Microstructure and Mechanical Properties of Explosive Weld Copper-Mild Steel Joint

Mrityunjoy Hazra* and G Madhusudhan Reddy
Defence Metallurgical Research Laboratory, P.O.-Kanchanbagh, Hyderabad- 58
*Corresponding author: mhazra@dmrl.drdo.gov.in, hazra.mrityunjoy@gmail.com

DOI : 10.22486/iwj/2018/v51/i1/166440

ABSTRACT

Mild steel and copper was joined with explosive welding using suitable parameters to obtain a copper-mild steel joint of high integrity. There was no diffusion, melting and formation of intermetallic zone between the bonded plates. An inter-mixed zone of the base materials is observed with a span of 1300 μm around the interface. Significant hardening and softening of the microstructure was observed on the copper and steel sides around the interface respectively by inter-mixing effect arising out of mechanical inter-locking. Shear strength of the joint (260 MPa) was quite higher with respect to that of the copper, the weaker metal of the copper-mild steel bimetal combination. Reasonably ductile shear failure occurred in the copper plate, and no failure was observed along the interface.

Keywords: Mild steel, copper, explosive weld interface, inter-mixed zone, shear strength

1.0 INTRODUCTION

Dissimilar joints may be made by adopting either a melting or a solid state welding route [1]. Recent need of joining of stainless steel to copper in corrosive environment demands the exploration of the different welding processes for this purpose. Various joints are prepared by fusion welding processes, as in these cases, tailoring of physical and mechanical properties become quite easy. Precipitates formed in fusion welding (during melting and solidification stages) corrode severely in suitable environments, thus hampering the integrity of the joints. In this regard, solid state welding processes, such as friction welding, diffusion bonding, explosive welding (cladding) etc. are better than their fusion welding counterpart.

Explosive welding is a process which involves welding of two or more plates by extensive deformation due to the effect of explosion induced high pressure and temperature. In this process, clean surfaces get welded to each other due to a combined effect of inter-atomic attraction and mechanical inter-locking. Undulations created on the surfaces of the colliding plates (base materials) helps in inter-locking. Welding of dissimilar metals is much feasible by this process, for which many of the conventional welding methods including solid state welding are not the alternative routes [2]. Welding of metals with vastly differing melting points and/or thermal expansion coefficients and/or hardness values is possible by this method. Its major applications include plate to plate, tube to tube, pipe to pipe etc. types. So far, it has been used to weld more than 260 combinations of metallic systems.

The explosive weld bond has some beautiful and sometimes superior traits as compared to those with other solid state welding processes [3-6], as follows: (i) wavy interface with good mechanical properties arising out of large contact area, (ii) nearly an ideal composite, consisting of virtually unaffected base materials, (iii) metallurgical bonding with strength equal to or even higher than the weaker parent metal, (iv) very insignificant heat affected zone, (v) absence of inter metallic compound(s). This process is employed to produce varieties of joint structure on a commercial scale for use in defence, aerospace, automobile and refinery industries.

Most of the studies on explosive welding have focused on microstructural modifications at joint interface [7,8]. Some of the studies also investigated the influence of lower (flyer) plate on the morphology of wavy interfaces [9]. Acarer et al. studied the effect of stand-off distance and explosive rate on microstructure, hardness, tensile and bending properties of the steel-steel explosive clad joints [10-12]. Kacar and Acarer, in a separate investigation, studied the characteristics of vessel steel-duplex stainless steel explosive weld joints [13]. Also, widespread work is reported in the open literature on structure-property correlation for welds of mutually insoluble systems such as HSLA steel-stainless steel, incoloy 800H-stainless steel, copper-brass etc. [14-16]. However, very limited data are there on structure-property correlations on explosive weld systems such as titanium-low carbon steel [17], titanium-stainless steel [18], copper-steel [19-21], titanium-aluminum [14], nickel-titanium [14] etc.

Few reports are there in the open literature on explosive weld copper-stainless steel joints [19-21]. Copper cladding is being applied traditionally on steels for achieving enhanced thermal conductivity and/or better corrosion resistance, depending on the requirement. However, there is very limited report about the explosive welding in copper-mild steel system, which is a prerequisite for understanding the joining of copper to stainless steel in a much better way [22]. Therefore, in the present study, weldability of mild steel to copper by explosive welding was investigated through microstructural and mechanical (micro hardness and shear strength) characterization.

2.0 EXPERIMENTAL PROCEDURE

2.1 Materials and explosive joining

Figure 1 shows schematically the most commonly used parallel preparation used for explosive welding [23]. Steel and copper were chosen to be overlay (flyer) plate and base plate respectively. This is based on consideration of the preferred corrosion as well as mechanical properties of steel along with large scale use of copper in vessel industry. **Table 1** shows chemical compositions of the flyer and base plates. Amatol (10 % TNT and 90 % ammonium nitrate) was chosen as explosive material. Detonation velocity and density of the explosive material are 3500–3800 m/s and 0.75 g/cm^3 respectively. The stand-off distance (s) and explosion rate (R) of the flyer plate was set up at 2t and 1.5 t respectively, prior to detonation. The joint thus produced is shown in **Fig. 2**. Explosive weld bimetal copper-steel combination was obtained in cylindrical configuration of length 38 mm, diameter 45 mm and with a copper layer of 2 mm thickness.

2.2 Microstructural work

Longitudinal (i.e. parallel to the explosion direction) specimens were extracted from the explosive weld and were mounted and polished to 1 µm finish for metallographic observations. Etchant used for both the plates is 20 ml distilled water with 20 ml HCl and 4 g $CuSO_4$. Optical microscope, scanning electron microscope (SEM) equipped with EDAX energy-dispersive X-ray spectrometry (EDS) facility and electron probe micro analyser (EPMA) equipped with wavelength-dispersive X-ray spectrometry (WDS) facility were used for metallographic characterization.

2.3 Microhardness measurement

Microhardness measurements were carried out on a Matsuzawa digital micro hardness tester following ASTM E384-11e1 standard, with a Vickers indenter and using 50 g load.

2.4 Shear test

ASTM D 3165-95 was adopted for making shear test

Table 1 : Chemical compositions of base materials

Material	Composition (Wt%)								
	Fe	Cu	C	S	P	Mn	Bi	Pb	O
Copper	-	Bal	-	-	0.0045	-	0.0005	0.005	0.040
Mild steel	Bal	-	0.12	0.05	0.05	0.60	-	-	-

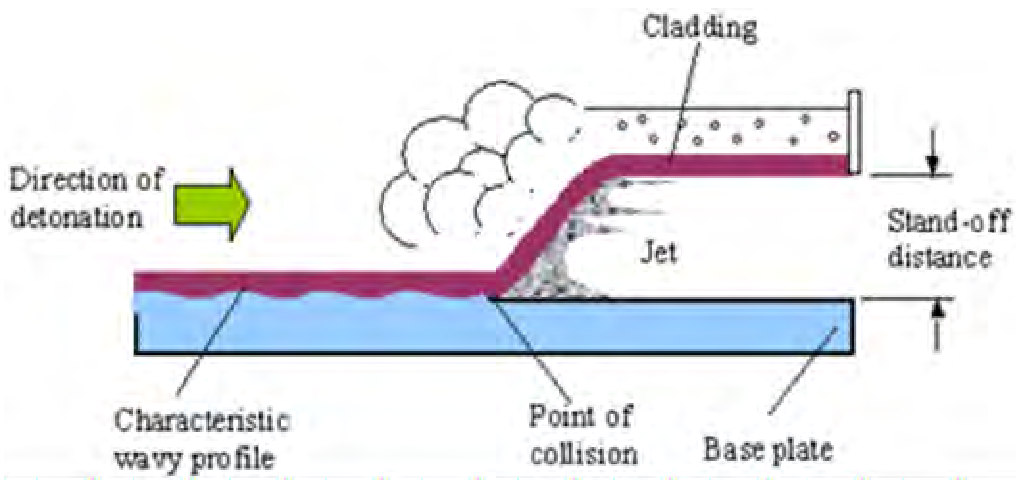


Fig. 1: Representation of a typical parallel type of explosion welding setup

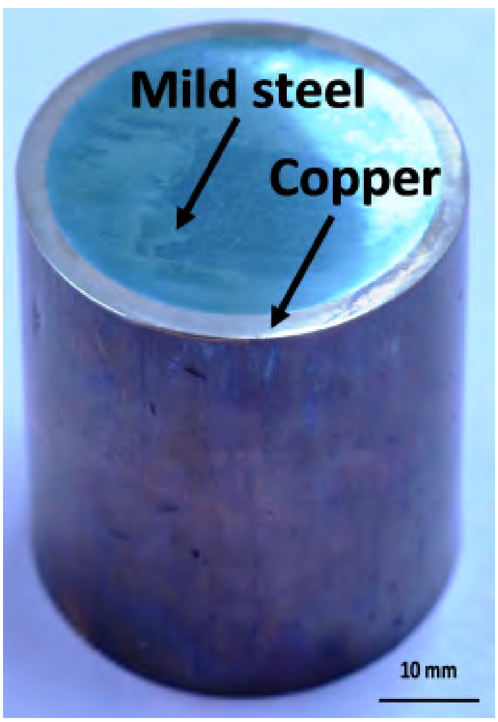


Fig. 2 : Macro image of explosive weld joint

specimens. One representative specimen is shown in **Fig. 3(a)**.

Fig. 3(b) shows the fixture used in the test. Instron-5500R was used for carrying out the test in the compression direction. The direction of application of load is as shown by the arrows in the figure. 0.5 mm/min speed of shearing was adopted. Six samples were tested and average value of the obtained shear strengths is reported.

3.0 RESULTS AND DISCUSSION

3.1. Microstructure

3.1.1. Optical Microscopy

The optical micrograph is presented in **Fig. 4**. Wavy interface is seen in major parts. This is mainly due to high collision velocity of the flyer plate, which, in turn, results in very high pressure near collision point. This evolved pressure usually surpasses material's yield strengths by a significant margin. Therefore, the accompanying deformation rate near the collision point is also enormously high. This resulted in very fine grained structure at the collision point and thus at the interface between two plates. In this study, copper-mild steel bond was majorly a metal/metal transition type. Grains near the interface were refined as well as elongated parallel to the impact direction, as has also often been reported in the literature [19-21]. However, in steel side, both refinement and elongation of grains was not observed to the extent of that in the copper side. This is due to lower hardness of the copper than steel. Also, very short duration of the welding operation might have caused deficiency of the required energy for recrystallization on steel plate near interface. All these things are also indirectly evident from the presence of mechanical twins at the steel side adjacent to the interface. The fineness of the structure was so high that optical microscopy was often unable to reveal any such structure. Sharp transition between two mating materials was observed at the weld interface. Two types of bond were usually obtained at wavy as well as straight form of weld interfaces; these are metal/solidified melt and metal/metal types [24].

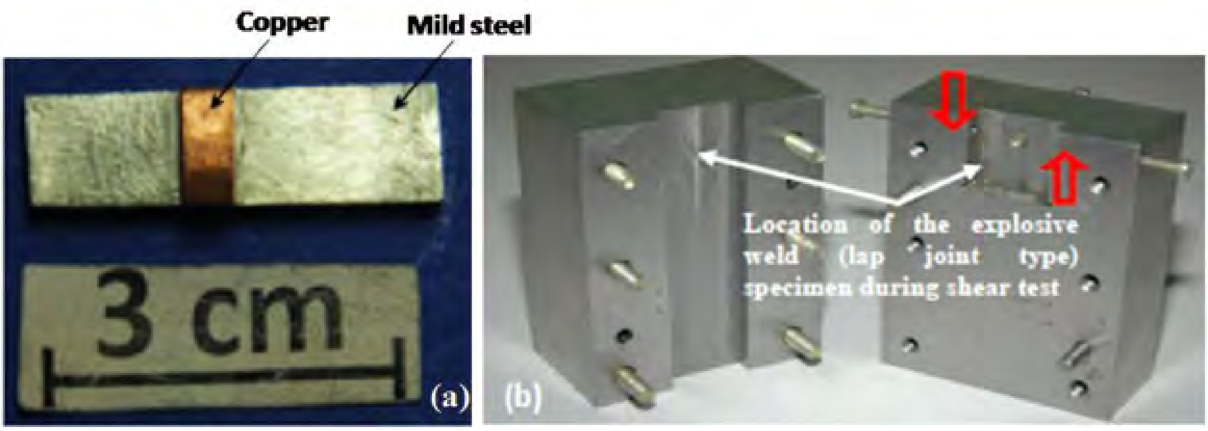


Fig. 3 : (a) Shear test specimen from explosive weld joint, (b) shear testing fixture

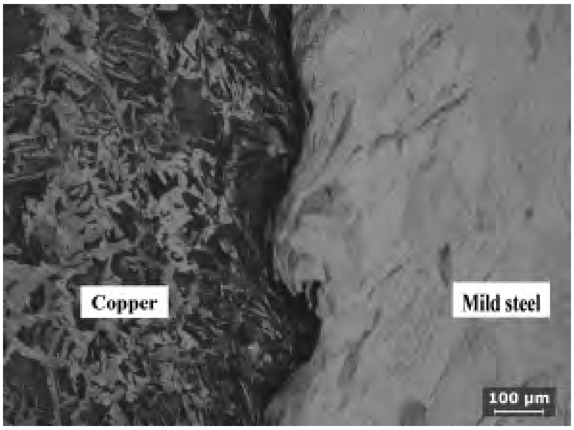


Fig. 4 : Optical micrograph of explosive weld joint

3.1.2. Scanning Electron Microscopy (SEM)

Fig. 5(a-c) shows low magnification image of the bond interface. It reveals waviness of the interface very clearly. Some dots like points are seen. These are etching defects and formed around the copper-mild steel interface due to use of the single etchant for etching of copper as well as steel simultaneously. This finding is supported by some of the earlier reported works in the literature [20,21] on copper-stainless steel explosive welds.

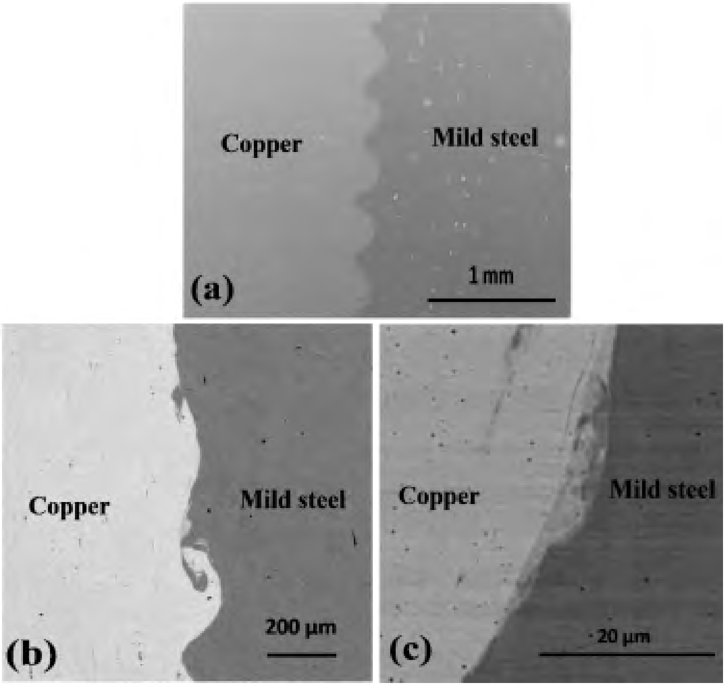


Fig. 5 : SEM micrograph of explosive weld joint at various locations (a,b,c)

It is clearly seen in **Fig. 5** that there is no diffusion and inter-mediate layer between the bonding layers. EDS result within 100 μm distance away from the interface at different locations on both plates also confirms the absence of elemental transfer across the interface. **Fig. 5(c)** shows presence of locally molten and solidified areas at few locations along the interfacial boundary. This has been often termed as melt pockets. This is found to be in line with the findings of Kosec et al. [17]. This local melting might have been possible by the heat energy produced from the transformation of explosion imparted kinetic energy [14]. The beneficial factor in getting limited amount of molten layer is the high heat conductivity of copper, which quickly distributed the formed heat into surrounding area during the explosive welding [21].

3.1.3. Electron Micro Probe Analysis (EPMA)

Representative EPMA X-ray maps across the bond interface are shown in **Fig. 6**.

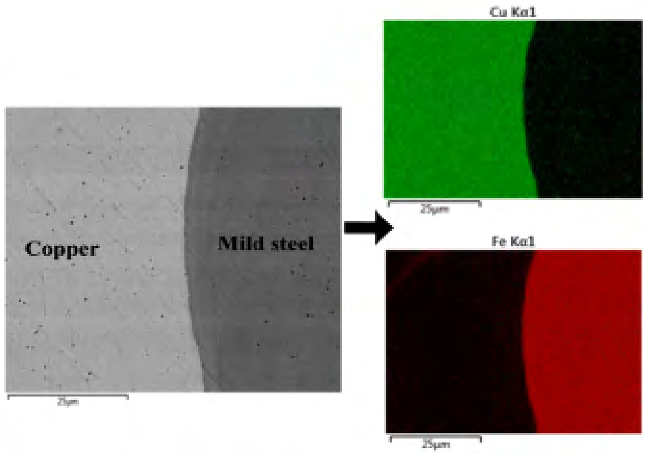
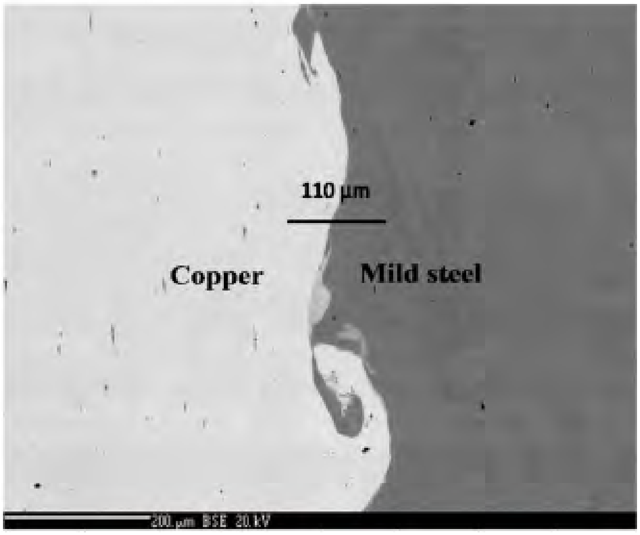


Fig. 6: EPMA X-ray maps along explosive weld joint

Those maps reveal visible absence of significant diffusion between the bonded plates. One typical quantitative line scan profile across the bond interface is presented in **Fig. 7**. This reveals presence of gradual transition in percentage element counts across the very small region (≈ 5 μm) at bond interface. Appreciable amount of mechanical locking (and/or alloying) driven mass transfer may have been responsible for this type of behaviour of the system.

3.2 Microhardness profile

Microhardness profile for the joint is shown in **Fig. 8**. Hardness of the interface seems to fall in a range of 125 HV at copper side to 275 HV at mild steel side. The reason for this type of distribution in hardness may be due to the high degree of cladding effect as a result of crash of the exploded plates at very high speed [19-22, 24]. It indirectly indicates that maximum deformation was experienced by the surface of both metals at the time of collision during explosion. This effect has been noticed in a significant way within very short distance of the interface forming a hardness band (up to 300 μm and 1000 μm distance away from the interface on copper and steel side respectively).



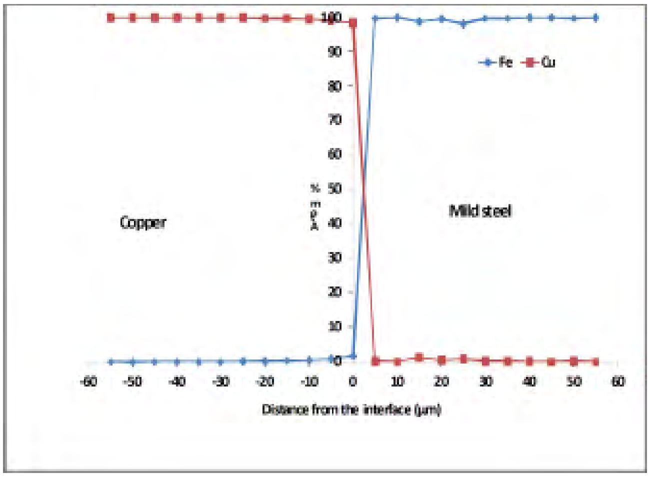


Fig. 7 : EPMA quantitative line scan along the explosive weld

Thereafter, the hardness values get stabilized in both the sides to that of the base materials. This may have been possible by a composite strengthening effect within a very short zone (of around 1300 μm span), as a result of mechanical inter-locking and subsequent alloying. This is marked as inter-mixed zone in **Fig. 8**. This is quite clear from the evidence of mass transfer seen in EPMA quantitative line scan profile shown in **Fig. 7**. However, there may not be formation of any inter-metallic layer. Additionally, increment in hardness in the copper side adjacent to the interface may have been also influenced by grain refinement from the recrystallization effect, as was mentioned earlier. Mamalis et al. in a study [25] reported that the zones near the collision interface showed higher hardness values in case of nickel to titanium explosive welds. They found that the hardness values at both sides of the interface start falling as one move away from the interface and towards the base materials. This was again due to the inter-mixing effect at the interfacial zone.

3.3. Shear strength

The shear test data of the present study indicates that the joint strength (260 MPa) was higher than that of the copper plate (≈ 170 MPa), the weaker of the copper-mild steel combination [26]. It is to be noted that the fracture took place in copper plate and not along joint interface. This indicates that the interfacial strength of the joint is quite higher than the overall joint strength (260 MPa). Thus, it satisfies the acceptance criteria for shear property requirement of this type of joint, as is governed by ASTM/ASME A263-265 and ASTM B-432 specifications. Additionally, this also indicates significant strengthening of the copper microstructure near the interface, as was mentioned earlier in section 3.2. The macrograph of fractured samples, showing the failed region, is shown in **Fig. 9**. Fracture in the copper plate in copper-mild steel explosive weld combination is also well supported by some earlier works in this field [21]. Two major factors contributing to the higher shear strength of the interface and thus contributing indirectly to the delayed fracture are: (i) increased interfacial area due to its wavy nature [19,21], (ii) absence of diffused and/or inter metallic layer [27,28].

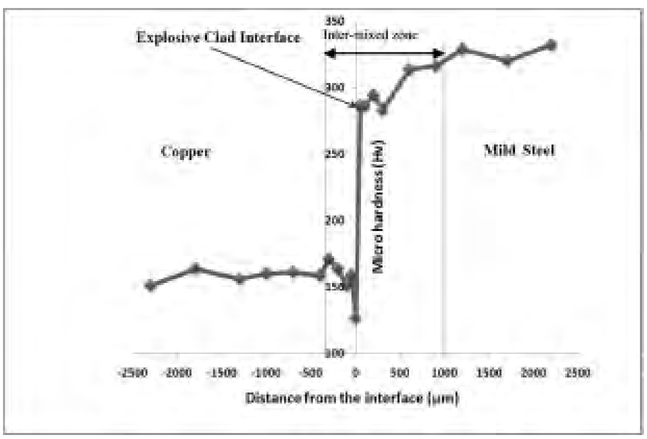


Fig. 8 : Microhardness profile along the explosive weld

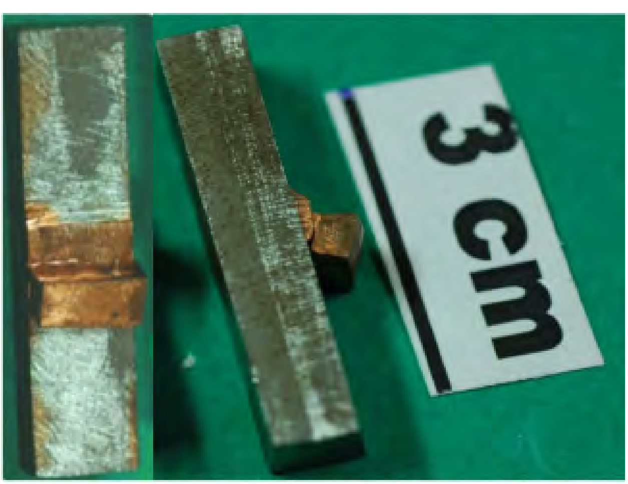


Fig. 9 : Macro image of the failed specimens after shear test

3.4. Fractography

Fractography is presented in **Fig. 10**. Both **Fig. 9** and **Fig. 10** clearly reveal that the failure at the copper plate happened in a pure shear (i.e. reasonably ductile) manner consuming high amount of energy.

4.0 CONCLUSIONS

i. Copper and mild steel having vastly differing melting points, can be joined with explosive welding using suitable parameters without problem of formation of intermetallic zone along the interface, to obtain a high strength and high-ductility mild steel/copper joint.

ii. There was no diffusion between the bonding plates.

iii. An inter-mixed zone of iron and copper with a span of 1300 µm was obtained surrounding the interface as a result of mechanical inter-locking and subsequent alloying. The zone spreaded more (1000 µm) into the iron side than that (300 µm) in the copper side.

iv. Significant hardening and softening of the microstructure was observed on the copper and steel sides around the interface respectively by inter-mixing effect.

v. Reasonable shear strength value (260 MPa) of the joint is achieved, which is quite higher with respect to that (170 MPa) of the copper, the weaker metal of the copper-mild steel combination.

vi. Interfacial strength is quite higher than 260 MPa.

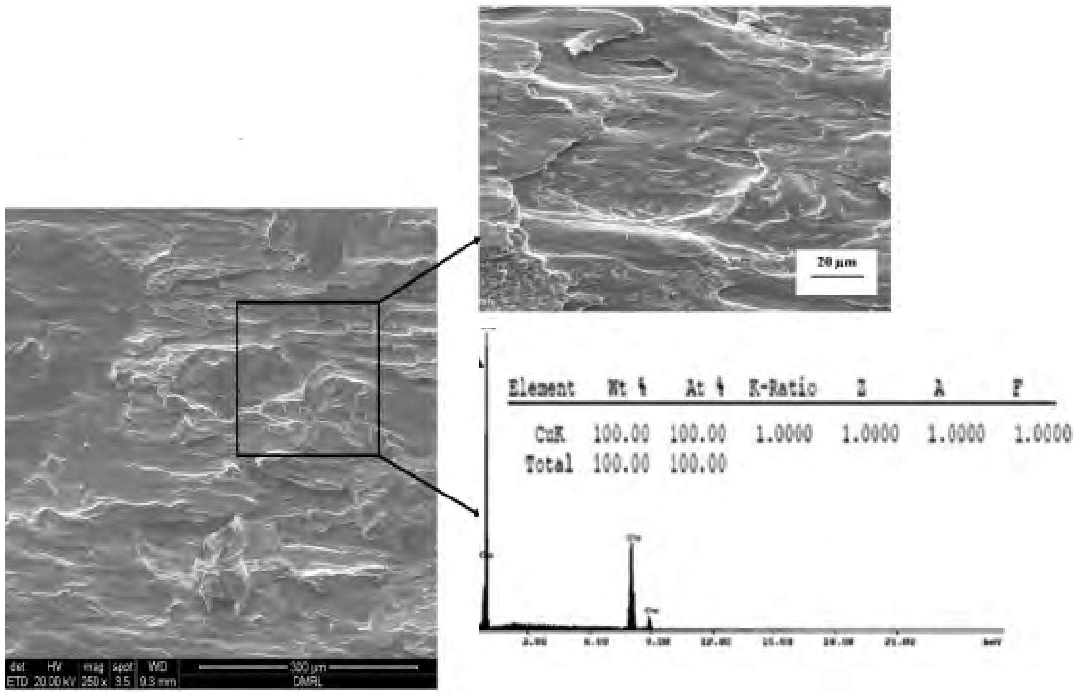


Fig. 10 : Fractographs from the failed specimens after shear test

REFERENCES

[1] ASM Handbook on Welding, Brazing and Soldering, (1993); Vol. 6, Materials Park (OH): American Society for Materials.

[2] Blazynski T (1983); Explosive welding of metals and its applications, Applied science publishers Ltd. England.

[3] Gulenc B (2008); Investigation of interface properties and weldability of aluminium and copper plates by explosive welding method, Mater Des, 29, 275–278.

[4] Acarer, M, Gulenc B and Findik, F (2004); The Influence of some factors on steel/steel bonding quality on their characteristics of explosive welding joints. J Mater Sci, 39, 6457–6466.

[5] Covan GR, Bergman OR and Holtzman AH (1971); Mechanism of bond zone wave formation in explosion-clad metals, Metall. Trans. 2, 3145–3155.

[6] Gerland M, Presles HN, Guin JP, Bertheau D (2000); Explosive cladding of a thin Ni-film to an aluminium alloy, Mater. Sci. Eng. A 280, 311–319.

[7] Brasher DG and Butler DJ (1995); Explosive welding: principles and potentials. Adv Mater Process, 3, 37.

[8] Nishida MH, Chibia A, Honda Y, Hirazumi J and Horikiri K (1995); Electron microscopy studies of bonding interface in explosively welded Ti/Steel clads. ISIJ Int, 35, 217.

[9] Jaramillov D, Inal OT and Szecket A (1987); On the transtition from a waveless to a wavy interface in explosive welding. J Mater Sci, 22, 3143.

[10] Acarer M, Gu¨lenc¸ B, Findik F (2000); Study of some welding parameters of explosively joined steel parts. In: Meran C, editor. Proceedings of the 8th Denizli materials symposium, Denizli, Turkey.

[11] Acarer M, Gu¨lenc¸ B and Findik F (2001); Examination of cracks and fracture on interfaces of explosive welded metals by using tensile shear and bending test. In: Proceedings of the 5th international fracture conference, Firat University, Elazig, Turkey, 301–309.

[12] Acarer M, Gu¨lenc¸ B and Findik F (2003); Investigation of explosive welding parameters and their effects on microhardness and shear strength. Mater Des, 24(8), 659–664.

[13] Kacar R and Acarer M (2003); Microstructure–property relationship in explosively welded duplex stainless steel–steel. Mater Sci Eng A, 363(1–2), 290–296.

[14] Crossland (1982); Explosive Welding of Metals and Its Applications, Clarendon Press, Oxford.

[15] Rao NV, Sarma DS, Nagarjuna S, Reddy GM (2011); Influence of hot rolling and heat treatment on structure and properties of HSLA steel explosively clad with austenitic stainless steel – Structure and Properties, Materials and design 32, 2496-2506.

[16] Hui Z, Pingcang Li, Yinggong Z, Zhanghang H and Hunian W (2011); Study on the technology of explosive welding Incoloy 800H-SS304, Journal of Materials engineering and Performance, August, 20 (6), 911-917.

[17] Kosec B, Kosec L, Cevnik G, Fajfar P, Gojic M, Anzel I (2004); Analysis of interface at explosive welded plates from low carbon steel and titanium, Metallurgia 43, 83-86.

[18] Manikandan P, Hokamoto K, Fujita M, Raghukandan K and Tomoshige R (2008); Control of energetic conditions by employing interlayer of different thickness for explosive welding of titanium/304 stainless steel cladding, Journal of Materials Processing Technology 195, 232-240.

[19] Findik F (2011); Recent developments in explosive welding. Mater Des, 32, 1081–93.

[20] Durgutlu A, Okuyucu H and Gulenc B (2008); Investigation of effect of the stand-off distance on interface characteristics of explosively welded copper and stainless steel. Mater Des, 29, 1480–1484.

[21] Durgutlu A, Gulenc B and Findik F (2005); Examination of copper/stainless steel joints formed by explosive welding. Mater Des, 26, 497–507.

[22] Livne Z and Munitz A (1987); Characterization of explosively bonded iron and copper plates, J. Mater. Sci. 22,1495–1500.

[23] http://www.twi-global.com/technical-knowledge/faqs/process-faqs/faq-what-is-explosive-cladding/, last accessed on 08-03-2017.

[24] Acarer M and Demir B (2008); An investigation of mechanical and metallurgical properties of explosive welded aluminum–dual phase steel. Mater Lett, 62, 4158–4160.

[25] Mamalis AG, Szalay A, Vaxevanidis NM and Pantelis DI (1994); Macroscopic and microscopik phenomena of nickel/titanium Shape memory bimetalic strips fabricated by explosive cladding and rolling, Mater. Sci. Eng. A 188, 267–275.

[26] http://www.unipunch.com/Tech-Support/Charts/Material-Specifications, last accessed on 08-03-2017.

[27] Acarer M, Gu¨lenc¸ B and Findik F (2003); Investigation of explosive welding parameters and their effects on microhardness and shear strength. Mater Des, 24(8), 659–664.

[28] Zimmerly CA, Inal OT and Richman RH (1994); Explosive welding of a near-equiatomic nickel–titanum alloy to low-carbon steel. Mater Sci Eng A, 188A(1–2), 251–254.