ABSTRACT

Industries are in continuous need of high-performance structural materials that provide greater strength at elevated temperatures and enhanced durability. Functionally Graded Composites (FGCs) are a unique type of Metal Matrix Composite (MMC) that has a gradient microstructure to offer enhanced properties across the thickness of the component. These composites are recently being used as automotive components such as transmission gears, cylinder liners, pistons, brake discs and pulleys. Further, the speciality of these FGCs is that property requirements can be incorporated into the matrix by careful selection and dispersion of appropriate reinforcements.

Owing to their low density, aluminium-based FGC components including high thermal resistance and enhanced toughness are now being commercially manufactured. One of the promising techniques for synthesizing cylindrical shaped FGCs is centrifugal casting, where the composite melt is subjected to centrifugal force, which dictates the movement of reinforcements across their radial cross-section during solidification. The hard reinforcements can be either added externally into the melt or created inside the melt by chemical reaction between the elements present during the manufacture of FGCs. The former is generally called the *ex-situ* technique and in centrifugal casting it is named as Centrifugal Solid-Particle Method (CSPM), whereas the latter is called the *in-situ* technique, which in centrifugal casting is termed as Centrifugal *In-Situ* Method (CISM).

Main emphasis of this investigation is to produce aluminium-based *in-situ* reinforced functionally graded composites using A413 (Al-Si eutectic) alloy and Al-26wt.%Ni master alloy using Horizontal Centrifugal Casting (HCC) technique by following CISM. Al-Ni master alloy was added

to A413 alloy melt in calculated quantities to prepare composite melts for fabricating three types of FGC cylinders designated as FGC1, FGC2 and FGC3 comprising 3, 6 and 9wt.% of Ni respectively. In addition, A413 alloy cylinder was also fabricated for comparison purposes. Casting parameters used in HCC were 1900 rpm of mould rotational speed and 820°C of pouring temperature. Microstructural features, mechanical properties including hardness, tensile properties and impact strength as well as tribological behaviour were studied extensively in three different regions namely outer (0-5 mm), middle (5-10 mm) and inner (10-15 mm) regions using samples taken across the radial thickness (15 mm) of both A413 alloy and FGC cylinders.

XRD results confirmed the presence of three phases namely α-Al, Si and *in-situ* Al_3Ni in the samples of all three FGC cylinders. Optical micrographs of FGC samples showed α-Al (white colour), primary Si cuboids (grey colour), eutectic Si needles (grey colour), primary Al_3Ni blocky particles (black colour) and eutectic Al_3Ni needles/flakes (black colour). Concentration of these primary Al_3Ni particles was found to be higher in the outer region, which decreased towards the inner region. While, concentration of primary Si particles was significantly high in the inner region and reduced towards the outer region of the FGC cylinders. As a result, a gradient microstructure was obtained across the radial cross-section and the gradation level increased with more stable *in-situ* Al_3Ni particles being precipitated.

A steep microstructural gradation was achieved in FGC3 cylinder with the segregation of more primary Al_3Ni particles in its outer region and more amount of primary Si particles in the inner region. Particulate segregation along the radial thickness of FGC cylinders can be attributed to the differences in density with the α-Al matrix. The density of

Al_3Ni intermetallic is 4.0 g/cc, which is higher than that of Al matrix (2.37 g/cc). Hence, Al_3Ni particles were more concentrated in the outer region of FGC cylinders. On the other hand, primary Si particles have a lower density as 2.33 g/cc than the Al matrix and were therefore more concentrated in the inner region of the same cylinder.

Quantitative microstructural evaluation has shown that these *in-situ* Al_3Ni intermetallic particles make a significant contribution to the formation of gradient microstructure in FGCs than primary Si particles. Brinell hardness evaluation indicated a higher hardness in the outer region, which decreased towards the inner region for all the FGCs. Highest hardness was obtained in FGC3 cylinder and the hardness variation along the radial cross-section between the outer and inner regions was 25%, which confirmed the presence of a steep microstructural gradation.

Tensile properties of the FGC cylinders were enhanced mainly due to precipitation of *in-situ* Al_3Ni intermetallic and its matrix-strengthening effect. Among the three regions, the outer region specimen displayed higher Ultimate Tensile Strength (UTS) and it was gradually decreased towards the inner region. Between all three FGCs, FGC3 cylinder with the highest volume fraction of primary Al_3Ni particles had a maximum tensile strength of 203.9 MPa in its outer region compared to the other two regions. SEM micrographs of the tensile test specimens revealed a highly ductile fracture with a significant amount of brittle cleavages for A413 alloy cylinder and a mixed ductile-brittle fracture mode for FGC cylinders.

Precipitation of extremely hard Al_3Ni intermetallic due to the addition of Ni had an adverse effect on the impact strength measured in all the three region specimens across the radial thickness of FGC cylinders. Among the three regions, the outer region specimen showed a low impact strength and increased significantly towards the inner region in all three FGC cylinders. Fractography of the A413 alloy cylinder exhibited both brittle cleavages and elongated dimples of Si phase, hence a mixed mode (ductile-brittle) of fracture has been suggested. While SEM micrographs of the impact test specimens of FGCs showed mainly the features of brittle fracture mode.

Wear rate of all the three FGCs has shown a continuous increase towards the inner region, consistent with their measured hardness values. Further, the observed wear resistance for all FGC cylinders was directly related to the population of *in-situ* Al_3Ni intermetallic across the radial thickness. SEM micrographs of worn surfaces revealed mainly plastic deformation and delamination for the A413 alloy cylinder. FGC cylinders displayed a consistent evolution on worn surfaces with less surface damage and the abrasive wear mechanism was identified as dominant.

EDM drilling characteristics of FGC3 cylinder was investigated using Taguchi method combined with Grey Relational Analysis (GRA). Grey theory multi-response optimization resulted in a gain of 7.25% in MRR, a decrease of 11.33% in TWR and a reduction of 7.59% in SR. Further, the middle region of FGC3 cylinder showed better machining characteristics then the other two regions. SEM micrograph of drilled sample taken from the middle region (28 vol.% of Al_3Ni particles) revealed small craters and few microvoids resulting in better surface finish.