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Friction welding of dissimilar pure metals

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Abstract

Joining of dissimilar metals is one of the most essential needs of industries. Dissimilar metal combinations Fe–Ti, Cu–Ti, Fe–Cu, Fe–Ni and Cu–Ni have been investigated in the present work as Fe, Cu, Ti and Ni are the most extensively used materials in engineering application in the alloyed form. Metals are taken in commercially pure form so as to understand the basic mechanism of joining, which can be then employed to complex alloy systems. Influence of interaction time in continuous drive friction welding on microstructure and tensile properties is studied. Increased interaction time led to decrease in strength in eutectoid forming and insoluble systems and improved strength in soluble systems. Mechanical transport of the material is predominant at the peripheral region of the weld.

Keywords: Friction welding; Dissimilar metals; Dynamic recrystallization

1. Introduction

Joints of dissimilar metal combinations are employed in different applications requiring certain special combination of properties as well as to save cost incurred towards costly and scarce materials. Conventional fusion welding of many such dissimilar metal combination is not feasible owing to the formation of brittle and low melting intermetallics due to metallurgical incompatibility, wide difference in melting point, thermal mismatch, etc. Solid-state welding processes that limit extent of intermixing are generally employed in such situations. Friction welding is one such solid-state welding process widely employed in such situations. This paper deals with an investigation on the effect of interaction time in friction welding on the microstructure and tensile properties of dissimilar metal combinations, consisting of eutectoid forming systems (Fe–Ti, Ti–Cu), insoluble system (Fe–Cu) and soluble systems (Fe–Ni and Cu–Ni).

Fe–Ni alloy combinations are in use in aero engine applications, Ti alloy–steel combinations are employed in cryogenic plumbing systems [1] and aero and chemical industries [2] while, copper and iron base alloys are employed for cooling tubes to avoid undesirable heating of whole component [3]. Hence, the study assumes technological importance.

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2. Experimental methods

Continuous drive friction welding studies were carried out on a continuous drive friction welding machine of 150 kN capacity at two levels of burn off (3 and 5 mm) at constant friction force (3 kN), forge force (5 kN) and speed of rotation (1000 rpm). The weld joints were subjected to metallographic characterization employing optical microscopy, scanning electron microscopy (SEM), electron probe microanalysis (EPMA) and X-ray diffraction (XRD) technique. The joint strength was determined using Instron 5500 universal testing machine. Specimens of 25 mm gauge length (G.L.) and 4 mm diameter were employed wherever elongation values are reported. In case of brittle joints standard specimens could not be made and the joints were tested for strength by removing the flash.

3. Results and discussion

3.1. Macro and microstructure

Fig. 1 shows the macro structure of the weld. In general it is observed that material having lower strength in the dissimilar metal combination experienced more deformation resulting in higher flash formation. In case of Fe–Ti joint though Ti has higher strength as compared to Fe, Ti experienced major deformation because it loses its strength at higher temperature due to allotropic transformation to low strength beta. In friction welding heat is generated due to the rubbing of the faying surfaces and this heat generation is directly proportional to the relative velocity, which is minimum at the center and maximum at the periphery. However, at the periphery the joints are subjected

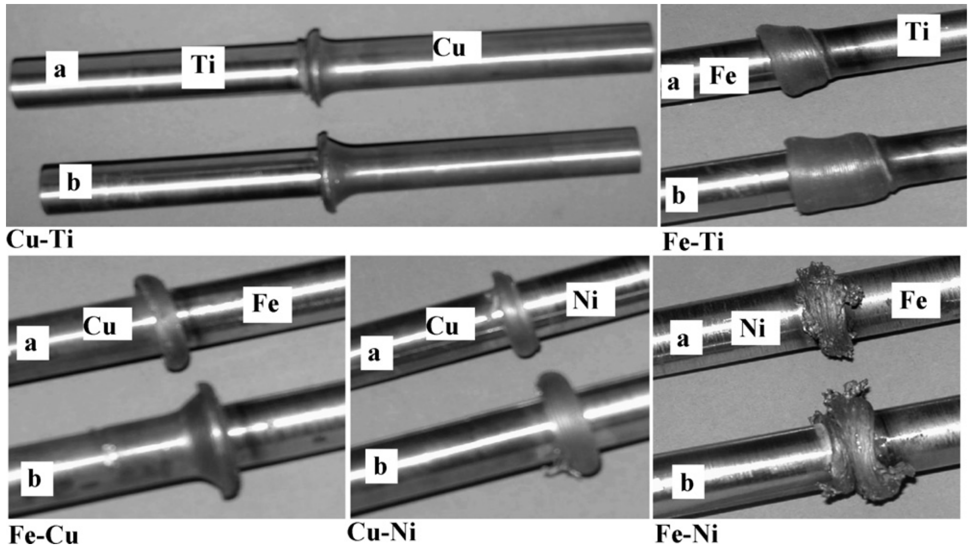

Fig. 1. Dissimilar metal joints: (a) 3 mm burn off (b) 5 mm burn off.

to convective heat loss to the surrounding and hence the maximum heat generation point can be seen somewhere close to the periphery beneath the surface [4]. This is evident from the flash formation observed in Fig. 2. Fig. 3 shows the influence of burn off on the weld interface at the central region for all the joints. It is observed that with an increase in burn off the width of the interaction layer increases. The weld interface is nearly straight except at the peripheral region where considerable mechanical intermixing is observed (Fig. 4). In friction welding the relative velocity and hence, the temperature would be minimum at center and maximum at the periphery, due to which more intermixing takes place at the peripheral region of the weld.

In all the systems thermomechanical deformation or dynamic recrystallization has been observed. In the case of friction welding process, the weld simultaneously undergoes plastic deformation and frictional heat due to high rotation under the influence of friction and upset pressures. This results in dynamic recrystallization that is predominant in low strength material. The width of this zone is also more for the low strength material. For example, in case of Fe–Cu system (Fig. 5) Cu grains are refined to nearly one tenth of the starting parent metal and the width of this zone is also more in copper (3.5 mm) as compared to that in Fe (12 μm) [5].

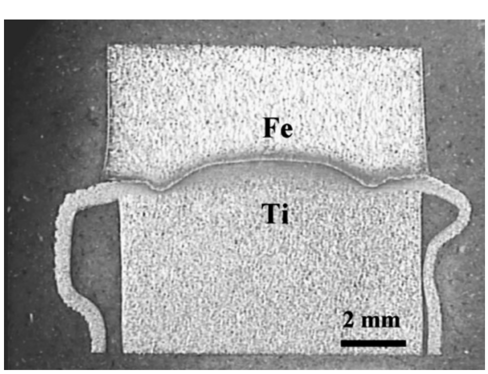

Fig. 2. Macrostructures of Fe–Ti 5 mm burn off joint.

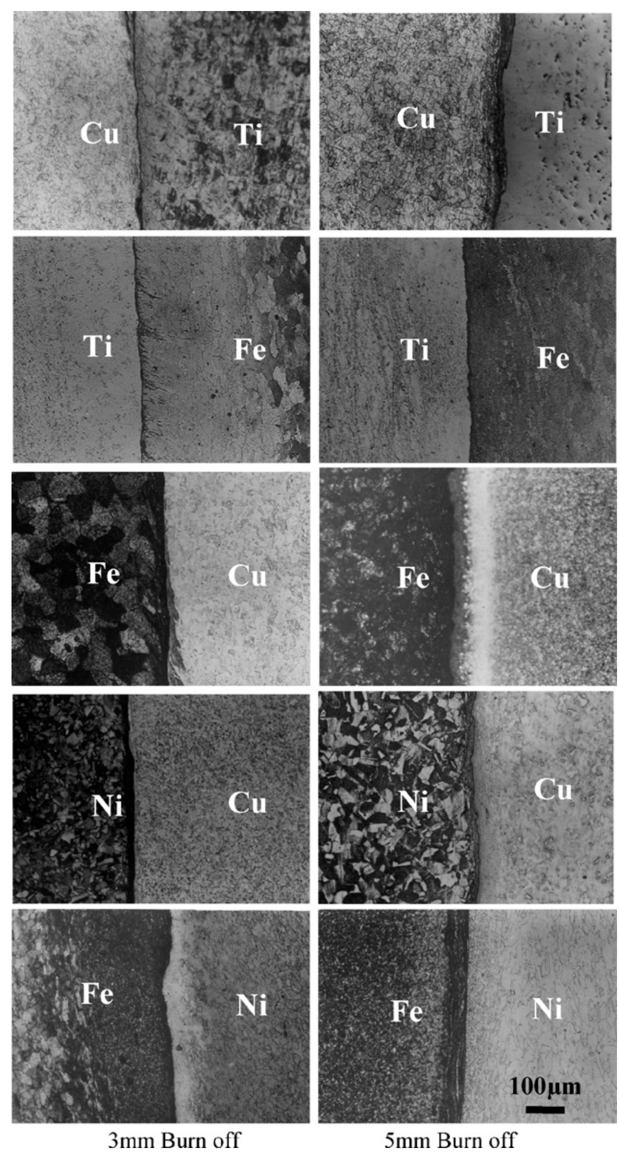

Fig. 3. Influence of burn off on the microstructure at the weld center.

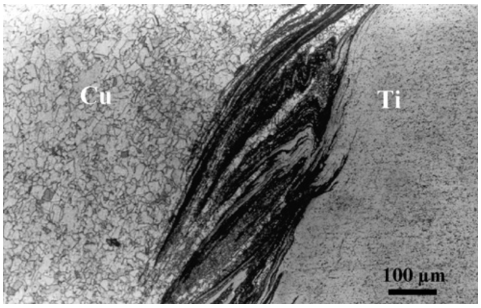

Fig. 4. Typical microstructure at the peripheral region of Cu–Ti 5 mm burn off joint.

3.2. SEPMA

Typical EPMA of the weld joint (Fig. 6) reveals distribution of elements in the form of bands as a consequence of mechanical transport of material mainly in the peripheral region. Conventional diffusion of elements is limited to 4–5 µm on either side of the interface that is evident from the X-ray mapping and quantitative analysis.

3.3. Fractography

3.3.1. Cu–Ti system

The central region of Cu–Ti joints exhibited non-faceted fracture while the peripheral region consisted of faceted fracture (Fig. 7a). However, the extent of faceted fracture is more in case of 3 mm burn off joints. The fracture may be considered more brittle in case of 3 mm burn off joints. Possibility of achieving ductile failure at the center of both 3 and 5 mm burn off specimens may not be ruled out.

3.3.2. Fe–Ti system

In 3 mm burn off weld the failure occurred on the Fe side and therefore exhibited fracture behavior similar to that of the parent metal (Fe), i.e. ductile. In 5 mm burn off weld sample the failure had taken place in the weld and the fracture was

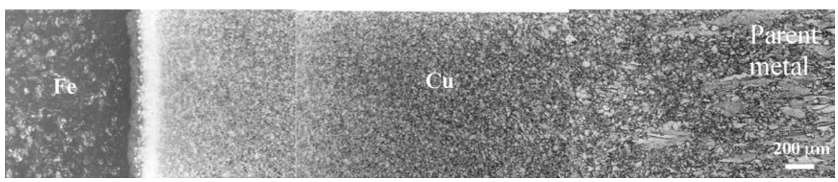

Fig. 5. Fe–Cu 5 mm burn off joint showing dynamic recrystallization.

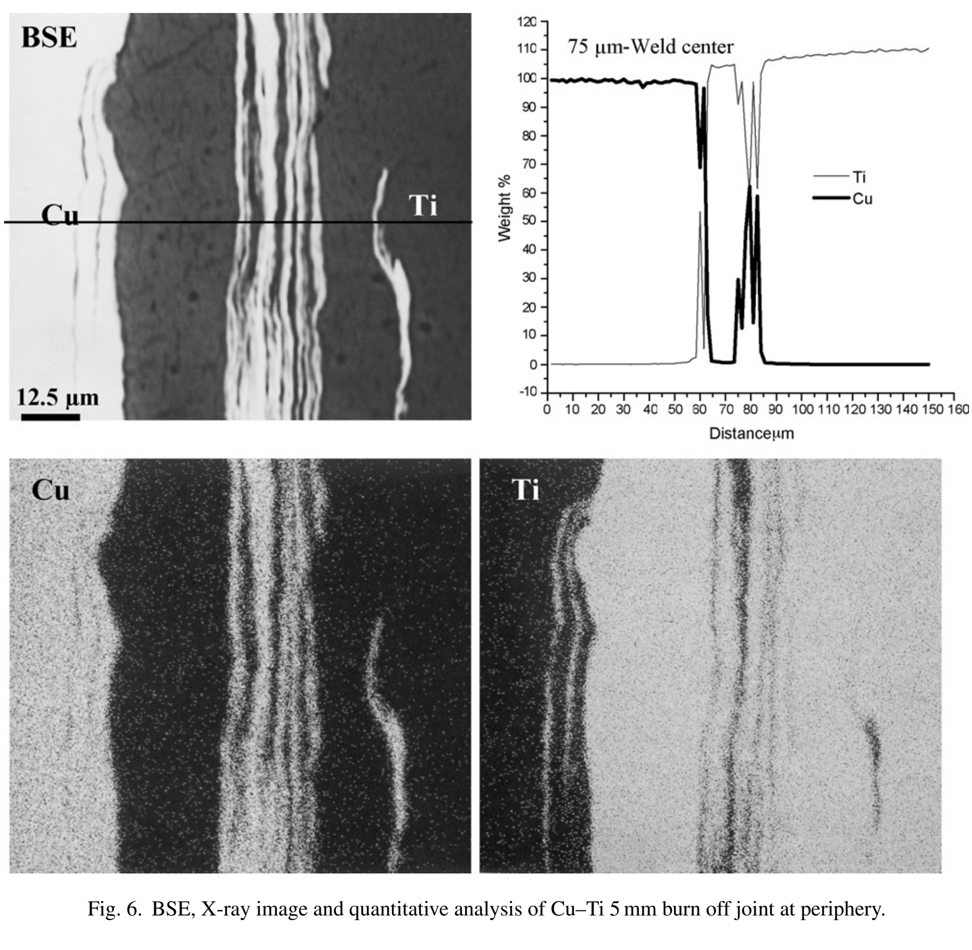

Fig. 6. BSE, X-ray image and quantitative analysis of Cu–Ti 5 mm burn off joint at periphery.

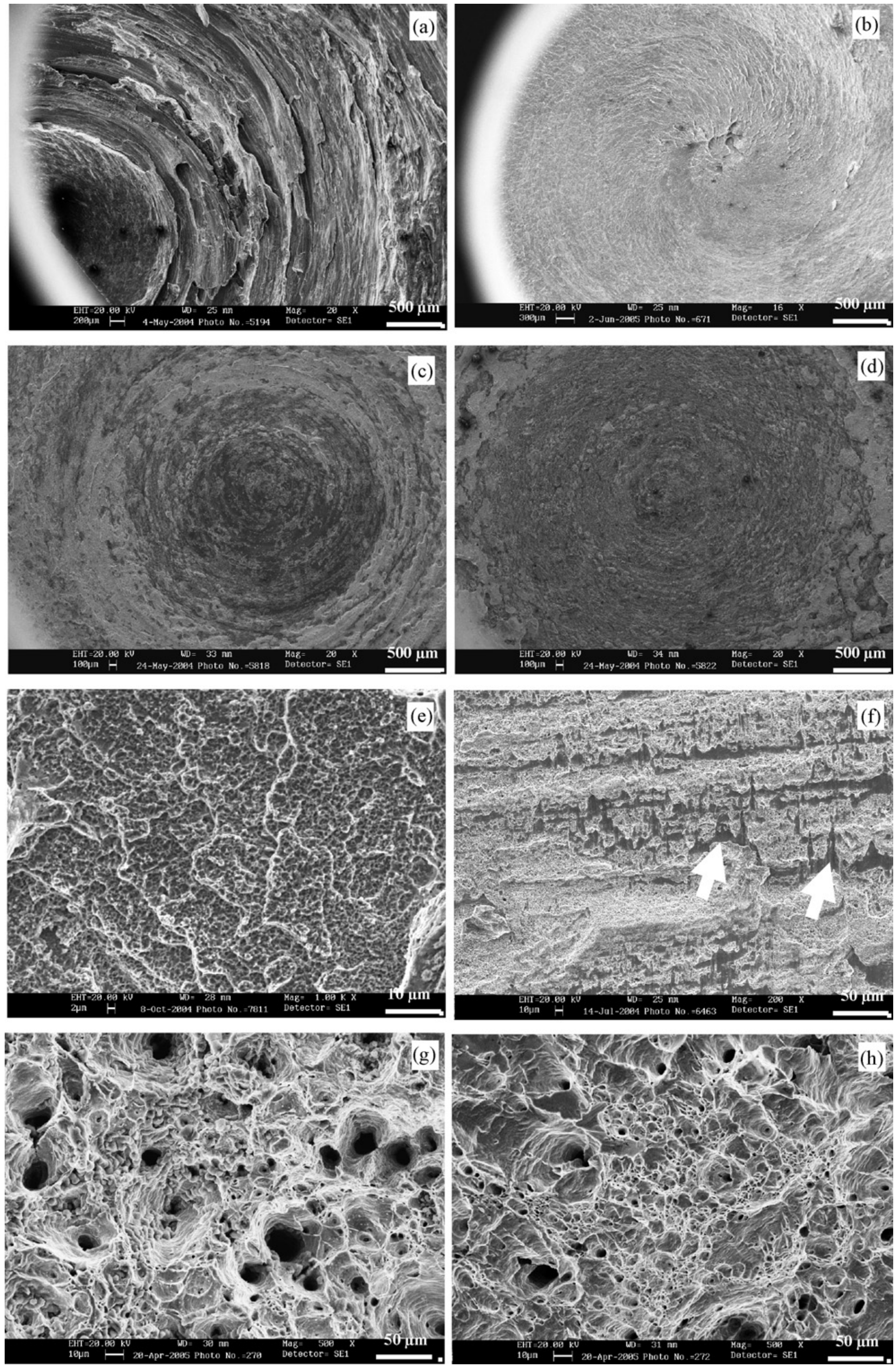

Fig. 7. Fractographs of tensile specimens. (a) Cu–Ti 3 mm center; (b) Fe–Ti 5 mm center; (c) Fe–Cu 3 mm center; (d) Fe–Cu 5 mm center; (e) Cu–Ni 3 mm center; (f) Cu–Ni 5 mm mid radius; (g) Fe–Ni 3 mm center; (h) Fe–Ni 5 mm center.

by cleavage. Macro fractograph shows material flow in a spiral form (Fig. 7b). Examination at higher magnification showed predominant cleavage fracture.

3.3.3. Fe–Cu system

Both (3 and 5 mm burn off samples) the fracture surfaces show concentric circular fracture patterns at low magnification SEM (Fig. 7c and d). Large proportion of bright phase is observed at the peripheral region of both the samples. However, for 3 mm burn off, the presence of the bright phase is significantly higher which can be seen right up to the center of the joint whereas in 5 mm burn off welds, it extends only up to the middle of the joint. This difference in microstructure can be attributed to less time available for homogenization at 3 mm burn

Table 1
EDS data of Cu–Fe system at the weld interface

Location	Fe–Cu (3 mm)				Fe–Cu (5 mm)			
	Element wt%		Element at%		Element wt%		Element at%	
	Fe	Cu	Fe	Cu	Fe	Cu	Fe	Cu
Center	91.86	8.14	92.77	7.23	91.33	8.67	92.3	7.7
Mid-radius	43.78	56.22	46.78	53.03	65.7	34.3	68.54	31.46
Periphery	7.12	92.88	8.02	91.98	35.75	64.25	38.76	61.24

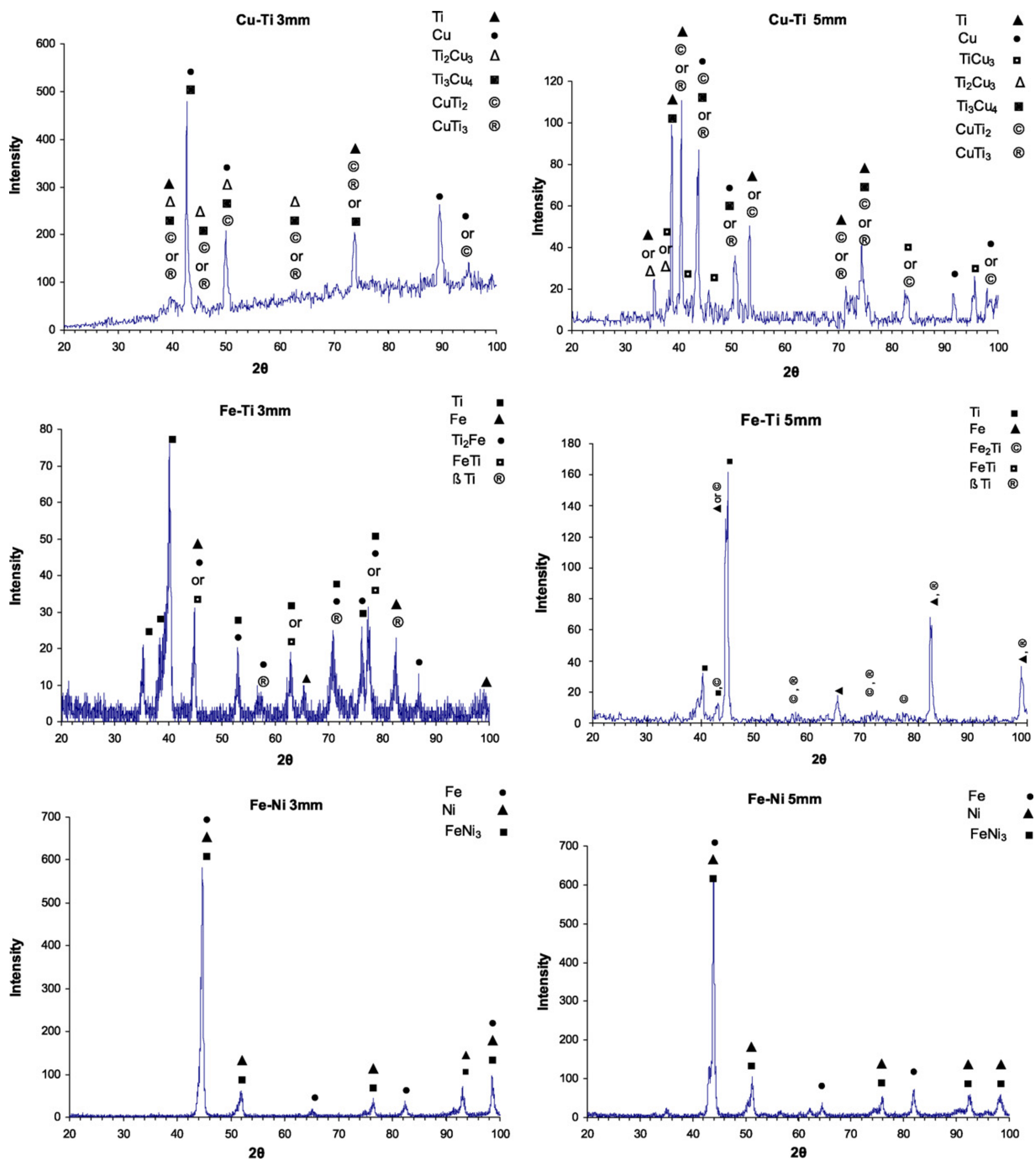

Fig. 8. X-ray diffraction analysis of the fracture surface of joints.

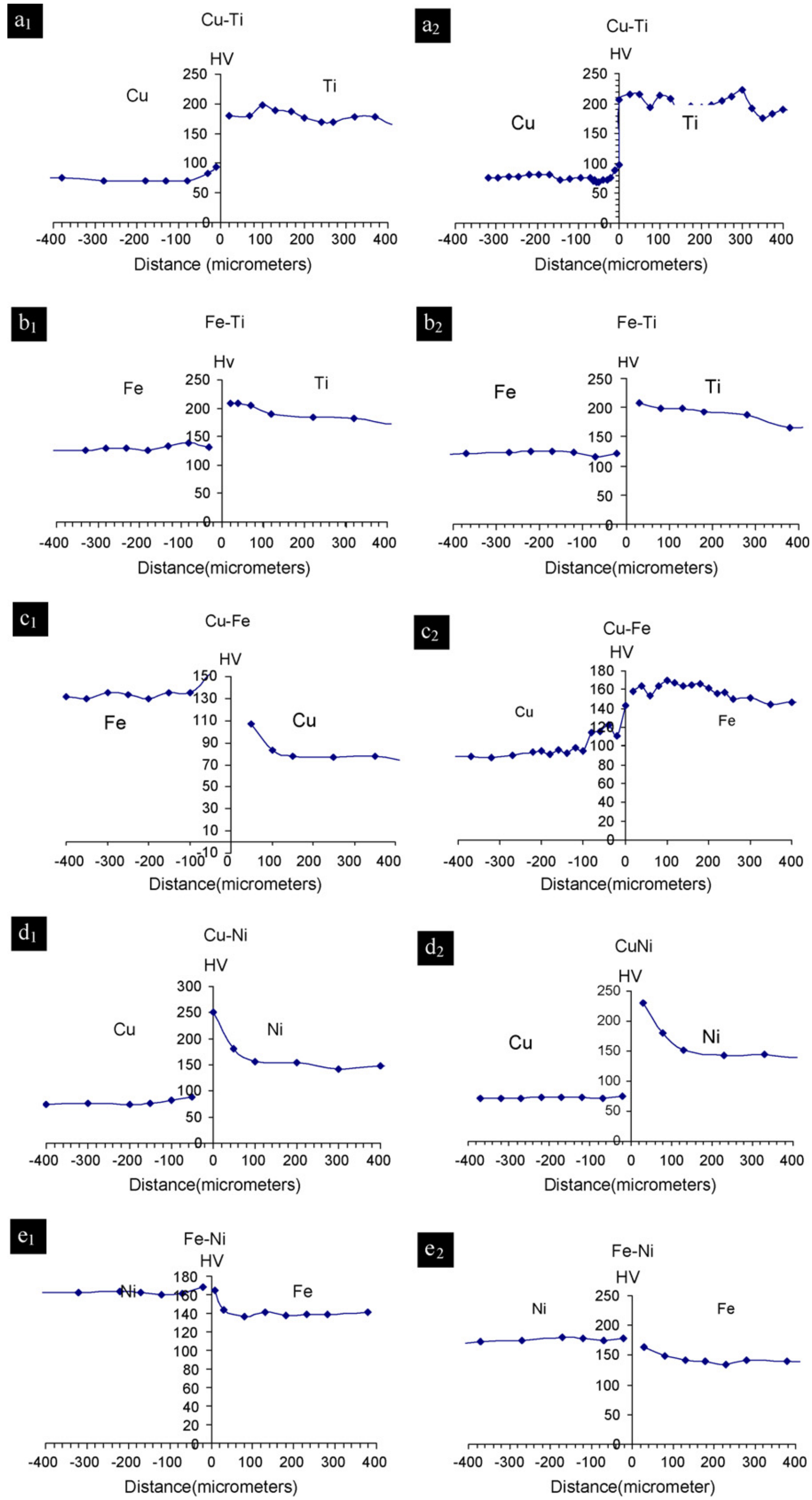

Fig. 9. Hardness variation across the welds. (a1–e1) 3 mm burn off; (a2–e2) 5 mm burn off.

Table 2
Tensile properties of base metal and welded samples

Properties	Pure metal				Joints					
	Cu	Fe	Ni	Ti	Burn off (mm)	Cu–Ti	Fe–Ti	Fe–Cu	Cu–Ni	Fe–Ni
0.2% YS (MPa)	419	197	309	313	3	–	243	–	187	205
					5	–	–	–	251	240
UTS (MPa)	424	286	419	470	3	228	305	229	222	286
					5	174	240	207	252	317
%El	27	58	66	44	3	–	20	–	<1.0	18
					5	–	–	–	–	30
%RA	70	80	88	68	3	–	88	–	–	88
					5	–	–	–	–	88
Location of failure					3	Weld	Outside the weld	Weld	Weld	Outside the weld
					5	Weld	Weld	Weld	Weld	Outside the weld

off resulting in compositional gradient. It is likely that 5 mm burn off will allow more time for the homogenization of the joint as evident from the EDS carried out at different locations of these joints (Table 1). In 3 mm burn off joint the concentration of Cu is higher in the peripheral regions and gets reduced as central regions are approached. Whereas this variation is significantly less in 5 mm burn off, possibly due to the availability of more time for homogenization at 5 mm burn off.

3.3.4. Cu–Ni system

In 3 mm burn off sample, small uniform dimples are seen along with particle cleavage features at certain locations (Fig. 7e). In 5 mm burn off sample, large numbers of troughs (marked with arrow) are observed at both center and mid radius. In mid radius the troughs are sharp and pointed, whereas blunt and non-directional troughs are observed in the center. The fracture surface reveals fine dimples along with some facets indicating brittle mode of rupture.

3.3.5. Fe–Ni system

In Fe–Ni the failure was located in Fe side irrespective of the burn off and therefore ductile fracture similar to that in pure Fe was observed (Fig. 7g and h).

3.4. XRD

X-ray diffraction analysis is reported only for the joints in which new phases or intermetallics are observed (Fig. 8). Since no new phases were observed in Fe–Cu and Cu–Ni systems XRD data for these joints are not presented.

3.5. Mechanical properties

3.5.1. Hardness

In general, an increase in hardness is observed adjacent to the interface with low strength material (Fig. 9). It may be added that hardness values in the interface region could not be determined due to level difference at the location of the joint. In Cu–Ni the hardness adjacent to the interface with nickel is 250 Hv compared to 150 Hv of pure nickel. This increase in the hardness resulted in the formation of cracks at the edge of hardness indentation. Higher hardness in all the welds can be attributed to the strain hardening effect due to upsetting.

3.5.2. Tensile properties

Tensile properties of parent metals and weld joints are presented in Table 2. From the data it may be noted that strength decreased with an increase in burn off in Fe–Ti and Cu–Ti which are intermetallic forming systems. This drop in the strength can be due to the presence of Fe_2Ti in case of Fe–Ti joint at 5 mm burn off. Joint with 3 mm burn off length failed outside the weld whereas that with 5 mm burn off failed in the weld. Fe–Ti system is very sensitive to the intermetallic layer thickness [6,7]; if the zone containing the intermetallic is less than 3 μm wide it will have negligible influence on the final joint mechanical properties. High burn off contributes to increase in the width of intermetallic layer which may also be the reason for the lower strength of Fe–Ti joint with 5 mm burn off Table 2.

Presence of $TiCu_3$ in case of Cu–Ti joint at 5 mm burn off may be the reason for its poor strength as compared to the Cu–Ti joint at 3 mm burn off. The failure location in Cu–Ti joints was in the weld at both levels off burn off.

Fe–Ni and Cu–Ni are the soluble systems. In Fe–Ni system both 3 and 5 mm burn off samples failed outside the weld. Ductile $FeNi_3$ an intermetallic was observed to form in Fe–Ni system. Although Cu–Ni is a completely soluble system the weld joint strength was poor with failure located in copper adjacent to the interface. Increase in the hardness and hence the strength towards the Ni side close to interface due to strain hardening led to failure on Cu side.

Fe–Cu is an insoluble system. Joints formed here were very brittle in nature and exhibited drop in strength with an increase in burn off and failure of the joint in either case (3 and 5 mm burn off) was in the weld region. Diffusivity of Fe is higher than that of Cu and hence a reaction layer is formed towards Cu side and the failure has taken place in this zone [5].

4. Conclusions

The influence of interaction time on microstructure and tensile properties of the friction welding of five dissimilar metal combinations, namely Fe–Ti, Cu–Ti, Fe–Cu, Fe–Ni and Cu–Ni system has been investigated. Extended interaction time led to decreased strength due to thicker intermetallic layer formation in eutectoid forming systems (Fe–Ti and Cu–Ti) and insoluble systems (Fe–Cu). In the soluble systems strength increment is observed with an increased interaction time due to solid solution formation.

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