Grain Refinement and Phase Transformation of Friction Welded Carbon Steel and Copper Joints

W. B. Lee, C. Y. Lee, Y. M. Yeon, K. K. Kim and S. B Jung

Abstract

The refinement of microstructure and phase transformation near the interface of pure copper/carbon steel dissimilar metals joints with various friction welding parameters have been studied in this paper. The microstructure of copper and carbon steel joints were changed to be a finer grain compared to those of the base metals due to the frictional heat and plastic deformation. The microstructure of copper side experienced wide range of deformed region from the weld interface and divided into very fine equaxied grains and elongated grains. Especially, the microstructures near the interface on carbon steel were transformed from ferrite and pearlite dual structure to fine ferrite, grain boundary pearlite and martensite due to the welding thermal cycle and rapid cooling rate after welding. These microstructures were varied with each friction welding parameters. The recrystallization on copper side is reason for softening in copper side and martensite transformation could explain the remarkable hardening region in carbon steel side.

Key Words : Friction welding, Phase transformation, Recrystallization, Steels, Copper.

1. Introduction

The joining of dissimilar materials plays a critical role in advanced manufacturing technology, since different properties are required within any particular application, which properties cannot be obtained by a single material. The techniques available for joining dissimilar metal combinations are generally limited to those which do not result in the melting and solidification of the metals to be welded. As a result, brazing or solid state bonding has been generally selected as joining process [1)].

Copper and steel combination can be applied to electrode and steel shaft in the electrical discharge machine (EDM) and should be joined by a sound welding technique. When brazing was applied to the joining of Cu and carbon steel or stainless steel[2)], this process resulted in high production cost and thermal degradation at the Cu side. Although this process successfully joined Cu and stainless steel, the thermal cycle also degraded the properties of the stainless steel and resulted in the sensitization of the stainless steel, which reduced the usefulness of the dissimilar metal combinations in corrosive environments. The solid state bonding technique was highly recommended to join the copper and steel in these days.

Friction welding is one of the solid state bonding processes, which means that the joining is carried out below the melting point of the metals to be joined [3,4)]. In the process, heat is generated by conversion of mechanical energy into thermal energy at the interface of the workpieces without use the electrical energy or

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heat from other sources during the rotation workpieces under pressure. Some of the advantages of friction welding are high material save, low production time, and being possible of welding of different metals or alloys. The fundamental friction welding process is that the relative motion of two contacting surfaces is used to generate heat, while an accompanying compressive force plastically deforms until the welding is finally completed. The friction welded interfaces receive the both frictional heat and plastic deformation and also experience the rapid cooling rate after welding. Therefore, microstructures of the weld interfaces may be transformed from that of the unaffected base metal to very fine and equiaxed structure on Cu side and phase transformation on steel side depending on the welding condition. The grain size of softer materials interface, which receive severe effect of frictional process, can be near by ten times smaller than that of the base metal according to the welded materials[5~7]. However, microstructural variation of harder materials has been still unknown.

In this study, a copper and carbon steel joints was welded by the friction welding method. The grain size refinement and the phase transformation of welded materials were observed and the effect of the microstructural variations on hardness distribution was also evaluated.

2. Experimental procedure

The materials used in the present work were commercially available copper, special oxygen free copper, and medium carbon steel (0.43% carbon), which were machined into rods 20mm in diameter and 120mm in length. But the real contact area was 15mm in diameter.

The friction welding parameters are rotating speed N, friction time t_1, upset time t_2, friction pressure P_1 and upset pressure P_2, when welding with brake type machine. In the present work, t_2, P_1 and N were fixed at 5sec, 100 MPa and 2000 rev/min, respectively. The friction time was varied from 0.1 to 3.0 s and the upset pressure was changed from 100 to 400 MPa. Schematic illustration of the friction welding process and geometry of the welded specimens are shown in Fig.1.

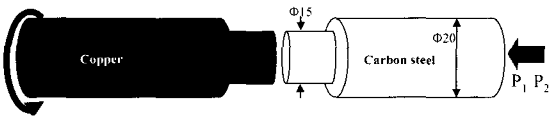

Fig. 1 Schematic illustration of friction welding process and geometry of welded specimens (unit : mm)

For metallurgical examination, the cross-section of welds was ground with SiC paper, and finally micropolishing using 0.3㎛ Al_2O_3 powder. Copper sides were etched with α reagent consist of dilute water, ammonia water and hydrogen peroxide, and the carbon steel sides were etched with nital reagent (3% nitric acid in methyl alcohol) for 15 s. The microstructures of friction welded interfaces were observed by OM (optical microscopy) and SEM (scanning electron microscopy).

After welding, the fractured surface of the carbon steel was investigated by the XRD (X-ray diffraction) to identify phases formed near the weld zone. The surface was cleaned to eliminate the surface contamination layer.

The Vickers hardness of each material in the vicinity of the weld interface was measured with a load of 1.96N, for 10s for various welding conditions to evaluate the effect of microstructural variation on the hardness.

3. Results and discussion

The optical microstructures of the base metals used in this study are shown in Fig. 2. The grains of copper were elongated along the extruded direction and had a large aspect ratio. The microstructure of carbon steel was composed of two phases, namely, ferrite (light) and pearlite (dark).

Fig. 3 show the microstructures of weld interfaces for various welding conditions. The joint line in all applied welding conditions exhibited no apparent discontinuities or lack of bonding. Fig. 3 (a), (b) represented the microstructure near weld zone for condition of P_2=100 MPa, t_1=0.1 s. Grain structure on

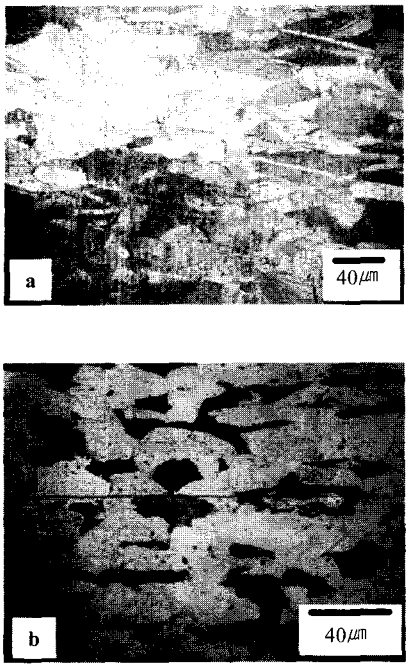

Fig. 2 Optical microstructures of base metals
(a) copper, (b) carbon steel

the copper side was fine and equiaxed in both the central and peripheral regions, with grain sizes of 9.1 and 13.1㎛, respectively. The elongated grains observed in the base metal, disappeared due to recrystallization. The grain structure on the carbon steel side was not changed at the central region, however, that of the peripheral region was slightly deformed and showed a 6.89㎛ ferrite grain size. Fig. 3 (c), (d) show the microstructures of weld interfaces for conditions P_2=137.5 MPa, t_1=2.5 s. The increasing friction time had an effect on the microstructure of the interface. The grain size on the copper side at the weld interface increased to 11.02 and 14.96㎛ at the center and periphery, respectively. The grain structure of carbon steel was deformed and the pearlite fraction increased at the central part. In the peripheral part of the carbon steel, mixed structures of ferrite and pearlite were formed near the interface and a structure, similar to that of the central region was observed at region which was 0.4mm apart from the interface.

Fig. 3 (e), (f) show the microstructures of the weld interface for conditions P_2=325 MPa, t_1=0.1s. The higher upset pressure made the grain structure of copper and carbon steel very fine and diminished the width of the deformed layer near the interface. Very fine and equiaxed copper grain was observed at both the central and peripheral regions. Although the grain size could not be exactly measured by optical microscopy, SEM micrograph revealed grain size of near 6.8㎛ at central region and 6.1㎛ at peripheral region.

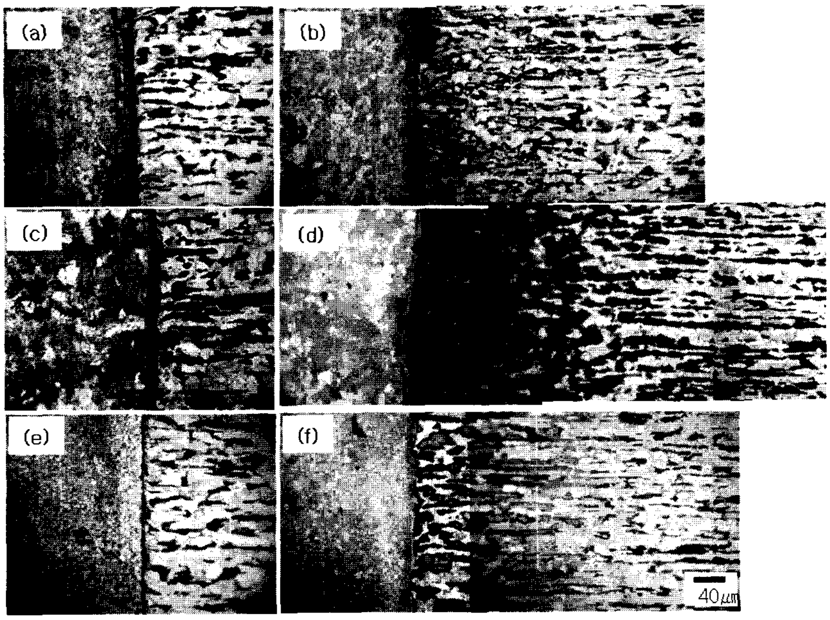

Fig. 3 Optical microstructures of central (left) and peripheral (right) weld interface with various welding conditions
(a, b) P_2=100 MPa, t_1=0.1 s, (c, d) P_2=137.5 MPa, t_1=2.5 s (e, f) P_2=325 MPa, t_1=0.1 s

Fig. 4 represented the optical microstructure at the interface of copper and carbon steel joints. The microstructures of the carbon steel near interface were composed of recrystallized fine ferrite (FF, or polygonal ferrite), fine grain boundary pearlite (GBP) and martensite (M, or bainate). During the friction welding process, the temperature near the weld interface would reach a value between A3 temperature and melting point of carbon steel [8]. Therefore, the microstructure of carbon steel was transformed to austenite. During the cooling from the austenite field, the carbon-rich austenite transforms to the high carbon martensite, bainate and pearlite, while the carbon-poor austenite produce polygonal ferrite[9]. The different phases, such as fine ferrite, grain boundary pearlite and martensite, were formed by the diffusion of the carbon to the grain boundary and a rapid cooling rate.

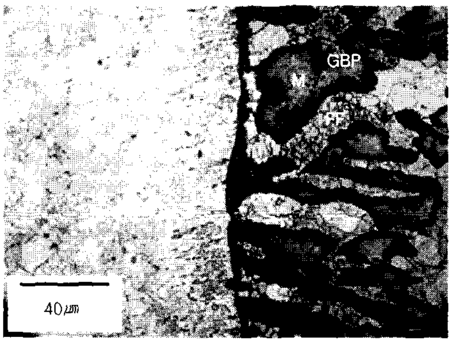

Fig. 4 High magnification optical microstructure of the peripheral interface of copper/carbon steel joints (GBF: grain boundary ferrite, FF: fine ferrite, M: martensite)

Fig. 5 shows microstructural variation of carbon steel from the central to peripheral interface obtained by SEM for conditions P_2=325 MPa, t_1=0.1s. The microstructure of the central region was not significantly changed in this welding condition. The microstructure of carbon steel at the interface had a higher fraction of pearlite than that of ferrite. Fine ferrite was observed through from mid-width to peripheral region of the interface. Specially, the microstructure of peripheral region was very different to that of base metal.

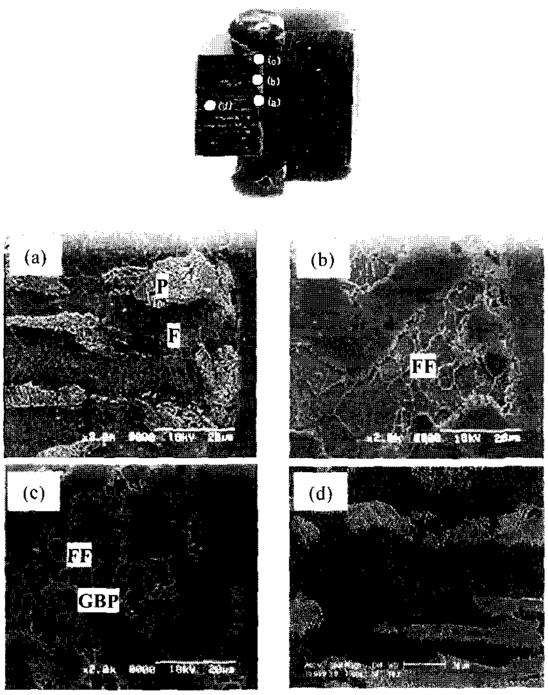

Fig. 5 SEM microstructures of carbon steel part near the weld interface with condition of P_2=325 MPa, t_1=0.1 s
(a) central part, (b) mid-width part,
(c) peripheral part, (d) carbon steel base metal

Fig. 6 shows the hardness distribution near the weld interface at both central and peripheral regions. In case of copper to stainless steel joint by an inertia type, the hardness of copper nearest interface showed no hardness change compared to that of copper base metal because the interface undergone dynamic recrystallization due to continuous combination of high temperature and severe plastic deformation. On the other hand, the hardness on the copper side showed a softened region near the weld interface in this study. The formation of a softening region at copper may be explained by the reason that an extruded copper used as the base metal in this study experienced dynamic recrystallization during welding process and followed by static grain growth during cooling in air after welding. Therefore, the microstructure of copper near the interface was annealed.

The width of the softened region was wider for longer friction times and lower upset pressures. In addition, the hardness of the peripheral region was less than that of the central region for conditions P_2=325 MPa, t_1=0.1 s. However, for a longer friction time, 2.5 s, the hardness at the periphery showed a higher value than that of the base metal.

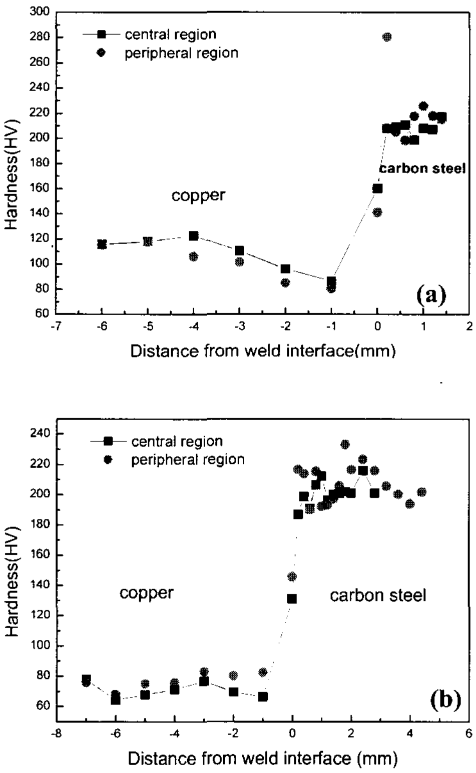

Fig. 6 Vickers hardness for copper and carbon steel in vicinity of the weld interface.
(a) P_2=325MPa, t_1=0.1 s
(b) P_2=137.5MPa, t_1=2.5 s

These results can be understood as follows: in the early stage of friction welding, there is a temperature gradient at the weld interface since the regional velocity at the periphery is higher than that at the center. Thus the center was slightly softened by the friction heat in the early stage of the welding process, but the copper at the periphery was plastically deformed and greatly softened owing to a dynamic recovery process [6]. As frictional time increased, 2.5 s, the temperature at the weld interface became homogeneous. The peripheral region received both thermal and mechanical treatments and the cooper was forged, but the central region of copper received a thermal treatment only.

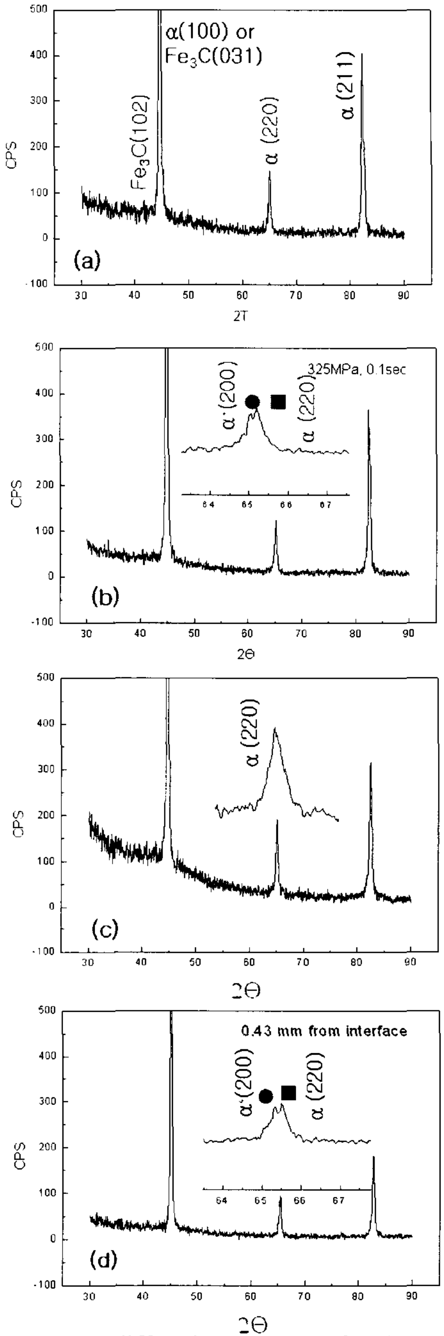

Fig. 7 X-ray diffraction patterns of carbon steel near the weld interface.
(a) Carbon steel base metal, (b) P_2=325 MPa, t_1=0.1 s,
(c) P_2=137.5 MPa, t_1=2.5 s,
(d) region 0.43mm from the interface for P_2=137.5 MPa, t_1=2.5 s

On the carbon steel side, the material was hardened at the weld interface for the conditions P_2=325 MPa, t_l=0.1 s and at the region which was 1mm away from the weld interface for the conditions P_2=137.5 MPa, t_l=2.5 s.

Fig.7 shows an X-ray diffraction analysis of the carbon steel side after welding. α' phase (martensite) was detected at the weld interface with condition of P_2=325MPa, t_l=0.1sec (b) and also detected at far away from weld interface with the condition of P_2=137.5MPa, t_l=2.5sec(d). The formation of martensite phase detected by microstructure observation and XRD analysis at these regions can explained the remarkable increasing hardness of carbon steel side. Fukumoto et al.[6)] reported that interface of austenite stainless steel friction welded to 1050Al was hardened because of a strain induced martensite.

4. Conclusion

Microstructural variation of friction welded copper and carbon steel were observed in this study. The major conclusions are summarized as follows:

1. Copper was greatly deformed and the grain size of weld interface was changed with different welding conditions. The grains were fine and equiaxed near the weld interface due to recrystallization.

2. The microstructure on the carbon steel side was slightly deformed and the size of this deformed layer was a few micrometers. Deformed structures were mainly due to the frictional heat and rapid cooling rate and composed of fine recrystallized ferrite, fine pearlite and martensite.

3. The softened region on the copper side showed nearly 70HV, which was lower than that of the base metal, due to recrystallization and annealing. The hardness of the carbon steel at the weld interface showed a higher value than that of the base metal due to the fine grain and martensite transformation.

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