X-ray welding of metal-matrix composites [1]

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Introduction

To a large extent, technological advances in the science of welding have resulted from the introduction of new energy sources to provide the thermal energy required for local melting. Present day welding techniques include gas-tungsten arc, gas-metal arc, submerged-arc, electron-beam, and laser-beam welding. These processes introduced stability, reproducibility, and accuracy. Nevertheless, they share a common limitation - the melt pool is formed on the surface of the material. In order to penetrate the full depth of the piece it is necessary to either specially machine the joint or cause violent vaporization of the material so that a "keyhole" is formed. For many classes of materials this is not a severe drawback and does little to hamper the mechanical strength of the joint. However, for certain types of materials, such as ceramics and metal-matrix composites (MMCs), such processing can be catastrophic, leading to partial or complete failure at the interface. MMCs are composed of a metal (usually Ti or Al) within which a reinforcing ceramic (usually Al_2O_3 or SiC) particulate, whisker, or fiber is imbedded. These materials are lighter and have superior mechanical and thermal properties as compared to the base metal and are finding widespread use in many areas. They have great potential for use in the aerospace industry, provided a joining process that maintains the strength of the material can be found.

X-rays with energies in the range 3–200 keV have penetration lengths on the order of 0.001–50 mm for various materials. Therefore, they have the potential for use as a volumetric heating source, provided a sufficiently intense source of x-rays is available. Until recently this was not possible. However, with the advent of third-generation synchrotron radiation sources, tunable x-rays with power densities greater than 10^4 W/cm^2 in a 1–2 mm spot can be produced with the use of insertion devices. At such high power levels, localized melting and even vaporization can be induced in a number of materials. If these x-ray beams can be utilized in a controlled manner, they have the potential for use as welding sources for classes of materials that have eluded conventional welding approaches. In this report, we present the results of our efforts in this area, which demonstrate that intense, insertion-device x-ray beams have great potential for use as welding sources for MMCs.

Methods and Materials

The experiments were performed on beamline 1-ID. The insertion device used in the beamline is a 72 period, 3.3 cm period length "undulator" capable of reaching a peak magnetic field of 0.849 T when the undulator gap is closed to its minimum setting of 10.5 cm, resulting in a peak x-ray heat flux of ~180 W/mm^2 for a storage ring beam current of 100 mA. At the first harmonic energy of 3.2 keV, calculations predict a spot size of 2.0 mm (horizontal) x 1.1 mm (vertical). As the undulator gap is increased, the energy of the first harmonic increases from 3.2 keV to 12 keV at 25 cm, while the peak heat flux decreases to 35 W/mm^2. The results presented here were performed with the gap set to 11 mm, resulting in a peak heat flux of 170 W/mm^2 and a first harmonic energy of 3.5 keV. The Al/Al_2O_3 MMC samples were obtained from MC-21, Incorporated. They consist of a 6061 Al alloy matrix reinforced with 20% calcined Al_2O_3 powder particulates. The particulates had a mean size distribution of 20.8 ± 6 μm.

Results and Discussion

Cross section scanning elecron microscope (SEM) images of the fusion zone are shown in Figure 1. The entire width of the sample is shown in (a). X-rays were incident on the sample at the lower left and exited from the upper right. Although some vaporization of matrix material did occur, most of the material is still intact and the distribution of particulates stays uniform. An enlarged region of the area where the x-rays impinged on the sample is shown in (b). Note that the density of particulates is slightly higher in this region. This is probably the result of selective vaporization of the Al matrix (Tvap = 2467^o C) leaving behind an excess of Al_2O_3 particulates (Tvap = 2980^o C). An enlarged view of the region where the x-rays exited is shown in (c). Here the distribution of particles is uniform when compared to an unirradiated region, shown in (d).

The significance of these results lies in the fact that although melting occurred throughout the heat-affected zone, the reinforcing particulates were unperturbed. This is in stark contrast to welding trials that were attempted using both electron beam and laser sources. Regardless of sample travel speed and beam power evaluated, violent vaporization always accompanied a full penetration weld. As a result, the particulates were destroyed and the piece was cut rather than fused. This is probably due to vaporization of the particulates, or dissolution of the Al_2O_3 in the molten Al. Similar behavior has also been observed in laser welding of Al/SiC MMCs.

Another important aspect of the results shown in Figure 1 is the total absence of cracks in the weld zone. The matrix metal, 6061 aluminum, is notorious for solidification cracking when welded autogenously using conventional methods. Examination of our weld trials on MMCs and 6061 Al showed no evidence of cracking. This behavior can not be totally explained. It is conjectured that the volumetric heating results in relatively slow heating and cooling rates, which in turn places less strain on the material in the melt zone

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Refernece

[1] R.A. Rosenberg, Q. Ma, W. Farrell, M. Keefe, and D.C. Mancini, *Review of Scientific Instruments* **68**, 2550 (1997).

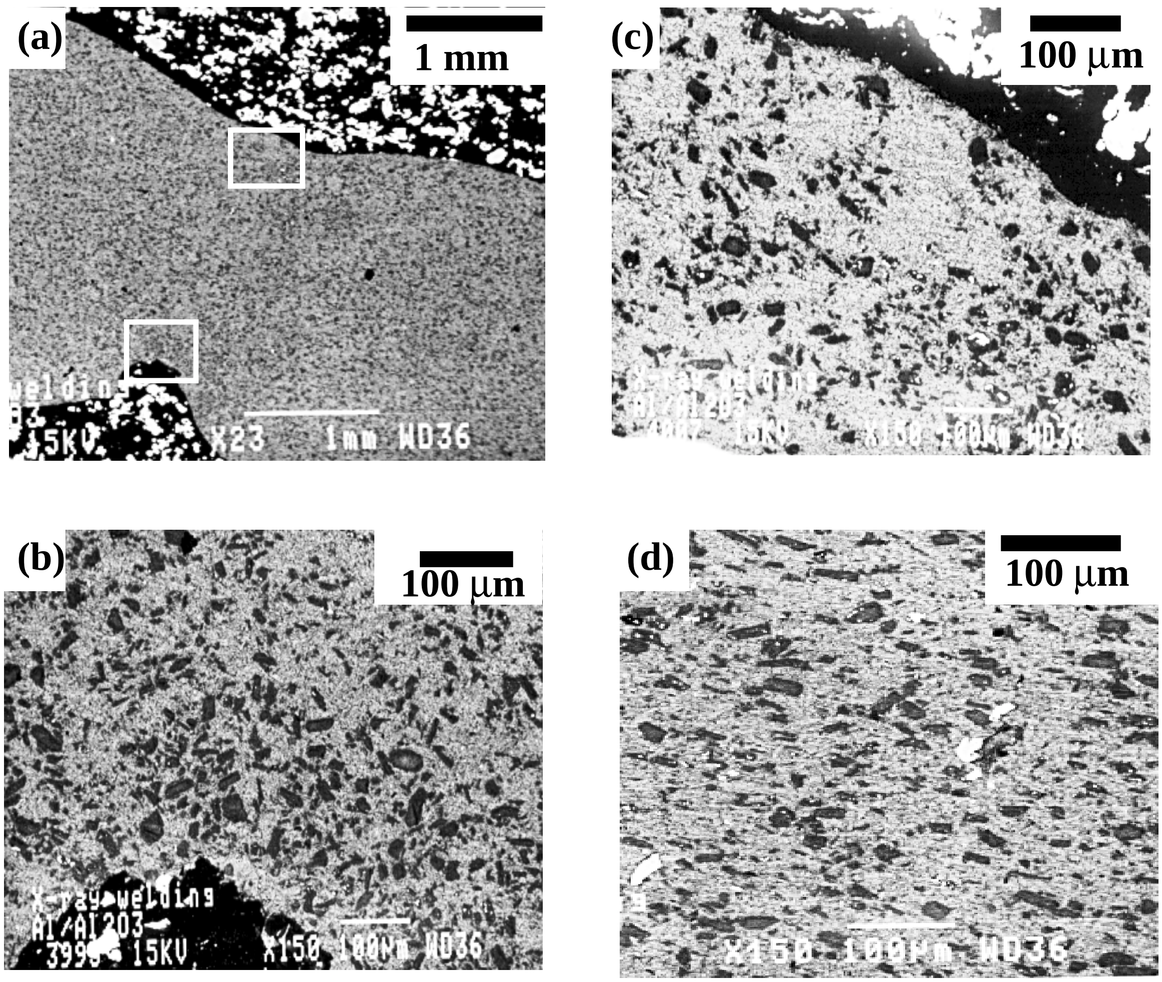

Figure 1: Cross-section SEM images of a 20% Al/Al_2O_3 metal-matrix composite sample following a bead-on-plate x-ray weld. In (a) is shown the entire cross-section. X-rays were incident on the lower left and exited from the middle top. An enlarged view of the region where the x-rays struck the target (lower box in (a)) is shown in (b). Note the higher density of particulates in this region. In (c) and (d) are shown enlarged views of the region where the x-rays exited (upper box in (a)) and an unirradiated region, respectively. The black and white material seen surrounding the sample is from the molding compound used for mounting.