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Bonding characteristics during very high power ultrasonic additive manufacturing of copper

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Welding of copper foils (150 μm thick) achieved at room temperature by very high power ultrasonic additive manufacturing was seen to involve appreciable softening and enhanced plastic flow. The initial coarse-grained structure (25 μm) in the material changed into fine dynamically recrystallized grains (0.3–10 μm) at the foil interface within the order of a few milliseconds of processing. This phenomenon led to metallurgical bonding through grain boundary migration and allowed for successive welding of tapes to form a three-dimensional part.
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Ultrasonic additive manufacturing (UAM) is a process used to produce parts of near net shape from metal tapes. It is based on ultrasonic seam welding, a solid state joining process, and involves the successive bonding of the tapes one over the other on a base plate using ultrasonic energy [1]. Ultrasonic vibrations, typically 20 kHz, are applied to the foil laterally (along its width) through a sonotrode (welding tool) that rolls along its length under a static normal force [1]. This induces scrubbing of the top foil with the bottom, leading to the rupture of the oxide layers between asperities of the foil surfaces, thus promoting nascent metal-to-metal contact. The nascent metal asperities are then subject to dynamic shearing and eventually bond. This process of bonding continues with newly established contact points between the tapes as the sonotrode advances along their length. In order to facilitate gripping of the top foil and subject it to vibrations, the sonotrode is given a surface texture. Such texturing of the sonotrode leaves behind a roughened surface on the foil influencing bonding of the next layer. The main parameters of the process are vibration amplitude, static normal force and sonotrode travel speed. The effect of processing parameters on microstructure and mechanical properties of welds in aluminum has been a subject of investigations [2,3]. Processing of other metals (similar metal welding) by UAM has also been attempted [4–6]. However, with the limited power (2 kW) available from current systems [7], all of these have always required a pre-heat.

Welding of copper has thus far not been satisfactory with the current UAM machines [4]. Hardening of the material during processing and issues of oxidation were seen to affect deposition of subsequent layers [4]. In this paper, bonding of C11000 electrolytic tough pitch copper using the process of very high power ultrasonic additive manufacturing (VHP UAM) is investigated. This material containing 99.95% Cu and 0.04% O by weight [8] is the most common of all electrical coppers used in conductor and heat exchanger applications [8–10]. VHP UAM, as the name suggests, is a UAM process that involves higher power levels and is expected to produce parts from a wide range of materials at reduced welding cycles with minimal or no external heat. One such machine delivering up to 9 kW of power at 20 kHz resonant frequency is currently being developed at Edison Welding Institute. It comprises two piezoelectric transducers (instead of just one as in current UAM machines [1]) on either side of the sonotrode that vibrate longitudinally, 180° out of phase, in "push–pull" mode, thereby reinforcing their displacements. Consequently, the sonotrode is set into vibrations at amplitudes of up to 52 μm (twice as large as that of the UAM machine) under a static normal force of up to 15 kN (seven times

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larger than in the UAM machine). The sonotrode has a surface texture of $R_A = 7$ μm imparted to it by electro-discharge machining [7].

Tapes of C11000 copper measuring 0.15 mm thick and 25 mm wide from the as-received material (hard temper) were successively laid one over the other to a length of 170 mm at room temperature on an Al (3003-H18) base plate measuring 12 mm × 350 mm × 350 mm. The processing parameters of 36 μm amplitude, 6.7 kN static force, and 30 mm s^{-1} travel speed were used. The part was built to a height of about 2 mm and comprised 13 layers, each welded through a single pass. The bonding characteristics were evaluated on a transverse section of the build. Scanning electron microscopy (SEM) and electron back-scattered diffraction (EBSD) were used to examine the interfacial microstructures of the build sample. Further, hardness mapping of the sample was also done using a Leco AMH-43 microhardness analyzer. For comparative studies, the as-received tape was characterized both by EBSD and hardness mapping on a similar transverse section.

The SEM image of the build sample in Figure 1 reveals features of interfacial instabilities. The wavy nature of the interfaces that is generally seen sometimes manifests into turbulent plastic flow (Fig. 1). This raised questions as to whether they might have occurred due to vibrational resonance in the lateral direction. However, it is notable that the wavy features do not follow any particular pattern along any given interface, nor do they bear any correspondence to each other across the layers. With the frequency and the longitudinal wave velocity in copper being 20 kHz and 3650 m s^{-1} [11], respectively, the wavelength would correspond to about 180 mm that is far greater than the spacing of these features, which was only of the order of microns. It therefore seems likely that these features are due to violent plastic flow of the material occurring along the ridges and valleys between the contacting layers during processing. Such a topology, although an effect of roughening due to the sonotrode's textured surface and its motion over the foil, is expected to continuously change at a rapid pace as the foil scrubs with the new foil above it. From Figure 1, it is also apparent that the tapes had individually thinned down by about 5% from the original thickness of 150 μm.

Hardness mapping of the build sample showed that there was a tendency for the material to soften (Fig. 2a). It is observed from Figure 2a that the hardness ranges between 75 and 95 HV spatially, although no specific trend is seen along the build height (denoted by depth in Fig. 2a). The variations in hardness along the orthogonal directions suggest possible microstructural/mechanical heterogeneities. Such heterogeneities could arise due to the plastic deformation/flow not being uniform along an interface or across a layer during processing. The variation in contact stresses due to the sonotrode's uneven texture and the fact that there is always some transfer of foil material (copper) onto the sonotrode surface during processing could be possible reasons for this non-uniformity [12]. However, it is quite clear that the hardness values throughout the build sample are consistently lower than in the as-received foil by about 11–23%. This is shown in Figure 2b, which gives the frequency distribution of the hardness values over the mapped region. The material therefore seems to have uniformly softened.

Figure 3a and b shows the inverse pole figure images of the as-received foil and the build sample, respectively, based on the data acquired from EBSD for 0.2 μm spacing. The following two features are striking from these images. The build sample has much finer grain size (Fig. 3b) than that of the as-received foil (Fig. 3a), and does not contain a distinct interface. The observation of an envelope of elongated grains surrounding the equiaxed grains in the build sample (Fig. 3b) is probably indicative of the shearing and flow associated with the process. The grain size distribution in the two cases is shown in Figure 3c. It is seen that a relatively coarse

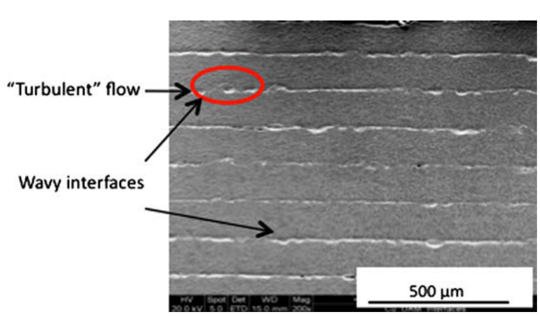

Figure 1. SEM image of the C11000 Cu build sample etched with 50% HNO_3.

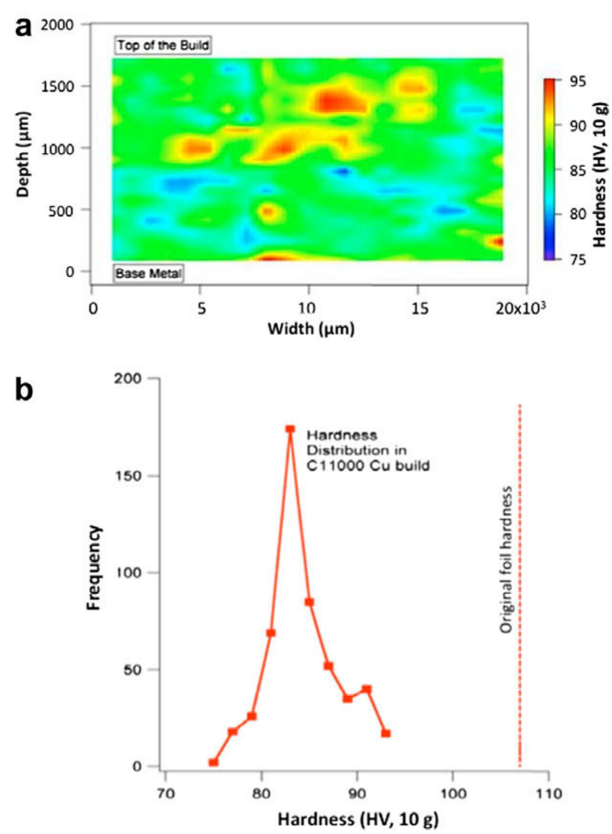

Figure 2. Hardness map (a) and distribution (b) over a transverse section of the C11000 Cu build sample.

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