

(1) Cu-steel joints

Figure 2 shows the results of the microhardness traverses of Cu-steel joint. A wide range of results was observed on the steel side of the joints, compared to the Cu side. This was probably due to the presence of a harder pearlite structure, in addition to the soft ferrite in the mild steel. In contrast, no such inconsistencies could be expected in the commercial purity, single phase Cu used in this study. In the presence of multi-phase microstructures, it is common to use macrohardness indentations or higher loads in order to obtain a reading, which is a representative of the average hardness of an area made up of both fields [20]. However, in this study, a small microhardness indentation was used in order to obtain the small changes in microhardness 0.5 mm apart across a traverse section of the joint. Therefore, a

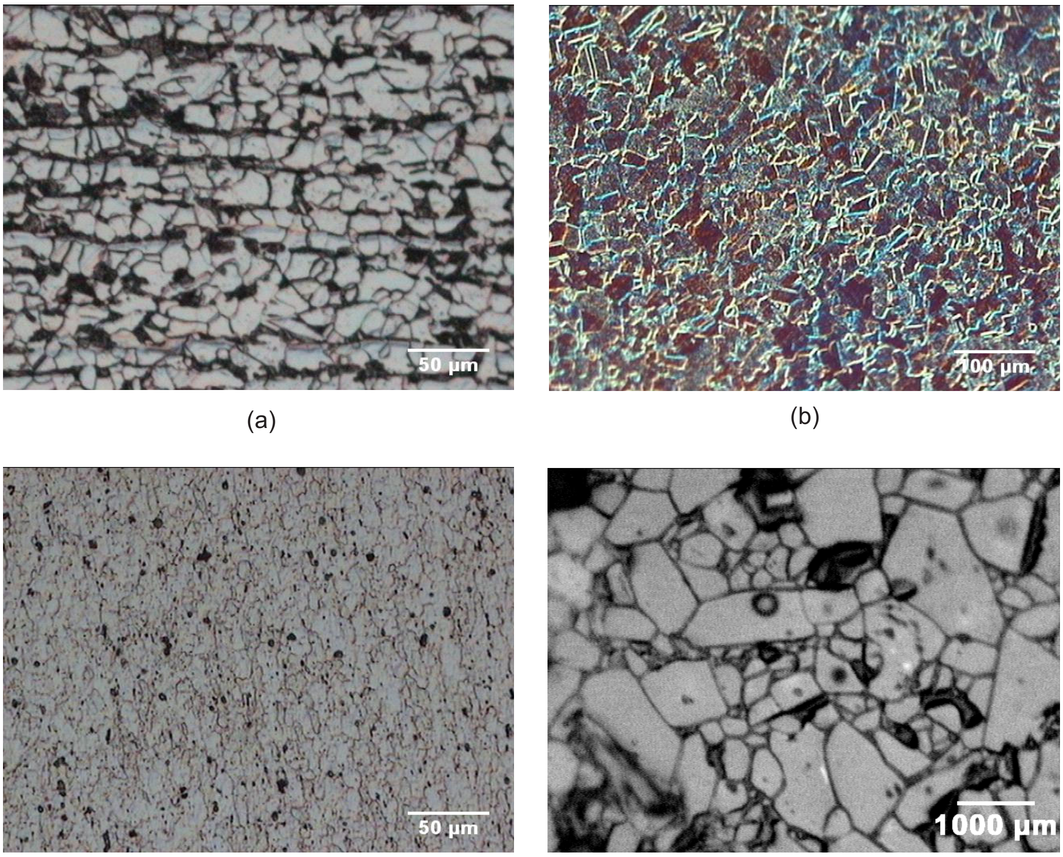



**Figure 1** Original microstructures of the (a) steel, (b) copper, (c) aluminum, and (d) alumina used

statistical method was needed in order to compare the average of several microhardness readings against the hardness of the parent material.

The scatter in the results presented in Figure 2 makes it simple to appreciate the need for a statistical test of significance. A *t*-test was used to compare the results from microhardness traverses with the hardness of the parent material. A summary of the results is shown in Table 2. At 900 rpm, the microhardness of the steel adjacent to the joint was higher than the microhardness of the parent steel, while the microhardness of the Cu was lower or similar to the microhardness of the parent Cu. At 1250 rpm, the microhardness of the steel adjacent to the joint was similar to the microhardness of the parent steel, while the microhardness of the Cu was lower than the microhardness of the parent Cu.

The change in the hardness values of the steel when 900 rpm rotational speed was used might indicate that at lower rotational speeds, the effects of work hardening are more dominant in comparison with the heat softening. However, when rotational speeds were increased to 1250 rpm, the effects of work hardening were balanced by

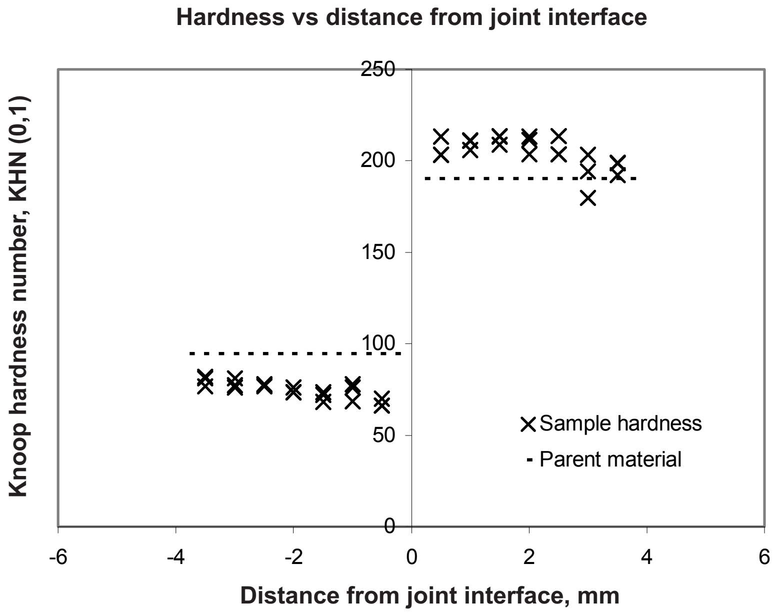



**Figure 2** Microhardness traverse of Cu-steel joint prepared using 1250 rpm rotational speeds and 90 MPa forging pressures. One to one comparisons of the hardness readings against measured hardness values of the parent materials is made difficult by the scatter. However, a rough observation shows that the Cu hardness might be lower than the parent material, while the steel hardness might be higher

**Table 2** *t*-tests comparing the sample hardness against the parent material using a null hypothesis, $h_o$: $k_1 = k_2$ and $\alpha = 0.05$. The tables summarise the change in hardness when (a) rotational speeds, S, is varied; forging pressures maintained at 90 MPa, and (b) speeds, S, kept constant at 1250 rpm while forging pressures, P, is varied.

| **Forging pressures = 90 MPa** | **Distance from interface** | | | |
|---|---|---|---|---|
| | **Cu side** | | **Steel side** | |
| | **-3.5 mm** | **-0.5 mm** | **0.5 mm** | **3.5 mm** |
| S = 900 rpm | $k_1 = k_o$ | $k_1 < k_o$ | $k_1 > k_o$ | $k_1 > k_o$ |
| S = 1250 rpm | $k_1 < k_o$ | $k_1 < k_o$ | $k_1 = k_o$ | $k_1 = k_o$ |
| S = 1800 rpm | $k_1 < k_o$ | $k_1 < k_o$ | $k_1 = k_o$ | $k_1 = k_o$ |

(a)

| **Rotational speed = 1250 rpm** | **Distance from interface** | | | |
|---|---|---|---|---|
| | **Cu side** | | **Steel side** | |
| | **-3.5 mm** | **-0.5 mm** | **0.5 mm** | **3.5 mm** |
| P = 70 MPa | $k_1 < k_o$ | $k_1 < k_o$ | $k_1 = k_o$ | $k_1 = k_o$ |
| P = 90 MPa | $k_1 < k_o$ | $k_1 < k_o$ | $k_1 = k_o$ | $k_1 = k_o$ |
| P = 110 MPa | $k_1 < k_o$ | $k_1 < k_o$ | $k_1 = k_o$ | $k_1 = k_o$ |

(b)

the effects of heating. The hardness of the Cu side of the joint is consistent with this view. However, the difference in values (i.e. softening of the Cu) might be due to the difference in thermal conductivities between Cu and steel. The higher thermal conductivities of the Cu might help in conducting heat away from the joint interface, resulting in a wider heat affected zone, compared to the steel.

No change was observed in the microhardness values when rotational speeds were fixed, and forging pressures varied. Therefore, varying the rotational speeds give a more pronounced effect on the mechanical properties of the joint, compared with varying the forging pressures. These might be attributed to increasing frictional heat (higher rotational speeds are used), causing softening of the material adjacent to the joint. The cold working introduced by forging might not be able to balance the effects of heat softening in the Cu. No significant change in the microhardness of the steel might mean that at a distance of 0.5 mm from the joint, the effects of heat softening are balanced by the cold work. It might also mean that at that distance, friction welding does not affect the steel.

Microstructural observation of the joint interface revealed that distortion of the microstructure was only observed at a distance < 0.5 mm from the joint interface (Figure 3). No significant change in the grain size of Cu or steel could be observed

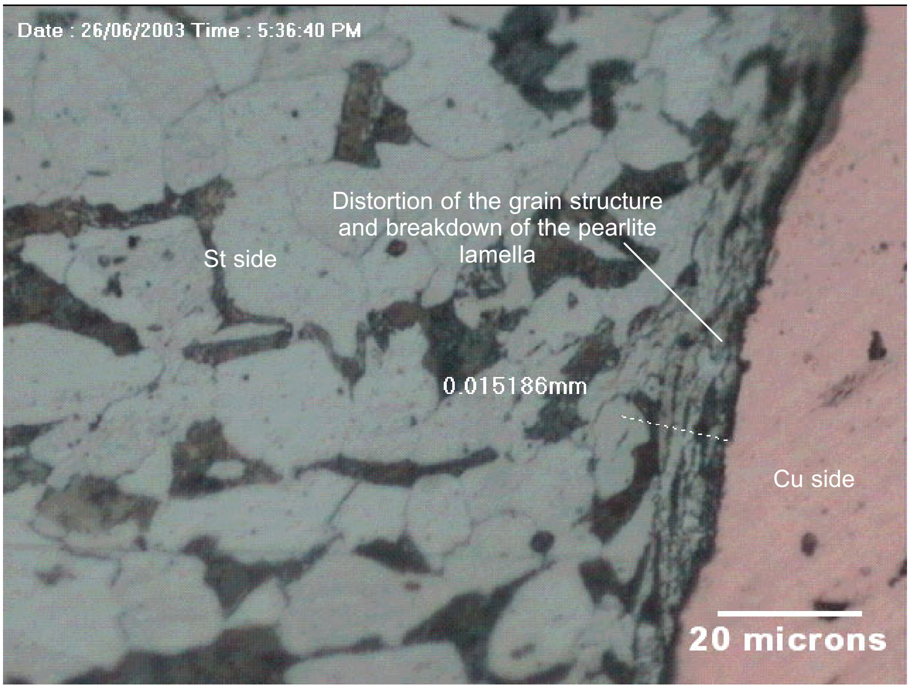
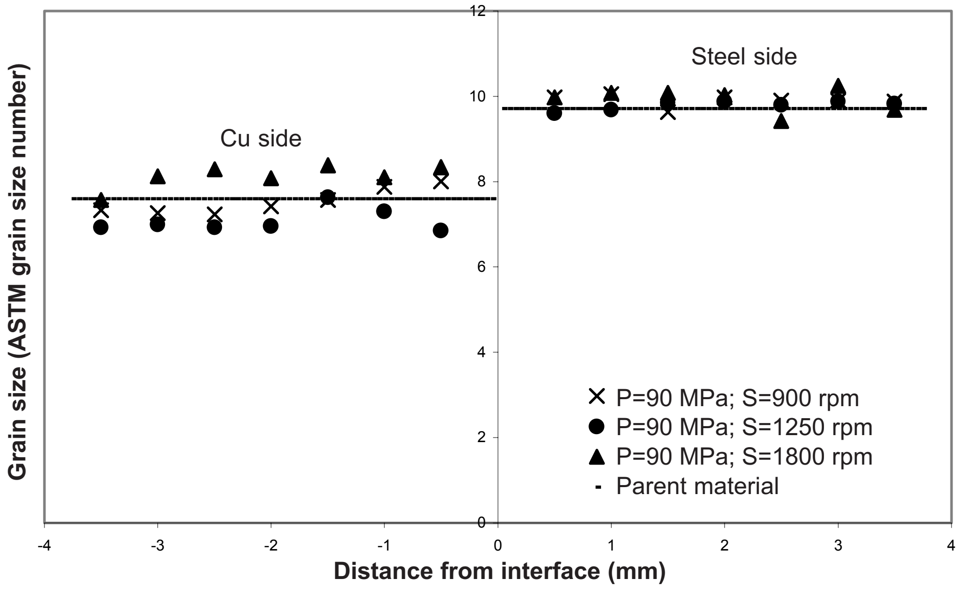
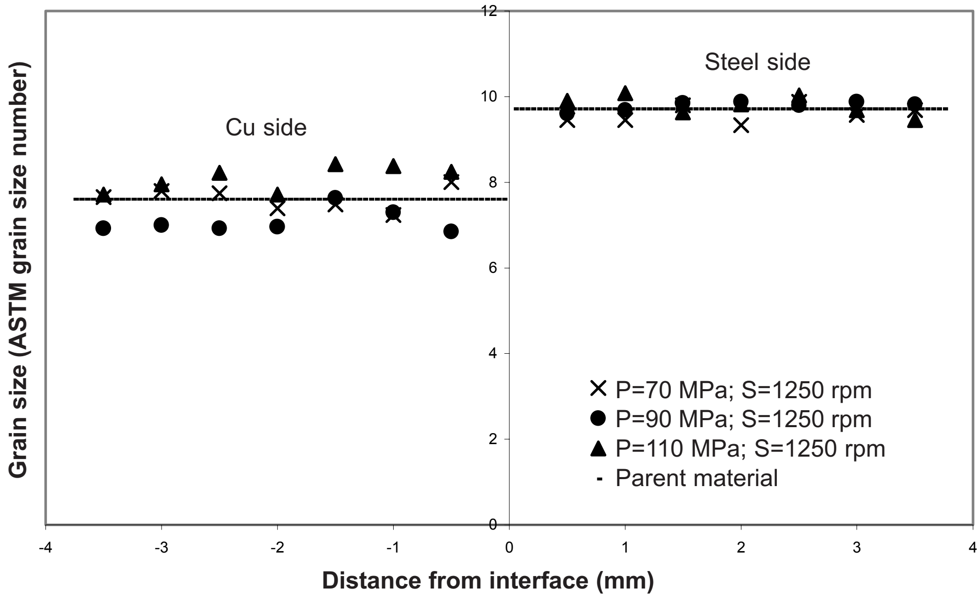



**Figure 3** Deformation of the steel could be observed in Cu-steel joints prepared using 1250 rpm rotational speeds, and 90 MPa forging pressures. The distortation observed in the microstructure was confined to a region of < 0.5 mm from the joint interface




(a)




(b)

**Figure 4** Variation of grain size across the joint interface when (a) rotational speeds, S, are varied; forging pressures, P, kept constant, and (b) forging pressures are varied; rotational speeds maintained. There is a larger scatter on the Cu side compared to the steel side probably because of the difficulty in revealing all grain boundaries in Cu, compared to steel. As the average grain size of the parent material falls within the scatter, no observable variation caused by the joining could be identified

(Figure 4). Therefore, any change in the grain size (recrystallization or deformation) could not be related to the materials' microhardness changes. As deformation of the steel was observed to be limited to an area < 20 μm from the joint line, deformation could be ruled out as the main factor that contributes towards the change in the steels microhardness. However, it is unclear whether the change in this region alone would significantly affect the properties of the joint itself.

(2) Al-$Al_2O_3$ joints

The hardness of the Al adjacent to the parent metal was lower than the microhardness of the parent Al (Figure 5). This was attributed to heat softening of the Al. In a previous paper, fracture was found to occur within the $Al_2O_3$ part of the joint, and it was concluded that the properties of the joint depended more on the properties of the $Al_2O_3$ than the properties of the Al. The results of the microhardness traverses across the Al-$Al_2$O3 joints were subjected to very wide scatter, particularly in the ceramic part of the joint (Figure 5). This scatter might be due to the influence of porosity upon the size of the indentations (Figure 6). Due to a very wide scatter, a conclusion about the properties of the $Al_2O_3$ via microhardness testing was not possible in this study. In order to properly characterise the properties of the joint, it might be necessary to model the residual stresses within the ceramic, and validate the results through methods other than microhardness indentations, possibly X-ray measurements of the $Al_2O_3$ lattice or thermocouple measurements of temperature in the $Al_2O_3$ at some distance from the joint line.

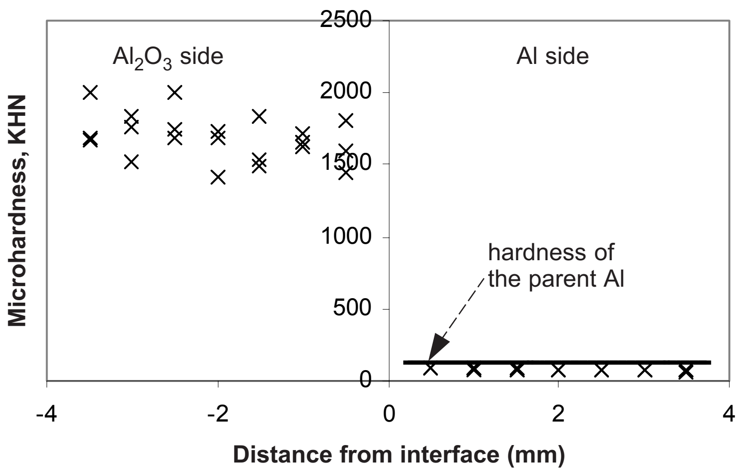
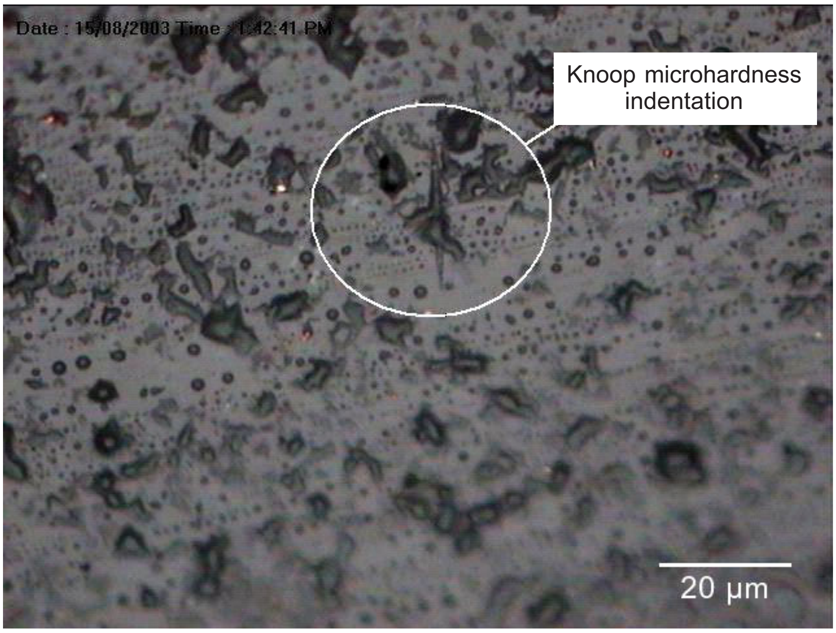
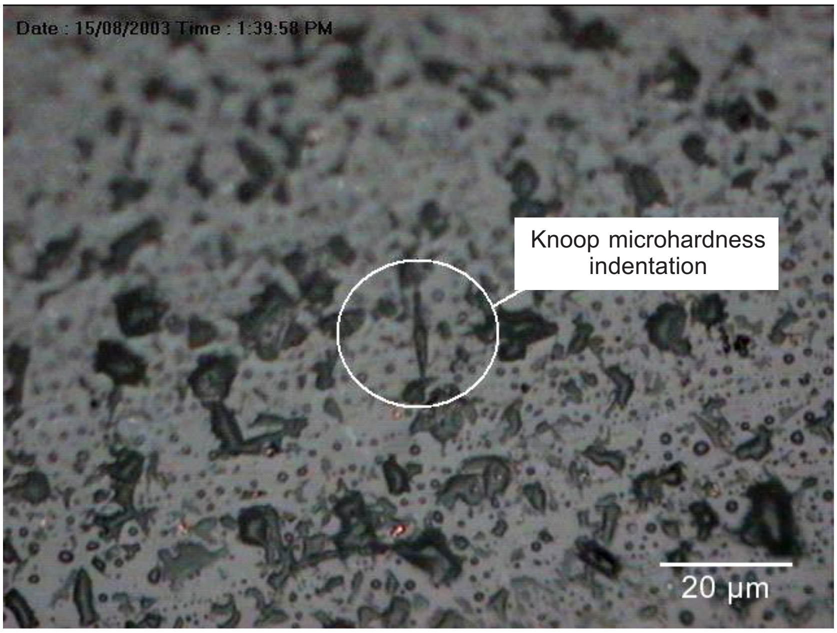



**Figure 5** A large scatter in the microhardness readings in the $Al_2O_3$ side of the joint makes it very difficult to draw a conclusion about the effects of joining on the microhardness of the $Al_2O_3$




(a)




(b)

**Figure 6** The presence of pores might affect measured microhardness values. Indentations upon the pores (a) might give a lower reading compared to indentations upon pore-free regions (b)

## 4.0 CONCLUSIONS

(1) Varying the rotational speed from 900 to 1800 rpm causes a significant softening of the material in Cu-steel joints. However, at 900 rpm, the effect of work hardening was more pronounced.

(2) The softening effects, probably caused by frictional heat, could not be negated by increasing the forging pressure from 70 to 110 MPa. The effect of work hardening was less pronounced than the softening effect at 1250 rpm rotational speeds, even when forging pressures were increased.

(3) Distortion of the microstructure was confined to a region of 0.5 mm from the joint interface. No change in the grain size beyond this region was observed.

(4) Microhardness traverses could not adequately describe the properties of the $Al_2O_3$ in the Al-$Al_2O_3$ joints. This was attributed to porosity in the slip cast alumina.

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