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Recent progress in micro and nano-joining

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Abstract. Micro and nano-joining has been identified as a key enabling technology in the construction of micromechanical and microelectronic devices. The current article reviews recent progress in micro and nano-joining. In particular, laser micro-welding (LMW) of crossed 316 LVM stainless steel (SS) wire was compared to conventional resistance micro-welding (RMW) and was successfully employed in welding a Pt-Ir /SS dissimilar combination. Welding of Au nanoparticles was realized using femtosecond laser irradiation and its application in the surface enhanced Raman spectroscopy was investigated. Brazing between carbon nanotube (CNT) bundles and Ni electrodes was attained in vacuum, resulting in the development of a novel CNT filament of incandescent lamps.

1. Introduction

Welding and joining is an essential step in the fabrication of various devices at all scales including macro, micro and nano. As devices become increasingly smaller, challenges faced in micro and nano-joining must be overcome before these joints are safely implemented. For examples, researchers must determine how to robustly join these miniature building blocks while avoiding excessive damage. The current article reviews recent challenges faced in micro and non-joining while detailing recent progress in these areas.

Crossed wire welding [1,2,3,4] is a critical fabrication technique in the manufacture of implantable medical devices. Difficulties associated with resistance micro-welding (RMW) of new materials and combinations has resulted in an initiative to explore alternative joining methods. Recently, laser micro-welding (LMW) has been shown to be a potential candidate to replace RMW [4]. In this study a comparison between RMW and LMW of crossed 316LVM SS wire was conducted. In addition, benefits associated with dissimilar welding using the LMW process are discussed.

Various nanojoining approaches have been developed, including e-beam exposure [5], focusing ion beam deposition [6], ultrasonic welding [7], sputtering/evaporating Au and post-annealing [8,9] and nanosoldering with low melting point solders [10,11]. This article will review current progress in nanojoining using femtosecond laser welding and vacuum brazing processes. Both processes have potential for large scaling and batch-nanojoining, which are promising for practical applications.

2. Experimental

2.1. Resistance and Laser Micro-welding

Laser welding was conducted using a Miyachi Unitek LW-50A laser welding system capable of 50J pulse energy and 5 kW peak power. A MacGregor DC400P direct-current (DC) controller and Unitek 80A/115 weld head are used for RMW. Fixturing was used to bond the wires at right angles (90°) for both the RMW and LMW process. 316 LVM SS (0.38 mm diameter) and Pt-Ir (0.4 mm diameter) wire was used in this study. Tensile testing was used to determine the joint breaking force (JBF). Stainless steel metallographic samples were etched using 5 ml HNO_3, 25 ml HCl, and 30 ml H_2O at an elevated temperature (80°C). Etching time varied between 3 to 5 seconds.

2.2. Nano-Welding

Femtosecond laser welding was carried out with a 100 fs 800 nm Ti:sapphire laser system with a pulse energy of 250 µJ/pulse and repeatition rate of 1 kHz [12]. Au nanoparticles were synthesized by the citrate redution of $HAuCl_4$. Welding was done in liquid by focusing the laser into a quatz cell or in solid by depositing Au nanoparticles onto a TEM Cu-grid.

Vaccum brazing was conducted using a high vacuum tube furnace under 10^{-6}Torr. The brazing material has a nominal composition of Ag–63.0%, Cu–35.25%,Ti – 1.75% with a melting point of 815°C, while solidifies at 775°C. A detailed brazing procedure was reported elsewhere [13]. The CNT filament made of CNT bundles and welded to two Ni electrodes was tested in a vacuum chamber (10^{-4} Torr).

3. Results and Discussion

3.1. Micro-welding of Crossed Stainless Wires

Figure 1 shows the joint breaking force (JBF) as a function of peak power and current for the resistance and laser micro welding processes, respectively [3,4]. Each process requires a minimum parameter input to provide enough energy to initiate bonding. The modification of the process parameters results in an increase in JBF up to a maximum. Similar peak joint breaking force near 80 N was attained for both processes. Excess energy inputs resulted in over welded joints having insufficient strength.

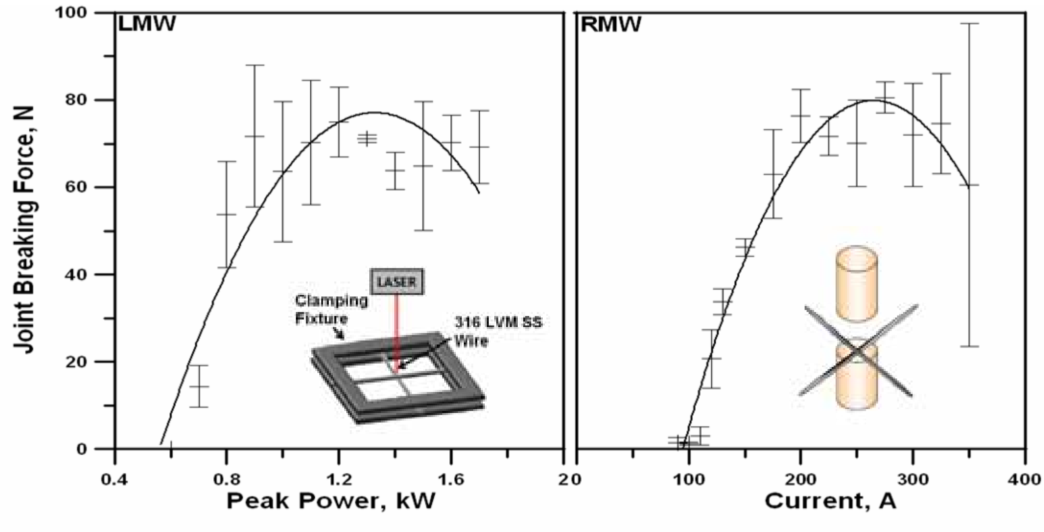

Figure 1: JBF of crossed SS wire for LMW and RMW [3,4]

Observed weld cross-section for laser and resistance welded 316LVM SS for conditions producing optimal JBF are shown in Figure 2. A dendritic solidification structure was observed for both welding processes, indicating peak temperatures surpassed the liquidus temperature. RMW exhibited a less directional structure compared to LMW, which is likely due to the contact of the copper electrodes. Thus, fusion welding mode and similar joint strengths can be achieved for both processes.

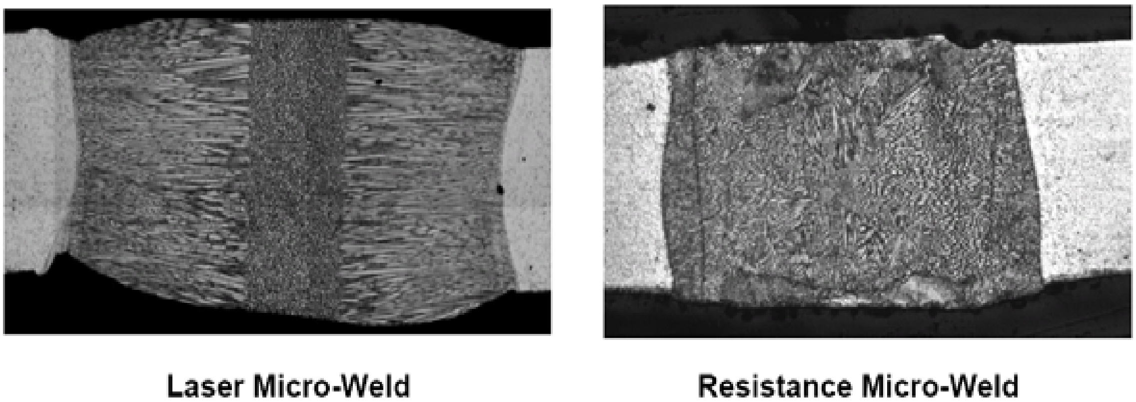

Figure 2: Fusion weld cross-section for 316LVM SS [3,4]

Limitations observed with RMW of dissimilar material have shown to be resolved using LMW. For example, differences in resistivity between Pt-Ir alloys and stainless steel make it difficult to attain acceptable dissimilar RMW joints. Figure 3a shows excessive melting of the higher resistivity SS in the dissimilar RMW joint. However, as shown in Figure 3b, the LMW joint results in an acceptable weld with a smoother surface. Hence, current challenges with micro-welding of new materials and combinations can be overcome by implementing alternative micro-welding processes.

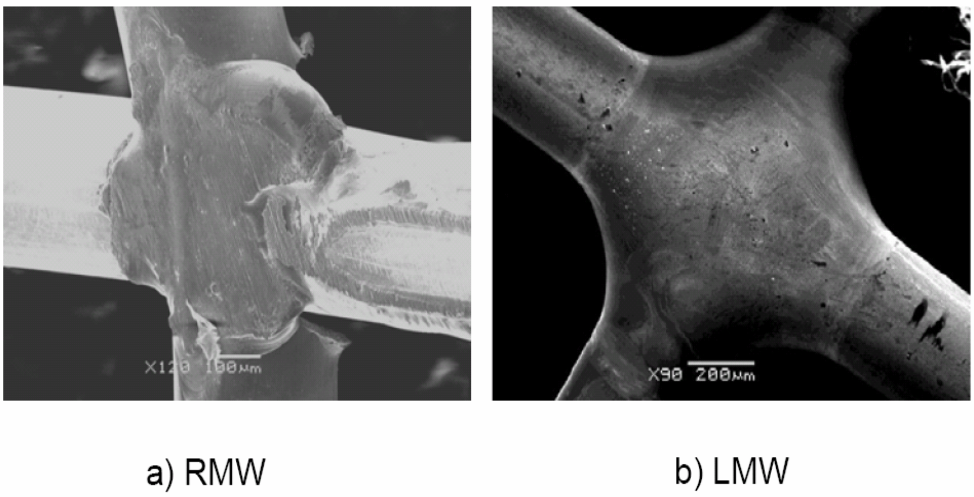

Figure 3: Crossed SS and Pt/IR dissimilar weld

3.2. Femtosecond Laser Welding of Au Nanoparticles

Figure 4 shows as-grown (before welding) and welded Au nanoparticles irradiated in water at a laser intensity of $4x10^{14}$ W/cm^2 for 10 min. As-grown Au nanoparticles (before welding) have a mean size of 15 nm. After femtosecond laser irradiation, some 1-3 nm Au particles were generated. These very tiny Au nanoparticles were formed through the fragmentation of Au nanoparticles by laser irradiation. A previous study has identified the electron ejection as the first step of photofragmentation [14]. This electron emission causes nanoparticles to become positively charged and the repulsion among the charges leads to the fragmentation. Meanwhile, we obtain about 70%-80% nanoparticle welded together. In some parts 2-3 particles join together. In some cases several particles (including both large particles around 15 nm and small particles around 1-3 nm) form a curved chain or a network. The dynamic procedure of welding between nanoparticles is still unclear. Our study shows that femtosecond laser can induce the melt of surface nanoscopic layer if the pulse energy is properly chosen [15]. As a result of electron ejection (8-10% of total bonding electrons), the lattice bond gets loose, leading to the lattice melt [16]. This melt occurs during the ultrafast pulse width and is thus ultrafast and nonthermal. The lattice beneath the surface melting layer keeps unchanged. Probably this ultrafast melt results in a nanojoining of Au nanoparticles. Our recent results show that the photofragmentation can be suppressed by lowering the focused light intensity.

Welded Au nanoparticles can work as the probe for surface enhanced Raman effect (SERS) for single molecular detection because the surface plasmon near the vicinity of welded neck region is enhanced. A 5 fold improvement of SERS signals was achieved using welded Au nanoparticles in comparison with as-grown Au nanoparticles for the polyyne molecules diluted in acetone at the same concentration.

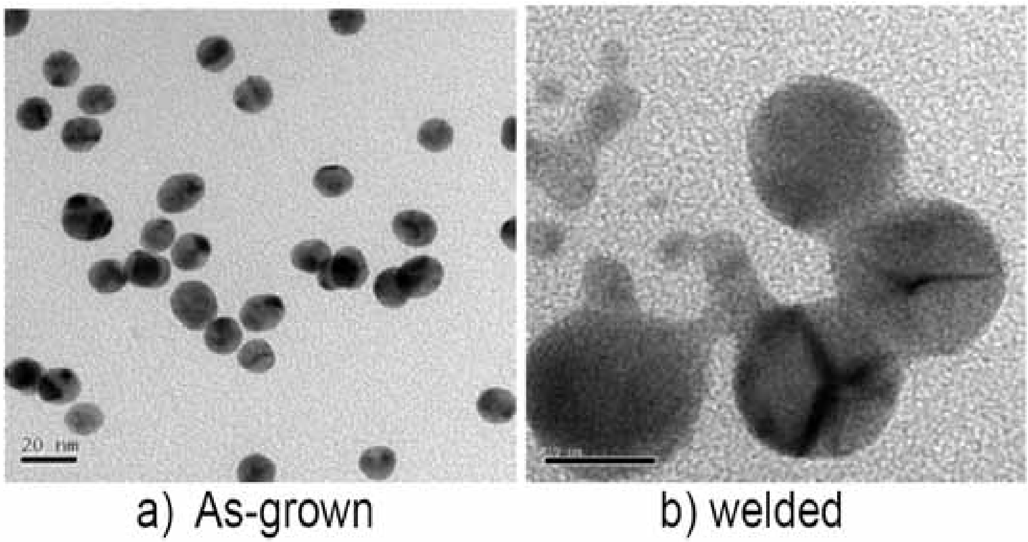

Figure 4: TEM images of (a) as-grown (before welding) and (b) welded Au nanoparticles. Note that the sacle bars are different, (a) 20 nm and 10 nm in (b).

3.3. Vaccum brazing of CNT

Cu-Ag-Ti brazing alloy has successfully wetted CNT surfaces at high temperatures by formation of C-Ti bonds. This is confirmed by the local composition analysis by X-ray energy dispersive spectroscopy, element mapping and X-ray photoelectron energy spectra [13]. This technique was employed in the fabrication of a filament with a 2 cm long CNT bundle. Figure 5 presents the transporting measurement in a vacuum chamber under 10^{-4} Torr. It is evident that the CNT-Ni electrode connection displays good Ohmic behaviour and brazing leads to a dramatic decrease of contacting resistance comparing to both mechanical connection and joining using Ag paste. Based on SEM characterization, the CNT bundle diameter was about 100 µm. At 15 V, the filament current density reaches 3000 A/cm^2 for brazing, which is near double of a reported value of 1670 A/cm^2 using the similar CNT bundle material while joining with Ag-paste [17].

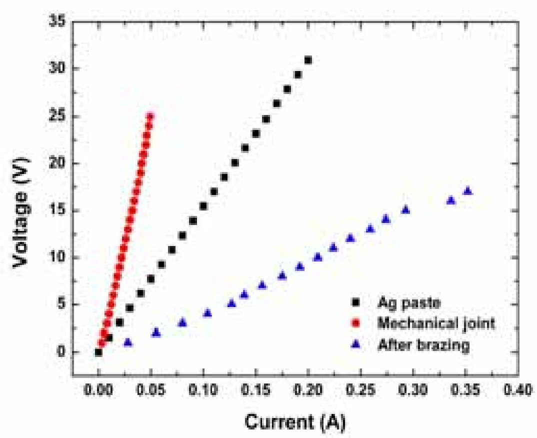

Figure 5: I-V curves of three kinds of jointed CNT filaments: (upper to lower) mechanical joint, Ag-pasted and vacuum brazing.

Figure 6 shows the emission spectra for the CNT and tungsten filament at 1570 °C. A stronger infrared luminescence (IR>750 nm) was observed for the CNT incandescent lamp when compared to the tungsten filament at the same temperature. This indicates that CNT filament is capable of working at higher temperatures; hence, higher emission effects are expected.

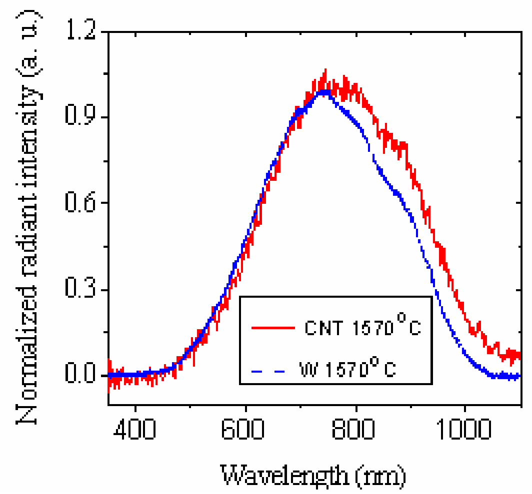

Figure 6: Emission spectra of a CNT filament and commercial tungsten lamp at a filament temperature of 1570°C.

4. Conclusions and Outlook

The current article detailed recent progress in micro and nano-joining. Key finding include:

1) Similar welds strengths and fusion welding modes can be achieved for crossed wire welding using the RMW and LMW process. The latter has versatile capacities to join various materials, especially for less conducting/insulating biomaterials, like bio-electrodes.

2) Nanojoining Au particles and brazed CNTs have been successfully implemented as probes for the surface enhanced Raman spectroscopy and energy saving filaments for incandescent lamp, respectively.

3) Developed nano-joining techniques can enable large scale batch processing and may open new frontiers in the construction of complicated nanodevices with 3D architecture and different building blocks.

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