

Characterization of Properties in Friction Welded Stainless Steel and Copper Materials

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The aim of this study is to investigate the metallurgical and mechanical properties of friction welded stainless steel-copper joints. One of the manufacturing methods used to produce parts made from different materials is the friction welding method. Application of classical welding techniques to such materials is difficult because of they have different thermal properties. Stainless steel-copper joints are inevitable for certain applications due to unique performances such as higher electric conductivity, heat conductivity, corrosion resistance, and mechanical properties. In the present study, austenitic stainless steel and copper parts were joined by friction welding. Tensile, fatigue, and notch-impact tests were applied to friction welded specimens, and the results were compared with those for the original materials. Microstructure, energy dispersive x-ray, and x-ray diffraction (XRD) analysis and hardness variations were conducted on the joints. Results showed that various intermetallic phases such as FeCu_4 and Cu_2NiZn occurred at the interface. It was found from the microstructure and XRD analysis that intermetallic phases formed in the interface which further caused a decrease in the strength of the joints. However, hardness of the copper increased slightly, whereas the hardness of steel decreases slightly on the horizontal distance from the center.

Keywords friction welding, mechanical characterization, metallography

1. Introduction

Welding technology is widely used in manufacturing. Development of new welding methods has gained importance along with developing technology (Ref 1-4). Welding of different metals and their alloys is a common application in engineering solutions. Conventional welding methods are nearly impossible in such cases due to incompatible physical characteristics and chemical composition of different metals and alloys. As a result, friction welding has been developed (Ref 5-7). In friction welding, heat is generated at the interface of the work pieces, since mechanical energy is dissipated as heat during rotation under pressure. Friction welding is classified as a solid state welding process where metallic bonding is produced at temperatures lower than the melting point of the base metals. Friction welding is generally used to join the parts which have axial symmetry and circular cross-section. But it can easily be used to join parts without circular sections with the aid of automation devices and computerized control facilities (Ref 8). It is an energy saver since heat is not applied. Friction time and pressure, upset time and pressure, and the speed of rotation are the principal variables in the friction welding (Ref 9-13). There are two types of friction

welding techniques: continuous drive friction welding and inertia friction welding. In the continuous drive friction method, one of the components is held stationary while the other is rotated at a constant speed (s). The two components are brought together under axial pressure (P_f) for a certain period of time (t_f). Then the clutch is separated from the drive, and the rotary component is brought to a stop while the axial pressure on the stationary part is increased to a higher upset pressure (P_u) for a predetermined period of time (t_u).

Kinetic energy of a flywheel is used in inertia friction welding. The flywheel is brought to a predetermined rotational speed, and then the drive motor is removed from the circuit. The parts to be joined are pressed together to be friction welded. The flywheel gradually slows down and stops. There is no upset time (t_u) in inertia welding, it takes shorter time.

Different metals have different hardness and different melting points. Interface activity during friction welding forms brittle intermetallic phases or eutectics with low melting. Clean welding surfaces are also of prime importance (Ref 14, 15). Heat of welding can be decreased to a safe zone by application of high friction pressure and by using clean surfaces. It is known that increase in rotational speed and thus friction on the surfaces results in deformation (Ref 16). Dirt and grease on welding surfaces decrease the quality of bonding (Ref 14, 15). Basic problem in aluminum-steel welds is undesired formation of intermetallic phases (FeAl). An incubation period, longer than the welding time has been suggested to overcome this problem. The incubation period concept is still under investigation, but it seems that control on the thickness of the intermetallic layer should be the key concept. Other defects such as lack of bonding between aluminum and copper, cracked copper surfaces, formation of a gray aluminum layer also occur during aluminum-copper welding (Ref 14, 15). In welded stainless-Cu joints, the joint strength increases with increasing upset pressure up to a

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critical value. Increasing friction time causes lower strength of the St-Cu joint compared to the Cu base metal (Ref 16). In friction welding heating is localized in a sufficiently narrow material layer immediately adjacent to the joint line, thus it enables welding of joints with appropriate strength properties of joints (Ref 17). The weldability of dissimilar metals is determined by their atomic diameter, crystal structure, and compositional solubility in the liquid and solid states. Diffusion in the weld pool often results in the formation of intermetallic phases, the majority of which are hard and brittle and are thus detrimental to the mechanical strength and ductility of the joint (Ref 18). Deformation of the material during friction welding is generally due to diffusion involving migration of lattice defects, which can be influenced by an external electric field (Ref 19). The absence of defects such as porosity and microfissures in steel-copper joints leads (from a microstructural point of view) to sound weld. On the other hand, it can be reasonably supposed that porosity and microfissures in the joints may reduce the ductility of the weld. Furthermore, copper penetrations and microfissures could reduce the fatigue strength (Ref 20). Sintered powder metallurgical preforms have low mass, high stiffness, and therefore their natural frequency is high. Having inherent porosity, they can also be good dampeners besides possessing the latent lubricant efficacy (Ref 21). Formation of hard interlayers such as intermetallic phases when joining of dissimilar materials may cause the joint to become brittle (Ref 22). Similar and dissimilar joints involving austenitic steels are susceptible to unexpected phase propagation. As a result of this, a series of negative metallurgical changes such as delta ferrite phase, grain boundary corrosion, sigma phase, and intermetallic phases occurs at the weld interface. The micro-segregation which occurs in weld fusion zones of dissimilar metals leads to a situation where interdendritic regions are enriched in Fe, Cr, and C. However, such problems can be minimized by judicious selection of the welding process and parameters (Ref 22, 23). However, the major problem in welding copper to steel is hot cracking in the heat-affected zone (HAZ) of steel due to copper melting and penetrating into the grain boundaries of solid steel. Friction welding is a solid state welding method used in industry to avoid these problems due to the rapid and intensive energy delivery.

Although stainless steel-copper joints by friction welding have been performed before, none of these studies involve detailed investigations on the metallurgical and mechanical properties of these joints. In the present study, tensile, fatigue, and notch-impact tests were performed on welded test parts and results obtained results were compared with those of the

original materials. Microstructure, EDX and XRD analysis, and hardness variations were also carried out on the test parts.

2. The Experimental Procedure

2.1 Material

In the experiments, AISI 304 austenitic stainless steel and copper were used. Austenitic stainless steels are very compatible with regard to forming capabilities, mechanical specifications and corrosion resistance. Austenitic stainless steels have perfect corrosion resistance and weldability. They are furnished with desired mechanical qualities at high temperatures, they are easily workable when ductile and they are not magnetic. On the other hand, copper is an excellent conductor of electricity and heat. It is strong, ductile and easily joined by soldering or brazing. It is hygienic, easy to alloy and resists corrosion. Composition of materials is given in Tables 1 and 2 (Ref 24).

2.2 Geometry of Parts

Specimens were machined from the materials described above according to geometry given in Fig. 1.

2.3 The Experiment Set-up

Experimental set-up was designed and constructed to apply the continuous drive friction welding method. A 4 kW motor drive with a rotational speed of 1410 rpm was used. The motor drive was selected so as to supply the torque needed to supply the friction and upset pressures necessary for friction welding of steel bars 10 mm in diameter. Stages of the welding sequence were controlled using the solenoid valve driven by an external timer. Parts to be joined were left in acetone for 10 min before welding. Optimum parameters found in a

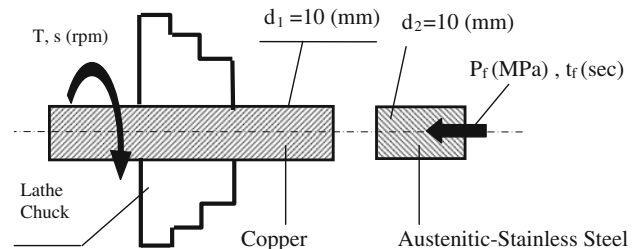


Fig. 1 Parts used in the experiments

Table 1 Chemical compositions of austenitic-stainless steel used in the experiment (Ref 24)

Material	% C	% P	% S	% Mn	% Si	% Cr	% Ni	Tensile strength, MPa
AISI 304 (X5CrNi1810)	<0.07	<0.045	<0.030	<2.0	<1.0	17-19	8.5-10.5	825

Table 2 Chemical compositions obtained using chemical analysis of copper used in the experiment

Copper	% Sn	% Pb	% Zn	% P	% Mn	% Fe	% Ni	% Si	% Mg	% Al	% Bi	% S	% Sb	% Cu	Tensile Strength, MPa
	0.00222	<0.00200	<0.00100	0.00137	<0.00050	0.0381	<0.00100	0.00745	0.00376	0.00500	<0.00050	0.00251	<0.00200	99.93	300

previous different study (Ref 25) were used in the experiments (friction time = 8.5 s, friction pressure = 75 MPa, upset time = 20 s, and upset pressure = 160 MPa). Later, tensile, fatigue, and notch-impact tests were applied to the joined parts, and the microstructure analysis and hardness variations of the joints were examined. These tests and analysis are given below in detail.

3. The Experimental Results

3.1 Tensile Tests

Tensile tests (ASTM E8M) were conducted using an Instron 8501 machine (Fig. 2). The specimen was clamped to the grips at both ends. The upper grip was fixed, but the vertical position could be adjusted to accommodate specimens of different sizes. The lower grip was driven by a hydraulic actuator. Vertical movement of the lower grip generated desired loading on the specimen.

Effects of friction time and friction pressure on the strength of the parts joined were examined by the welding parts having the same diameter. Results reported are the arithmetic mean for three specimens for a set of given friction welding conditions. In order to determine friction time and friction pressure, a two-step welding experiment was conducted in which upset time (20 s) and pressure (160 MPa) were maintained constant. In the first step, friction pressure (75 MPa) was kept constant while friction time was changed. In the second step, the friction time was held constant (8.5 s) while the friction pressure was changed.



Fig. 2 Instron test machine

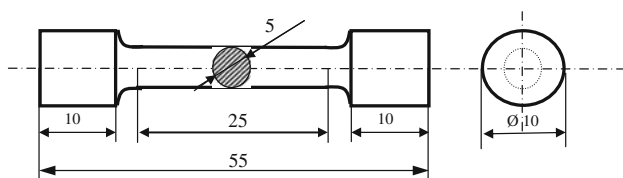


Fig. 3 The geometry of the fatigue test part exposed axially tension, dimensions in mm

3.2 Fatigue Tests

The fatigue tests (ASTM E21) were performed in an Instron 8501 machine (Fig. 2). Load was applied at a frequency was 20 Hz. Some of the machined and welded parts were exposed to the fatigue tests under axially tension. The geometry of parts tested is given in Fig. 3. The fatigue test machine stopped automatically as soon as specimen failure occurred. Copper and stainless steel parts and the joints were analyzed by applying various constant tensile loads and stress amplitudes. In all experiments, fatigue tests were conducted so as to superimpose fluctuating tensile loads on a constant tensile load.

3.3 Notch-Impact Tests

Welded and machined base parts were exposed to the Notch-impact tests (ASTM E23) were performed on machined base parts and welded parts according to Charpy method by machining a notch at the interface. The geometry of parts tested is given in Fig. 4. Fracture energy values on machined stainless steel and copper parts, and also stainless steel-copper welds were determined. Later, the notch-impact tests of welded parts were investigated.

3.4 Microstructure of Welded Parts

Differences in thermal and physical properties of the materials generally result in asymmetric deformation in welding of dissimilar metals. Axial shortening on the copper side of joints is more than the axial shortening on the stainless steel side (Fig. 5). Since the melting temperature of copper is lower than the melting temperature of steel, welding flashes occur the copper side of the interface. However, while copper undergoes extensive melting due to high generated and concentrated frictional heat; stainless steel does not undergo extensive deformation (Ref 9, 21). Moreover, the microstructure of interface in joint is given in Fig. 11.

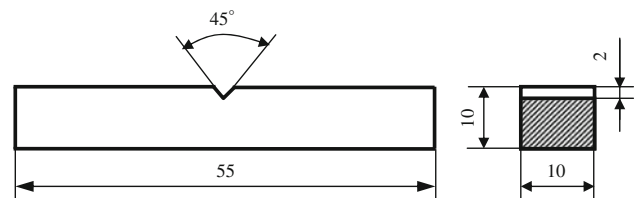


Fig. 4 The Charpy notch-impact part, dimensions in mm

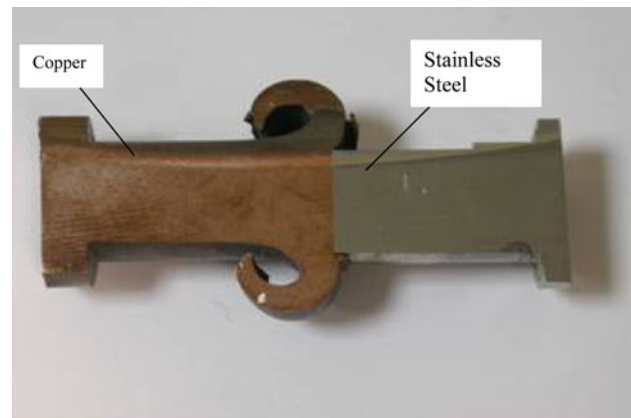


Fig. 5 Macrophoto of the joints

3.5 EDX and XRD Analysis at Interface of Joints

In order to examine the intermetallic phases formed at the interface of the joints, scanning electron microscopy (SEM) and energy dispersive x-ray analysis (EDX) were applied to the joints. Examinations were carried out with an SEM-JEOL JSM 5410 LV microscope and in the field of 20 kV. An EDS analysis with the SEM microscope was conducted on the zone which is defined on the SEM pictures.

The SEM microstructure and spectrum analysis results at the interface of joints of both the intermetallic phase and the copper and steel sides are given in Fig. 12, 13, and 14, respectively. Moreover, EDS analysis results belonging to the defined zones are given in section 4. The EDS results confirm that stainless-Cu joints contain some intermetallic compounds. However, an XRD analysis of phase constituents in the weld zone is quite important. In this experiment, the weld zone of the joint was analyzed. The XRD results of weld zone in the joints are given

in Fig. 15. Therefore, formation of brittle intermetallic compounds degrades the strength of the joints.

3.6 Hardness Variations of Welded Parts

The strength of the joints is related with the hardness variation within HAZ. Hardness variations were obtained by using 300 g load Vickers microhardness testing.

The hardness variations on the horizontal and vertical distance to the center in the welding zone of the joints are shown in Fig. 17 and 18, respectively.

4. Discussion

The strengths of the welded zones were determined through tensile tests and the results were compared with the strength of

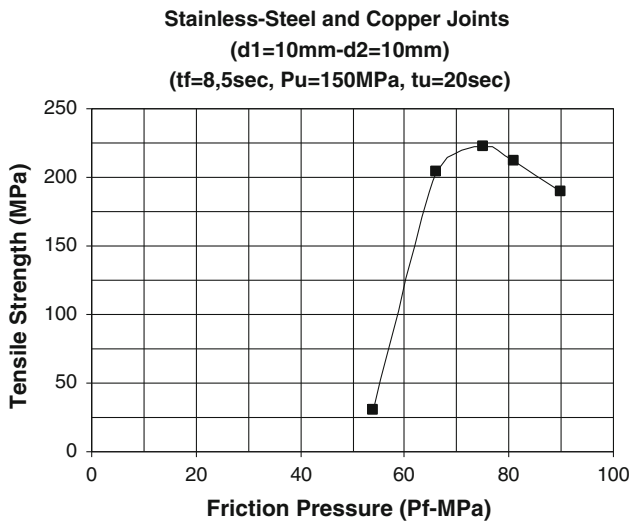


Fig. 6 Relationship between tensile strength vs. friction pressure

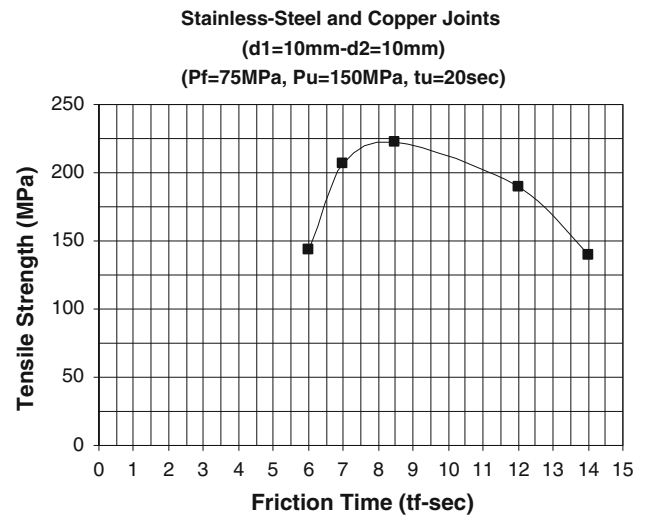


Fig. 7 Relationship between tensile strength vs. friction time

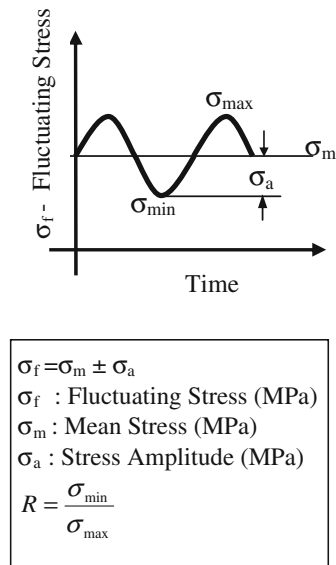
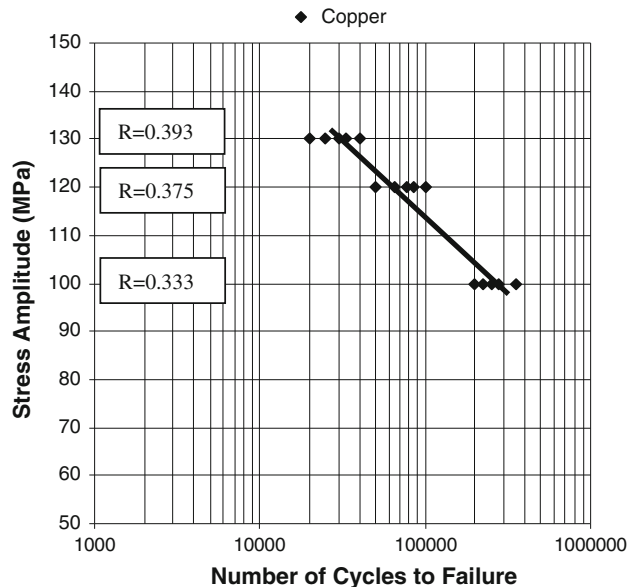


Fig. 8 The copper fatigue test results

The Fatigue Results of Base Copper Material



the fully machined parts. Tensile strength of the joined parts was calculated by dividing the tensile force to an area of 10 mm in diameter. The variations of tensile strength in accordance with the change in friction time and friction pressure are shown in Fig. 6 and 7. Tensile strength of the joints increased with increase in friction time and pressure up to a certain critical value beyond which the parts were deformed (Fig. 6, 7). The highest strength obtained for the joints was equal to 75% of the strength of copper, which is known to have the lowest strength. Superiority of the welds made by dissimilar materials strongly depends on the temperature attained by each substrate during the welding processes. Differences in mechanical, thermophysical properties, and behavior of each substrate at the interface during welding influence the quality of the joint (Ref 21).

In fatigue tests, constant tensile load was found to specimens and the stainless steel-copper joints, respectively. Fluctuating tensile stress amplitudes cause 200, 300, and 50 MPa tensile stresses on copper and stainless steel were varied between 100 and 130 MPa for the copper specimens (Fig. 8), between 150 and 250 MPa for stainless steel specimens (Fig. 9), and

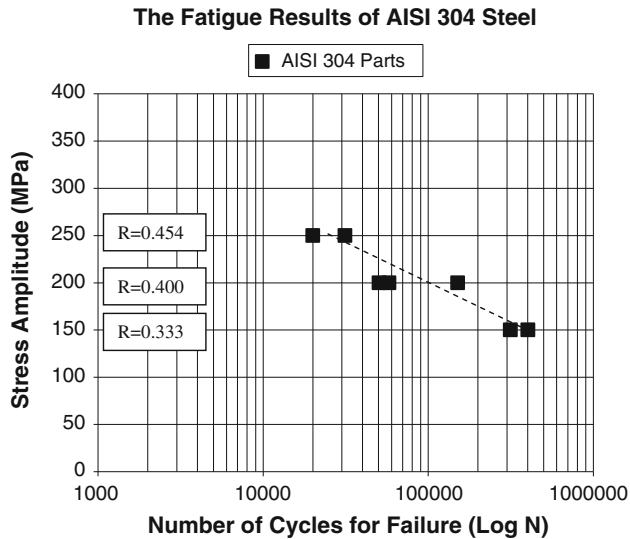


Fig. 9 The stainless steel fatigue test results

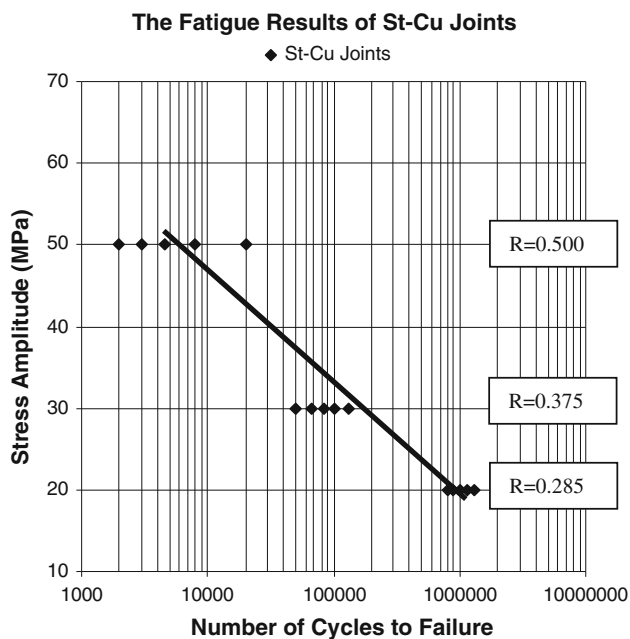


Fig. 10 Fatigue test results of friction welded stainless steel and copper joints

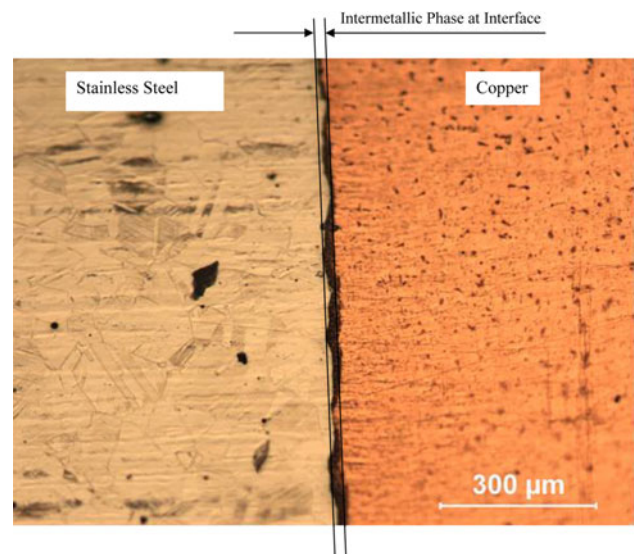
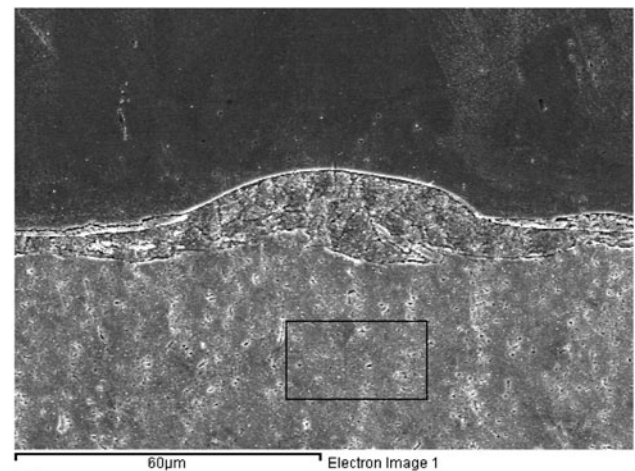
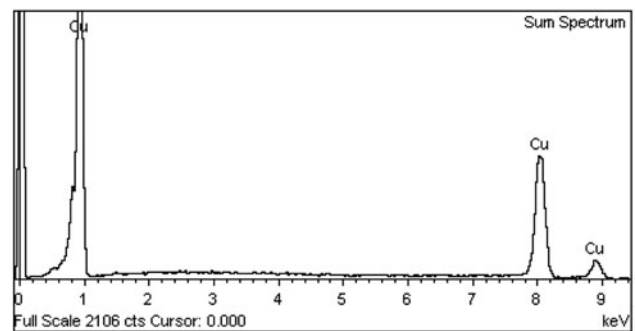


Fig. 11 Image of the interface in joints

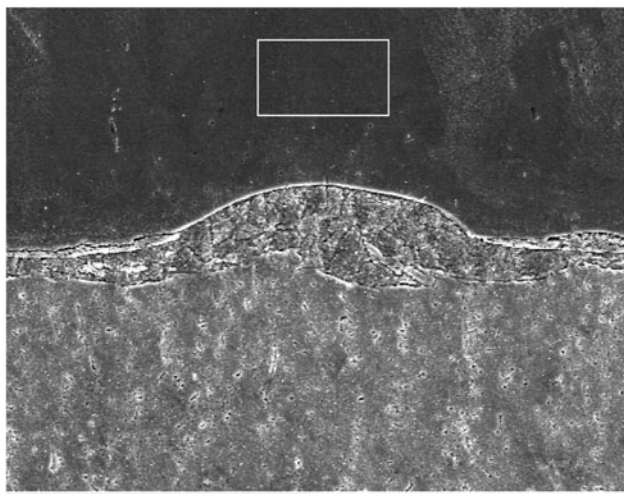


(a) SEM Microstructure in Joints and the Defined Zone on the Copper Side

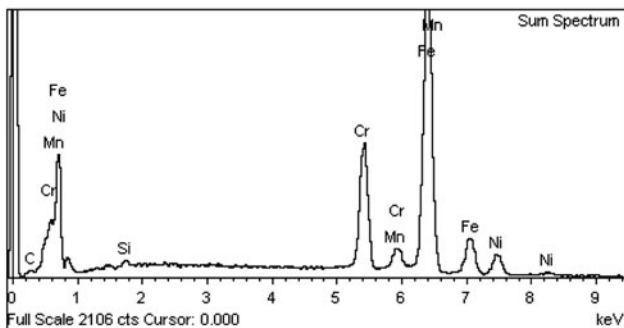


(b) Spectrum Analysis of Copper in Joints

Fig. 12 EDX analysis on copper side of joints



(a) SEM Microstructure in Joints and the Defined Zone on the Steel Side



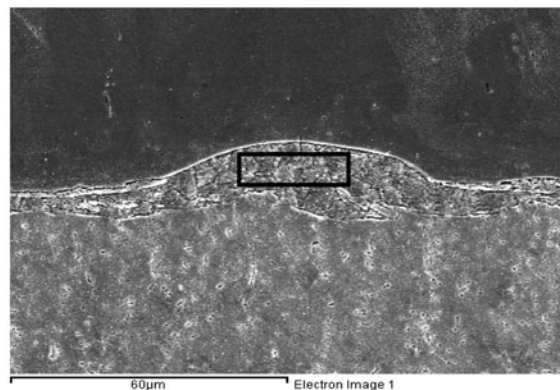
(b) Spectrum Analysis of Steel in Joints

Fig. 13 EDX analysis on steel side of joints

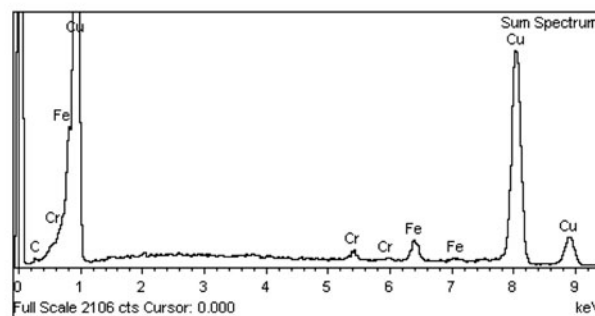
between 20 and 50 MPa (Fig. 10) for the stainless steel-copper joints. In all cases numbers of cycles to fracture were recorded. As it can be shown from the fatigue graphics, stainless steel (Fig. 9) had higher fluctuating stress than copper (Fig. 8). Fluctuating stress of stainless steel-copper joints is quite low (Fig. 10) because of the intermetallic phases formed at the interface.

Energy absorbed in the Charpy-V notch-impact test for each specimen was divided with its net area according to DIN 50115. While the notch-impact toughness value of stainless steel is 181 J/cm², these of copper is 200 J/cm². Then, the notch-impact toughness value of welded parts was found to be 9.6 J/cm². Notch-impact toughness of stainless steel-copper welds was lower than the base metal parts as in the case of fatigue tests.

Stainless steel is in the austenitic grain structure, which is the natural structure of this type of steel at room temperature. On the other hand, copper is formed of eutectic particles (dark points) indicating that it is a mixture of pure copper and cuprous oxide, dispersed into ground copper. HAZ was small, thus the effect of melting was minimal at the interface (Fig. 11). Copper has higher thermal conductivity than steel, thus the HAZ on the copper side was wider than that of the steel side. There was no change in the grain size of the steel side. Presence of small particles on the copper side revealed that there is hardening on the copper side. There are equiaxed grains and Cu₂O particles on the copper side. The interface elements of



(a) SEM Microstructure in the Joint and the Defined Interface (Intermetallic Phase Zone)



(b) Spectrum Analysis of the Intermetallic Phase in the Joints

Fig. 14 EDX analysis in intermetallic phase zone of joints

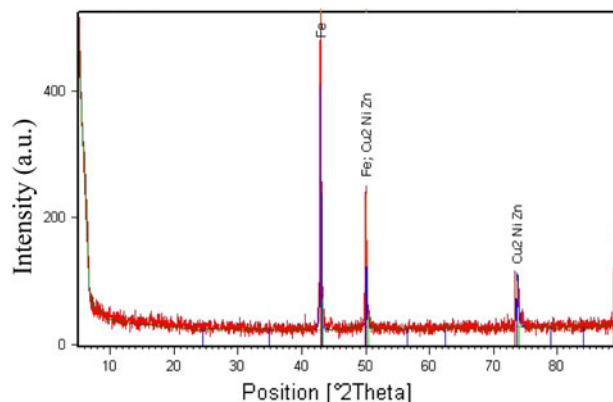


Fig. 15 XRD results in welding zone of joints

both materials diffused along the interface and some intermetallic phases were formed at the interface (Ref 22).

EDS analysis performed on the copper and steel side and the interface of the joint. However, the elemental compositions (in wt.%) on copper side are Cu (100). Then, iron did not penetrate the copper zone (Fig. 12, 13, 14). The elemental compositions (in wt.%) on steel side are C (1.82), Si (0.50), Cr (18.86), Mn (1.48), Fe (69.60), and Ni (7.74). The elemental compositions (in wt.%) at the interface are C (2.55), Cr (1.16), Fe (3.71), and Cu (92.58). Thus, the presence of intermetallic phases at the interface is obvious. Copper oxide films were broken into pieces due to excessive deformation at the interface caused by rotation (Fig. 12, 13, 14). According to Fig. 15, the x-ray diffraction results in friction welded stainless steel-copper indicated that there are FeCu₄ and Cu₂NiZn intermetallics

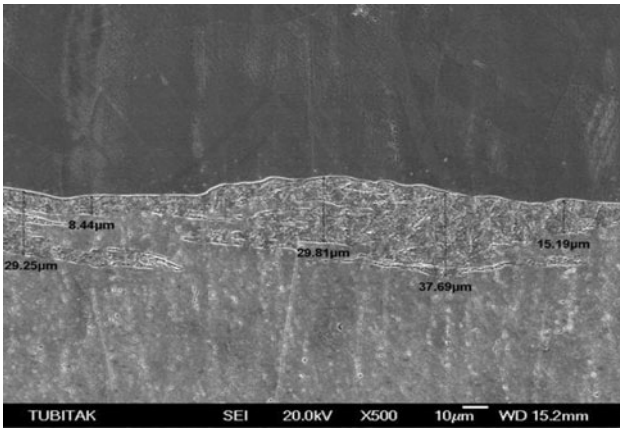


Fig. 16 Thicknesses of the intermetallic phase compounds at the interface

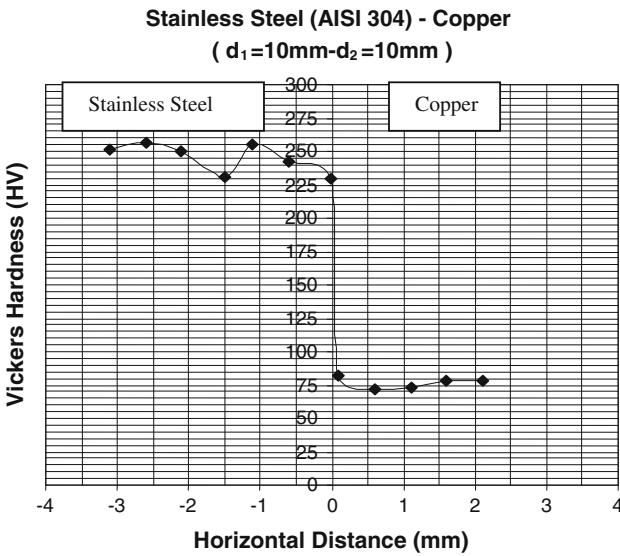


Fig. 17 Hardness distribution on the horizontal distance of joints

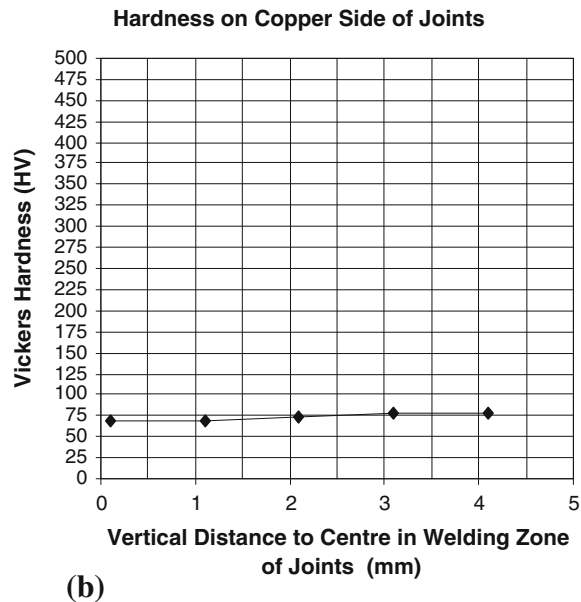
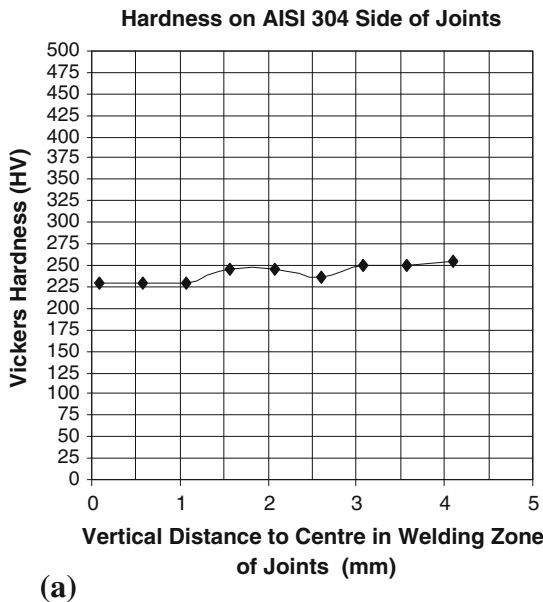


Fig. 18 Hardness distribution on the vertical distance of joints

formed in welding zone (Fig. 15). Thickness of the layer containing intermetallic phase compounds varied between 8.44 and 37.69 μm (Fig. 16).

Figure 17 showed that hardness on the copper side of the joint increased slightly. Hardness increased in the direction from the center towards the ends (Fig. 18). Hardness variations at the interface are probably due to the difference in thermal conductivities of the materials. Intermetallic phases at the interface are also expected to play a role in hardness variations.

5. Conclusions

In this study, steel and copper materials were friction joined successfully and tensile tests, fatigue tests and notch-impact tests were applied to the joined parts. Moreover, at the interface of these parts, microstructure, EDS analysis, and hardness variations were examined. As a result, the obtained results can be summarized as follows:

- Optimum friction time and pressure were found to be 8.5 s and 75 MPa, respectively. Tensile strength of the joints increased with the friction time and friction pressure up to a certain point. The optimum is dictated by a competition between inadequate heat dissipation that can stabilize the joints, and excessive formation of intermetallic phases that decrease strength of the joints.
- The fluctuating stresses of the stainless steels, which have high strength, are higher than the fluctuating stresses of the copper. In addition, the fluctuating stress of the stainless steel and copper joints is quite low due to intermetallic phases which occur at the interface.
- Notch-impact toughness of stainless steel-copper welds was lower than the base metal parts as in the case of fatigue tests.
- Iron did not penetrate the copper zone. However, various intermetallic phases such as FeCu_4 and Cu_2NiZn occurred at the interface. Copper oxide films were broken into

pieces due to excessive deformation at the interface caused by rotation, and thus dirt repellent surfaces were formed.

- Hardness of the copper increased slightly, whereas the hardness of steel decreases slightly on the horizontal distance from the center. This is because steel reached its annealing temperature during welding. This, in turn, caused a loss in ductility leading to a decrease in the strength and hardness of steel within the joint. Conversely, hardness on the copper side increased slightly due to rapid cooling of copper that has higher thermal conductivity.
- Friction welding permits a controlled heat distribution and a minimized interaction of the joining materials due to the direct conversion of mechanical energy into thermal energy at the joint interface. However, proper optimum parameters should be selected during welding. Thus, the formation of brittle intermetallic phases could be avoided.
- However, the results of the present study can be used for further investigations into joining of electrical and micro-system's components with conventional and modern welding methods of stainless steel-copper joints.

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