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Microstructure and mechanical properties investigations of copper-steel composite fabricated by explosive welding

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ABSTRACT

This paper presented a systematic study of microstructure and mechanical properties of Cu/Fe explosive-bonded interfaces. The periodic wavy bonding structure with both vortex region and solid-solid bonding region was embedded in the interface. Typical annealing twin structures were observed in the texture and orientation analysis of Cu matrix. The ASBs filled with some much smaller size equiaxed grains and orientation variations in different areas were found in the Fe matrix. The transition layer consisted of nano-sized grains of 60 nm was formed between the copper and steel plate. The microindentation results showed that the hardness of the interface (330.9 MPa) and deformation area (Cu 100 HV and Fe 286.8 HV) was higher than the matrix regions. The higher hardness of the transition layer (15.707 GPa) determined by nanoindentation analysis was explained by the existence of nanocrystallines in this zone. The induced tensile tests showed that the cracks didn't extent along the interface wave structure but inside the copper matrix, reflecting the high quality of the bonding.

1. Introduction

Copper as a traditional thermal conductive material has been extensively used in metallurgy, chemical and petroleum industries due to its excellent thermal conductivity, good ductility and high corrosion resistance. With the increasing demand of heat conduction from the heat exchangers such as the cooling stave in the blast furnace, the application of copper has actively progressed. However, poor deformation resistance and high thermal expansion of pure copper hinder its further applications because of deformation, breakage and water pipe cracking. Considering high strength and lower cost of the steel, copper-steel cladding plate has drawn increasing interests owing to its simultaneously both high thermal conductivity and high mechanical strength.

Compared with a single metal material, the composite material can fully exert the advantages of the component materials respectively, optimize the allocation of material resources in each group, save valuable materials and meet the unmet performance requirements of a single metal [1–5]. Up to now, various welding techniques have been attempted to fabricate copper-steel composite plate, such as diffusion welding [6], explosive welding [7], friction stir welding [8] and laser beam welding [9]. Among some techniques, although the steel plate was completely melted, the high thermal conductivity of copper makes it difficult to obtain a complete metallurgical bond. In addition, the solubility limit of Cu in Fe is poor, especially no Fe-Cu phase existing at low temperature. Explosive welding as a solid-phase welding process is the optimum selection to make large laminated plates.

Recently, the explosive welding technique has been developed not only to make multilayer cladding plates with high interfacial bonding strength but also to join similar and dissimilar workpieces that cannot be welded by traditional welding techniques. The process parameters such as collision angle and the impact velocity which are essential to obtain consistently high-quality welds were studied in the form of welding windows. Mustafa Acarer, etc. [10] investigated the explosive welding parameters and their effects on microhardness and shear strength. Different welding interfaces (straight, wavy and continuous solidified-melted) were used with changing explosive welding parameters (stand-off distance (s), explosive loading (*R*) and anvils). The joined metals were investigated under heat-treated and untreated conditions. S.A.A. Akbari Mousavi, etc. [11] carried out an experimental investigation of explosive welding of cp-titanium/AISI 304 stainless steel. The analytical calculation for determination of weldability domain or welding window was presented. In terms of copper-steel composite, Ahmet Durgutlu, etc. [12] investigated the bonding ability of copper and steel with explosion welding using different ratios of explosive and different stand-off distance. Microstructure and mechanical properties of weld joints were examined via scanning electron

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microscopy (SEM) and energy dispersive spectroscopy (EDS). However, detailed information of the grains was not studied. So far, the mechanical properties of the deformation near the interface are mainly distinguished by measuring the micro-hardness distribution across the interface [13]. Nevertheless, the transition region between two workpieces is only 200 µm wide or even narrower, which is so small that the micro-hardness can't characterize the deformation appropriately. To provide a more suitable and accurate way, the nanoindentation technique has been developed to probe the deformation and mechanical responses in the transition region near the interface [14].

In this work, the copper-steel composite with a sound metallurgical bond was produced based on the parameters concluded in the previous studies [15–35]. The microstructure evolution in the interface has been conducted by optical microscopy (OM) and SEM. The unambiguous information about the microstructure (texture and orientation analysis, grain size and shape distribution, grain boundaries and sub-boundary) at the interfaces was investigated by electron backscatter diffraction (EBSD). Microindentation was employed to identify micro-area properties of materials and the mechanical properties in the transition layer was identified by nanoindentation. The mechanical properties were tested by mechanical experiments finally.

2. Material and methods

In the fabrication of copper/steel composite process, as illustrated in Fig. 1, the flyer plate (steel plate) with a dimension of 2500 mm × 950 mm × 22 mm and the base plate (copper plate) with a dimension of 2500 mm × 950 mm × 56 mm were arranged in a classical parallel scheme. Table 1 shows the chemical composition of the copper plate and steel plate. The density of explosive material was 850 kg/m^3, and detonation velocity was 2.5 km/s. The stand-off distance of 2 mm was used. Welding assembly was placed on a steel anvil (5000 mm × 3000 mm × 200 mm) and all explosions were carried out in a sand pool. The copper steel composite welded by EW was annealed in a chamber furnace at 550 °C for 2 h.

Interfaces in the specimens for metallographic analyses were prepared to be the central part. A mechanical polishing was carried out using grinding papers down to 2000 grid. The samples were then polished by diamond polishing using 9, 4.5, 2.5, 1 µm diamond slurry. For EBSD and nanoindentation measurements, further polishing is necessary to receive high-quality results. TIC 3X iron beam cutter equipment was utilized to prepare EBSD samples.

The zeiss supra55 field emission scanning electron microscope equipped with an Oxford Instruments Nordlys Nano EBSD and EDS detectors were used to investigate the microstructure and chemical distribution. The Kikuchi patterns were generated with an accelerating voltage of 20 kV and the working distance was set at 20 mm. The grain size diameter in EBSD is obtained on the basis of the particle area of the assumed "equivalent circle diameter", which is the diameter of a circle having the same area.

Microhardness tests were carried out using a Vickers microindenter (Leica VMHT MOT) testing machine under a load of 50 g with a dwell time of 20 s. The distance between the dents was at least four times as much as the diagonal of the Vickers indenter to prevent the impact of adjacent dents. Measurements were performed on the copper, steel and interface areas respectively and the values were evaluated as the average of three indentations. More details in the interface region were obtained using TI 900 Tribolndenter of Hysitron inc., MN, USA performing nanoindentation experiments to determine. The nanohardness was measured with a Berkovich trip, maximum load of 5000 µN and a constant loading rate of 500 µN/s. The fused quartz with known modulus of elasticity (69.6 GPa +5%) and hardness (9.25 GPa + 10%) is carefully calibrated for the function of the tip area [19]. TECNAIG-20 Transmission Electron Microscopy (TEM, FEI, USA) was used to observe high magnification of the transition layer, and the ion beam milling of Precision Ion Polishing System Gatan-691 was used to prepare samples for TEM analysis.

To investigate the mechanical properties of the copper-steel composite, the mechanical tests were carried out in this study. The induced tensile sample, as shown in Fig. 2, was notched at single edge (Fig. 2, zone A) and the test was carried out on a laser confocal scanning microscope with tensile compression function (VL2000DX) to investigate the occurrence, direction and failure of the cracks.

Table 1
Chemical composition of the copper plate and steel plate.

Material	Fe	Cu	C	Si	S	P	Mn	O
Copper plate	–	Bal.	–	–	0.19	0.22	–	0.08
Steel plate	Bal.	–	0.2	0.35	0.045	0.045	1.4	–

3. Results and discussion

3.1. Microstructure observation

After the explosive welding, the chemical composition and microstructure of the interface of dissimilar materials have changed, which depends on the performance of the two materials and the welding process parameters [16–18]. In the following sections, the basic properties and microstructure of the interface were emphatically investigated.

Fig. 3 shows the microstructure on the cross section of copper-steel interface obtained by SEM. In the Fig. 3(a), there is a typical wavy interface structure with the amplitude ranged between 300 and 600 µm and wavelength varied from 1 to 2 mm, containing vortex regions which are marked as dashed red frame. The formation of the wavy can be explained by the steep pressure gradient at the interface caused by self-induced oscillation near the impact point [36]. The matrixes of the copper and steel in the interface present the fluid properties due to the high pressure generated in the vicinity of the interface whose value greatly exceed the dynamic yield limit of copper and steel themselves.

Additionally, as depicted in the Fig. 3(b), a peninsula-like or island-

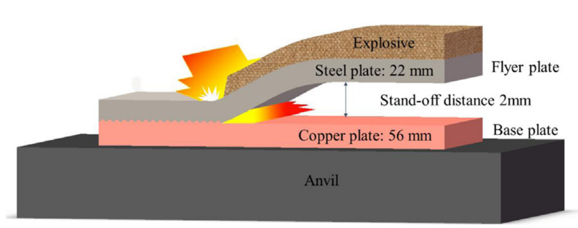

Fig. 1. Schematic sketch of explosive welding.

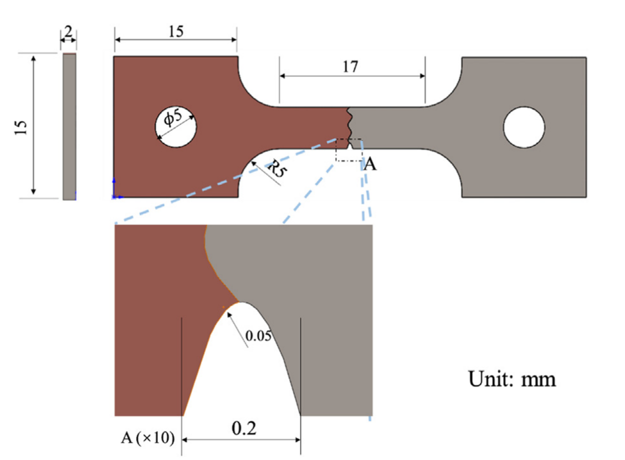

Fig. 2. Schematic and dimension of induced test samples.