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research note

Evaluation of microstructure and mechanical properties of friction stir welded copper / 316L stainless steel dissimilar metals

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Abstract
In the present research, friction stir welding (FSW) process was used for butt joining of pure copper plate to 316L stainless steel plate. Mechanical properties and microstructural characteristics of the joint were evaluated by microhardness and tensile tests as well as optical and scanning electron microscope (SEM). It was found that microstructure of the weld nugget (WN) has fine grains whereas the elongated grains are located in the thermo mechanically affected zone (TMAZ) into 316L stainless steel. Also, coarse grains are observed in the heat affected zone (HAZ) into pure copper. The microhardness values of the WN are much higher than the base metals. The HAZ zone shows minimum hardness values. The butt joint has 85% weld efficiency compared to the copper base meal.

Keywords: 316L stainless steel, pure copper, FSW process, dissimilar joint.

1. Introduction
Development of sound joints between dissimilar materials is a very important consideration for many emerging applications including chemical, aerospace, transportation, power generation and electronics industries [1-3]. Steel and nonferrous metals are widely used in various industries. On the other hand, dissimilar joints (i.e. steels to nonferrous metals) may be necessary in some applications. In dissimilar joint of 316L stainless steel to pure copper, the former material with austenite microstructure is considered as a structural section whereas pure copper is used as a heat transfer element from 316L stainless steel. However, the welding of two metals or alloys with different melting temperatures or thermal conductivities is complicated because one material melts prior to the other. Therefore, development of reliable joints between copper alloys and 316L stainless steel is important [4-8]. Friction Stir Welding (FSW), invented by The Welding Institute (TWI) of the UK in 1991 [9], is a new solid state welding process for joining metallic alloys and composites, and has enormous potentials in manufacturing applications [10]. High welding speed, low power input, low welding temperature, low distortion, autogenously welding and reduced need for human skills are the most important advantages of FSW in comparison to conventional fusion welding methods [11-13].

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During processing, a non-consumable tool attached to a desired designed pin is inserted to weld line of the plates to be joined. Tool shoulder should touch the plate surface. Under this case, the tool is rotated and traversed along bond line. Frictional heat is generated, material gets softened locally and plastic deformation of the work piece occurs. Like other solid state welding processes, in this method, the temperature is about 85% of the base metal which has a lower melting point [14]. Tool rotation and translation expedite material flow from front to back of the pin and welded joint is produced. The process is suitable for joining plates and sheets; however, it can be employed for pipes, hollow sections and positional welding [15].
Welding of aluminum and its alloys by FSW technique, has been investigated by many researchers. Most of the investigations have been performed on dissimilar joints of aluminum to other metals [16, 17]. In this study, an acceptable joint between pure copper and 316L stainless steel has been introduced.

2. Experimental procedure
Joining two dissimilar metals, pure copper to 316L stainless steel, by FSW technique was performed at 720 rpm tool rotating speed and 16 mm/min tool linear speed. Mechanical properties of base metals are given in table (1). The dimensions of samples for joining were 300×150×5 mm. Before the welding process, contact surfaces were ground and cleaned by acetone. Samples were fastened at a steel backing plate tightly for butt joining. A tool with two pieces, the pin made from tungsten carbide and the shoulder made from molybdenum, was used. The reason for this design of tool was the high working temperature ($0.8T_m$ cu, Kelvin). The height and diameter of cylindrical

pin were selected 4.9 and 5 mm, respectively. The shoulder diameter was chosen 22 mm. Argon gas was used for surface protection. Fig. 1 shows the schematic diagram of materials status and FSW technique. After joining process, cross sections of samples were prepared from weld line for optical microscopic studies. Metallographic tests were carried out by etch solution H_2O_2 (30ml) +HNO_3 (20ml) + HCL (10ml). Tensile test samples were made according to ASTM E8. These samples were prepared from the transverse section. Vickers micro hardness measurement with 300g force was carried out for examination of hardness distribution. Fractography analysis was performed by using scanning electron microscope (SEM).

Table 1. Mechanical properties of pure copper and 316L stainless steel before joint.

Material	Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)
Copper	250.4	261.7	8.65
SS316	354.2	632	53.19

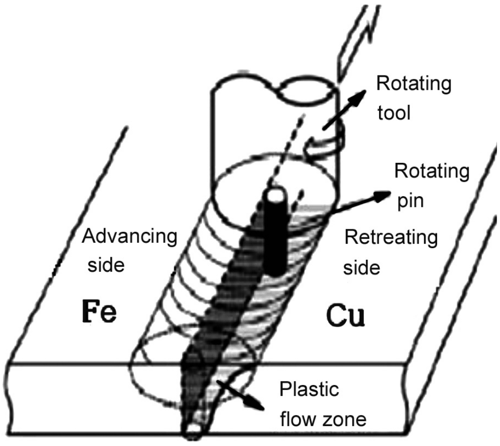


Fig.1. Schematic illustration of the FSW process as well as tool/materials.

3. Results and discussion

The macrostructure of the weld is shown in Fig. 2. This dissimilar joint includes seven regions that are : a- Base metal (BM) in 316L stainless steel, b- Heat affected zone (HAZ) in 316L stainless steel in advancing side of joint, c- Thermomechanical affected zone (TMAZ) in 316L stainless steel in advancing side of joint, d- weld nugget (WN), e- TMAZ in pure copper in retreating side of joint, f- HAZ in pure copper in retreating side of joint, g- BM in pure copper. The microstructures of these seven areas are presented in Fig. 3.

The microstructure of pure copper has coarse mechanical twines and reformed grains in rolling direction. However, reformed microstructure has disappeared from the near side of the weld zone. Also, annealed grains observed in the microstructure can be attributed to high temperature. The grains of HAZ don't tolerate dynamic crystallization, then coursing happens in this zone. The TMAZ in copper is an area that has been affected by temperature and severe plastic deformation. In this zone, recrystallization has taken placed and mechanical properties are varied. The WN includes combination of copper and dispersed/forged particles of stainless steel. The stainless steel particles have separated from the contact surface of stainless steel because of rotational movement of tool pin that is in the copper side. Thus, it can be claimed that the WN has a composite structure. The matrix of this composite is copper, and reinforcements are dispersed particles of stainless steel. Dispersed particles of stainless steel have a non-homogenized distribution in WN. The WN has very fine eqaxial grains. These fine grains have been recrystallized by severe plastic deformation and high temperature during FSW process.

The TMAZ in 316L stainless steel is specified with its elongated grains that have rotated 90˚. The mechanical properties of HAZ in 316L stainless steel has been changed due to high temperature as well as grains growth in copper retreating side. The 316L stainless steel base metal has incoherent fine grains as well as mechanical twines. Microstructure of HAZ in 316L stainless steel is very similar to the base metal. Microhardness profiles of three transverse sections of weld are given in Fig. 4. These profiles are related to up, center and down sections of weld zone.

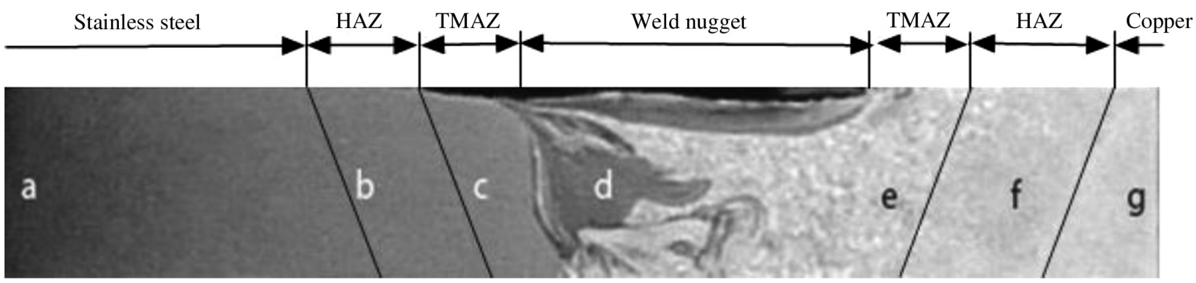


Fig.2. Macroscopic overview of the cross-section of the friction stir welded pure copper to 316L stainless.

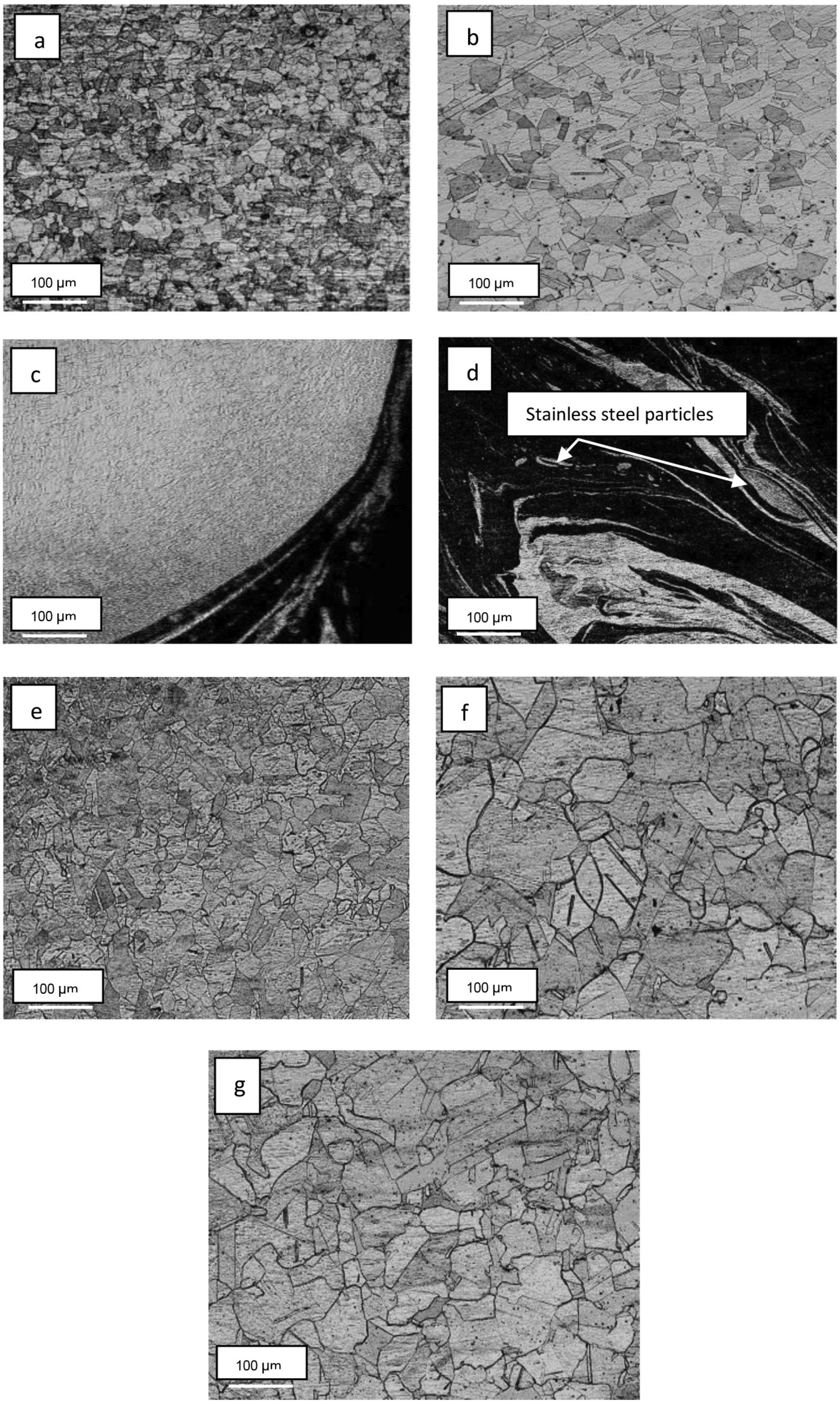


Fig. 3. Optical microstructures of the "(a)-(g)" regions shown in Fig.2: (a) grain structure of 316L stainless steel, (b) HAZ at advancing side, (c) TMAZ at advancing side, (d) stainless steel particles surrounded by fine equiaxed grains of copper in the weld nugget, (e) TMAZ at retreating side, (f) HAZ at retreating side, (g) grain structure of pure copper.

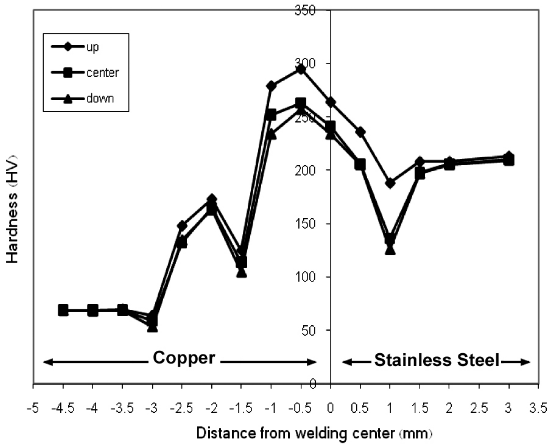
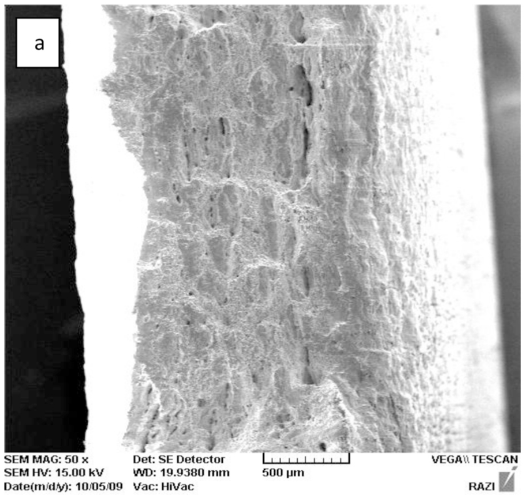


Fig. 4.The microhardness profiles along the up, center and down lines of the transverse cross-section.

As seen, two materials; pure copper and 316L stainless steel, with different properties show different hardness profiles in advancing side (stainless steel side) and retreating side (copper side). The higher value of hardness is in the TMAZ advancing side. This value decreases sharply adjacent to the WN. The higher values of hardness in WN zone may be related to indenter contact with dispersed stainless steel particles.

The hardness value sharply decreases in the HAZ at the retreating side (copper side). The decrease in hardness in this zone is attributed to lack of heat generation for plastic deformation phenomenon during joining process. The hardness value in upper side of weld is more than that in the center and down side. Work hardening phenomenon in 316L stainless steel is the reason why upper side has higher hardness than the other side. HAZ in copper has minimum hardness because of presence of coarse grains.

All of the samples have fractured from copper side during tensile test. Fracture has occurred in HAZ, the zone that had the minimum hardness. Fracture surfaces of samples were evaluated by SEM. The fractography results verify ductile fracture in copper. It can be confirmed by presence of dimples with different size distribution. Fig. 5a shows the fracture section of the sample after tensile test in a low magnification. As observed, the surface has no defects and is also homogeneous. Fig. 5b shows the fracture surface of the sample with a higher magnification. It is obvious that fracture surface has a homogenous distribution of equxial dimples with some cavitations. The ultimate strength of this dissimilar joint was 225.6 MPa. This indicates that weld strength is 85% of copper strength, the material with lower strength.



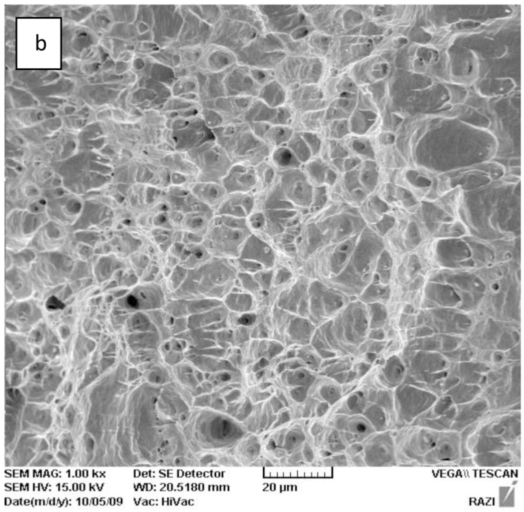


Fig. 5. Fracture surface morphology of joint in (a) low magnification, (b) high magnification.

4. Conclusions

Butt joint of pure copper to 316L stainless steel was done successfully by FSW process. Mechanical properties and microstructural details in weld zone were discussed. The major results are given as follows:

- The microstructure of the joint region of pure copper to 316L stainless steel includes seven zones that are: base metal (BM) in 316L stainless steel, heat affected zone (HAZ) in 316L stainless steel in advancing side of joint, thermomechanical affected zone (TMAZ) in 316L stainless steel in advancing side of joint, weld nugget (WN), TMAZ in pure copper in retreating side of joint, HAZ in pure copper in retreating side of joint, BM in pure copper.
- The hardness of joint in weld zone from 316L stainless steel side to copper side sharply reduces. Due to the presence of fine particles of 316L stainless steel in the center of weld zone, different hardnesses are

obtained. The presence of very fine grains in TMAZ is the reason for maximum hardness value in this zone. HAZ in copper has the minimum hardness because of high temperature. This zone has grains with greatest size.

● All samples are fractured from HAZ of copper and the fracture nature is ductile. Hardness variations show a mutual connection between fracture zone and hardness value. Strength of this dissimilar joint is 85% of the material with lower strength.

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