MICROSTRUCTURE AND MECHANICAL PROPERTIES OF MONOLITHIC ALUMINIUM-CNT (Al-CNT) AND GRADED ALUMINIUM-B_4C-CNT (Al-B_4C-CNT) COMPOSITES FABRICATED BY A MELTING-CASTING ROUTE

Abstract

This work investigates the development and characterization of monolithic AA6061-based composites reinforced with carbon nanotubes (CNTs) and functionally graded hybrid AA6061-boron carbide (B_4C)-CNT composite using melting casting techniques.

Three dispersion strategies—direct CNT drop (DD), Al–CNT pellet drop (PD), and ultrasonicated CNT drop (USDD) were employed to fabricate monolithic AA6061-0.5 wt. % CNT composites via combined stir-casting and squeeze-casting, with the addition of Al–20Mg master alloy to enhance CNT wettability. Among these, the PD route achieved the highest CNT retention and uniform distribution, confirmed by TEM. XRD analysis revealed the formation of Mg_2Si precipitates. The PD composite exhibited the best mechanical performance, with ultimate tensile strength and yield strength improvements of ~40% and ~33%, respectively, over as-cast AA6061, without significant loss of ductility. The enhanced strength was attributed to grain refinement, increased dislocation density, and strong CNT–matrix interfacial bonding, as evidenced by CNT bridging and rupture on fracture surfaces. Further, serrated stress-strain behaviour of the PD sample was evaluated through tensile tests along with digital image correlation (DIC) at three different strain rates (6.6×10^{-5}, 6.6×10^{-4}, and 6.6×10^{-3} s^{-1}, respectively), revealing that the intensity of serrated flow diminished progressively with increasing strain rate. A clear transition was observed from mixed Type A + B serrations toward Type A dominance as strain rate increased.

The wear performance of AA6061–0.5 wt.% CNT composites was systematically evaluated against a steel counter body. All composites exhibited a lower coefficient of friction (COF) and specific wear rate (SWR) compared to unreinforced AA6061, with the pellet-drop (PD) composite showing the best results. Under ambient conditions, the PD sample achieved reductions of 68 % in COF and 77 % in SWR relative to as-cast AA6061. Load-dependent tests revealed that COF increased from 0.19 to 0.41 when the load increased from 5 N to 10 N, but decreased to 0.34 at 15 N, while SWR remained lower at 15N loads compared to 10 N (8.03×10^{-4} and 7.9×10^{-4} mm^3/Nm for 10 N and 15 N, respectively). At 150 °C, the PD composite maintained significantly lower COF (by 72.94 %, 14.47 %, and 16.94 % at 5 N, 10 N, and 15

N, respectively) and SWR (reduced by 78.51 %, 35.71 %, and 42.85 %, respectively) than the as-cast alloy. SEM and Raman analysis indicated CNT structural degradation (crushing, bonding with the wear track) while cross-sectional analysis confirmed tribolayer formation. X-ray photoelectron spectroscopy (XPS) confirmed Al_2O_3-based oxide layers at the surface of the wear tracks. Post-wear hardness of PD samples increased up to 8-fold over AA6061, attributed to oxide formation, tribolayer stability, and CNT dispersion, which collectively enhanced wear resistance and reduced material loss.

The effect of artificial aging on PD composites was further investigated to exploit the synergy between strengthening due to CNT and precipitation hardening. Compared to unreinforced AA6061, the composites exhibited a markedly accelerated age-hardening response, attaining higher peak hardness at a shorter time (~135 HV within 2 h for the composites compared to ~112 HV in 8 h for the alloy). TEM analysis revealed dense β″ precipitates in CNT-free regions and Mg_2Si phases preferentially nucleated near CNTs due to local strain fields. Peak-aged composites (2 h) achieved the highest strength (UTS ~ 338 MPa), while over-aging led to precipitate coarsening and reduced ductility. The CNTs were found to modify precipitation pathways, enhance solute diffusion, and suppress the Portevin-Le Chatelier effect with aging.

A functionally graded hybrid Al–B_4C–CNT composite (FGCM) cylinder was further developed via combined stir-casting and centrifugal casting. Due to density differences, a ~1 mm B_4C-rich outer layer and CNT-enriched inner regions were obtained. Electron backscattered diffraction (EBSD) analysis revealed grain refinement and increased local strain in reinforcement-rich zones, while Raman spectroscopy confirmed CNT gradients, and TEM analysis verified the formation of an Al_4C_3 interfacial bonding layer. The FGCM displayed a hardness gradient, peaking at 520 ± 30 $HV_{0.5}$ in the outer B_4C-rich layer. The hardness of the inner-middle region was higher than the middle region due to the presence of CNTs. Mechanical and wear tests across five radial zones showed that the middle–inner region achieved the best property balance (flexural strength ~350 MPa, strain ~11%, COF = 0.23), demonstrating the potential of hybrid reinforcement gradients to simultaneously strengthen both inner and outer surfaces, overcoming the typical inner-surface property deficit in conventional FGCMs.

Keywords: Aluminium-Carbon nanotubes (CNTs) bulk composites, Stir casting, squeeze casting, centrifugal casting, Serrated flow, Mg_2Si precipitates, Functionally graded composite material (FGCM)