ABSTRACT

Conventional monolithic alloys fall short to meet the ever increasing demand to enhance product capabilities. Ceramic particulate reinforced metal matrix composites (MMCs) have gained the attention of the present era. MMCs exhibit superior properties over conventional monolithic alloys such as high wear resistance, low thermal expansion, high strength-weight ratio etc. MMCs find application in aircraft structures, space shuttles, military and shipbuilding. MMCs research has to go a long way to attain maturity for its application to all fields of engineering. Intensive research is required to fabricate MMCs economically. SiC and Al₂O₃ were predominantly used as reinforcements in the early decades of MMCs development. This trend has shifted over the last decade and different reinforcements such as fly ash, SiO₂, TiO₂, AlN, Si₃N₄, TiC, B₄C, TiB₂ and ZrB₂ are tried in the fabrication of MMCs. However, the mechanical, wear and corrosion behavior of those new MMCs have not been explored adequately. Researchers find it difficult to predict the behavior of those MMCs than that of monolithic alloys.

Inadequate development of secondary processes such as cutting, forming, machining and joining of MMCs limits its applications. The presence of ceramic particles reduces the weldability of MMCs. Attempts to join MMCs using established fusion welding processes resulted in porosity, coarse microstructure, segregation and decomposition of ceramic particles and formation of brittle intermetallic compounds. The high temperature attained in fusion welding increases the tendency of ceramic particles to react with aluminum matrix. Achieving homogeneous distribution of ceramic particles in the weld zone was found to be difficult. Friction stir welding (FSW), the relatively new welding technology is a promising candidate to join MMCs which eliminates those defects.
The above considerations formed the background of the present investigation in which AA6061 reinforced with ZrB2 MMC was fabricated and joined using FSW.

AA6061/ZrB2 MMC was successfully fabricated using the in-situ method. The inorganic salts K$_2$ZrF$_6$ and KBF$_4$ reacted with molten aluminum at 850°C and formed ZrB$_2$ inside the melt itself. MMC castings were obtained with different content of ZrB$_2$ (0, 2.5, 5, 7.5 and 10 wt.%). The maximum content was limited to 10 wt.% due to excessive formation of slag. The fabricated MMC was characterized using optical and scanning electron microscopy and XRD. The XRD patterns clearly indicated the presence of ZrB$_2$ particles without the formation of intermediate phases. The in-situ formed ZrB$_2$ particles were characterized with uniform distribution, spherical in shape, good bonding and clear interface. The mechanical properties such as hardness and ultimate tensile strength of AA6061/ZrB$_2$ MMC increased with increased content of ZrB$_2$ particles. However, the corrosion resistance of AA6061/ZrB$_2$ MMC was reduced.

The dry sliding wear behavior of AA6061/ZrB$_2$ MMC was evaluated using pin-on-disc wear apparatus. The wear experiments were conducted as per central composite design (CCD). A mathematical model was developed to predict the wear rate of the composite and was validated by conducting conformity experiments. The influence of wear parameters such as sliding velocity, sliding distance and normal load on wear rate and content of ZrB$_2$ particles was analyzed using the developed mathematical model. ZrB$_2$ particles enhanced the wear resistance of the MMC. The dry sliding wear behavior of AA6061/ZrB$_2$ MMC was observed to be non-linear. The other wear parameters sliding velocity, sliding distance and normal load bore proportional relationship with wear rate. The worn surfaces revealed an increase in number of cracks when sliding velocity, sliding distance and normal load increased. The worn surface of AA6061/ZrB$_2$ MMC showed that the wear mode was abrasive.
Plates of 6 mm thickness were prepared from the castings to carry out FSW using an indigenously developed FSW machine. The FSW experiments were conducted as per CCD. The tensile and dry sliding wear behaviors of the welded joints were measured. Mathematical models were developed to predict the tensile and dry sliding wear behaviors of the butt welded composite and were validated by conducting conformity experiments. The FSW window for obtaining sound weldment was observed to be narrow. The presence of ceramic particles reduced the ductility of the matrix alloy and affected the material flow during FSW. The effect of FSW parameters such as tool rotational speed, welding speed, axial force and content of ZrB₂ particles on tensile and dry sliding wear behaviors were analyzed using the developed mathematical models. Each process parameter significantly and independently influenced the joint behavior. A low or high range of parameters developed several defects in the joint which reduced the joint properties.

The mathematical models were optimized using generalized reduced gradient method (GRG). Seven set of constraints were used for optimization. One set of optimized weld was subjected to post weld heat treatment (PWHT) and observed an increase in hardness and tensile strength.

Extensive metallurgical characterization of FS welded AA6061/ZrB₂ MMC joints were carried out. FS welded AA6061/ZrB₂ MMC joints exhibited the presence of different zones such as weld zone (WZ), thermo mechanically affected zone (TMAZ) and heat affected zone (HAZ). The microstructure of the parent composite and HAZ were similar except in FS welded matrix alloy where the dendrite structure is modified by frictional heat. The transition zone was limited to TMAZ due to low thermal variations of the composite. The weld zone exhibited a homogenous distribution of ZrB₂ particles irrespective of its content. The number of particles in the weld zone was observed to be more than that of the parent composite. The stirring action of the tool resulted in fragmentation of ZrB₂ particles during FSW.
The microhardness survey across FS welded AA6061/ZrB₂ MMC joints indicated that the weld zone hardened subsequent to FSW due to particle fragmentation. The fracture surfaces confirmed the reduced ductility of the joints. The worn surfaces revealed a change in wear mode from adhesive to abrasive with increased content of ZrB₂ particles.

The present research work concludes that AA6061/ZrB₂ MMC with particulate content up to 10 wt.% could be manufactured through the in-situ reactive processing route and sound joints of AA6061/ZrB₂ MMC could be fabricated using FSW technique by appropriately controlling the process parameters.