ABSTRACT

The primary objective of the present work is to understand the effect of bimodal microstructure on multi-scale mechanical properties of multi walled carbon nanotube (MWCNT) reinforced aluminium (Al) nanocomposites synthesized via spark plasma sintering (SPS). Prior to the synthesis of bimodal Al-CNT nanocomposites, the starting materials viz. microcrystalline Al powder and as-received MWCNTs were processed and several key parameters viz. ball milling and SPS parameters and CNT content were optimized. Microcrystalline Al powder was ball milled to achieve nanocrystalline grained Al powder with flake morphology. Flaky morphology of Al powder offered large surface area which aided CNT dispersion and also enhanced the sinterability. The CNTs were dispersed by utilising a novel dispersion technique, physio-chemical functionalisation, which although caused slight fragmentation but considerably improved their dispersion. The aspect ratio of pristine CNT was ~59, which reduced to ~46 post functionalisation.

While optimising the sintering parameters, it was observed that an increase in sintering temperature led to an increase in crystallite size and density; whereas an increase in heating rate exerted the opposite effect. Anomalous behaviour was observed as far as the effect of sintering pressure on crystallite size and density is concerned. Both, crystallite size and density, increased with increase in the sintering pressure. Mechanical properties of the sintered Al-CNT nanocomposites were governed by the collective effect resulting from the variation in crystallite size, density and interparticle bonding. The mechanical properties enhanced substantially with the increase in sintering temperature and pressure, whereas the heating rate did not exert significant impact on the mechanical properties. Increase in sintering temperature from 400 °C to 600 °C led to a 19% increase in microhardness and a decrease in heating rate from 100 °C/min to 25 °C/min caused a marginal improvement of 4% in the microhardness.

The optimum CNT loading was experimentally determined prior to the synthesis of bimodal Al-CNT nanocomposites. The addition of CNT (0.5 and 1.0 wt%) in Al matrix resulted in grain growth restriction. While sintering, the punch displacement and corresponding punch displacement rate with respect to the sintering temperature was recorded, which showed that the addition of CNT led to increase in the temperature at which the sintering commenced, delay in the temperature at which maximum displacement rate was achieved, decrease in the maximum punch displacement rate and magnitude of total punch displacement. These changes in the sintering indicators clearly indicated that the addition of CNT hindered the densification process. However, the reduction in density was marginal as milled Al powder compact exhibited a relative density of 98.9%, which reduced to 98.2% for Al-0.5 wt% CNT composite. Consequently, Al-0.5 wt% CNT nanocomposite exhibited the best mechanical properties among the sintered specimens. The yield strength of Al-0.5 wt% CNT was 136 MPa, which was about 91% of the theoretically predicted value. The sample, however, exhibited poor ductility (4.7% failure elongation). Increasing the CNT content to 1.0 wt% resulted in drastic deterioration in the mechanical properties due to excessive CNT agglomeration.

To achieve high strength along with fairly high ductility, nanocomposites with bimodal grain distribution were synthesized. Bimodal nanocomposites comprised of nanocrystalline and microcrystalline Al powders (10, 20, 30, 40 and 50 wt%) reinforced with 0.5 wt% CNT. Al-CNT nanocomposite containing 30 wt% microcrystalline grained Al powder (Al_{30M70N}-CNT) displayed the best combination of strength (127 MPa, UTS:187 MPa) and ductility (10.8%), exhibiting 149% higher yield strength and 78% higher tensile strength than the microcrystalline grained Al compact and 130% higher elongation than the milled Al-CNT nanocomposite. It was found that the yield strength of Al_{30M70N}-CNT was about 94% closer to the theoretically predicted value confirming the effective translation of different strengthening mechanisms towards the strength of the nanocomposite. However, for nano and micro-scale mechanical properties, the bimodal compacts showed huge variations in the mechanical properties. While calculating elastic modulus and microhardness, Al-CNT nanocomposite with microcrystalline matrix (Al_{100M}-CNT) exhibited a standard deviation of 4.6% and 5.5%, respectively, whereas Al_{30M70N}-CNT showed a standard deviation of 5.5% and 14.4%, respectively.

Keywords: Aluminium matrix nanocomposite; Multi walled carbon nanotube; Functionalization; Spark plasma sintering; Densification behaviour; Bimodal microstructure; Mechanical properties; Strengthening mechanisms