CHAPTER – 7

SUMMARY OF WORK AND SUGGESTIONS FOR FUTURE WORK

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7. 1 Summary of the present work

7.1.1 EN AW6082 metal matrix composites reinforced with garnet particles

The high energy ball milling method used for the preparation of composite powders with hard particle reinforcement namely industrial by-product, garnet resulted in refined microstructure and randomly oriented interfacial grain boundaries. It is evident from the XRD results that no phase transformation was observed during milling of unreinforced EN AW6082, EN AW6082/Garnet, and Al/Garnet composite blends. However, α-Al peaks evidenced a shift in their original position. Intense effect was observed in unreinforced EN AW6082 alloy due to formation of supersaturated solid solution, contrary to other composite mixture where the peak shift is minimal due to presence of hard dispersoids. Crystallite size of the aluminum alloy in the composite powder was smaller than that of the unreinforced alloy for same milling time and minimum grain size refinement up to 36 nm was achieved for EN AW6082/Garnet after 50 h of milling. Of the various composites investigated, EN AW6082/Garnet was found to be most effective in terms of microstructural refinement and improved mechanical properties. The contributing effects to strengthening mechanism in these composites was investigated and found that the strengthening model prediction involving Orowan effects was found to be in agreement with the experimental data for both aluminum and aluminum alloy composites.

7.1.2 EN AW6082 metal matrix composites reinforced with garnet multiwalled carbon nanotubes

EN AW6082 Al-alloy was successfully reinforced by the dispersion of 2 wt.% MWCNTs through high-energy ball milling and the composite powders resulted in drastic crystallite size refinement from 165 nm to about 28 nm after 50 h of milling due to the impediment of the movement of the dislocation by Orowan strengthening and embedment of CNT at grain boundaries. Morphological studies showed that the CNTs were shortened to a greater extent and got homogenously dispersed and embedded in the soft Al-alloy matrix. The presence of nanoscale CNTs in Al-alloy matrix was evidenced in transmission electron micrographs.

The nanoscale CNTs used as reinforcement has led to a two fold increase in hardness and modulus of EN AW6082 alloy. Both micro and nanohardness of the composites displayed significant increase for the composite reinforced with 2 wt.% MWCNT over the unreinforced EN AW6082 alloy produced by the same route and maximum hardness of about 436 ± 52 HV after 50 h of milling was obtained. Further comparative studies on EN AW6082 composites reinforced with garnet and multi-wall carbon nanotubes was made and found MWCNTs as a better reinforcing candidate for EN AW6082 compared to garnet. However, garnet being an industrial by-product shows enhanced properties than that of pure aluminum and unreinforced Al-alloy and hence can form a potential reinforcement for Al and Al-alloys.

7.1.3 Structural transition and softening in Al-Fe intermetallic compounds

Al-25 at.%Fe and Al-34.5 at.%Fe alloys, resulted in Al_3Fe and Al_2Fe intermetallic phases after normal casting and annealing routes, were milled at various times to understand their stability. The monoclinic Al_3Fe and triclinic Al_2Fe phases are found to be unstable under high-energy milling condition and transformed to orthorhombic Al_5Fe_2 phase. Upon further milling, structural transformation from crystalline to amorphous phase was observed in both the compositions. Thermodynamic analysis shows that Al-25 at.%Fe and Al-34.5 at.% Fe has the highest ability to form amorphous phase. Mechanical property measured in microhardness for Al-25 at.%Fe alloy showed strengthening down to a grain size of 42 nm and Hall-Petch behavior is, thus, demonstrated over the range of grain sizes from 132 to 42 nm. Maximum hardness was achieved for 30 h of milling where both nanocrystalline and amorphous phase co-exist. For smaller grain sizes, the microhardness falls and indicates a softening behavior. Below 33 nm, slope of HP plot becomes negative. This critical grain size was not corroborated by the dislocation pile-up model and, thus, indicates that the softening is due to the major contributions from the amorphous phase formation. Transition from hardening to softening behavior upon milling was also observed for Al-34.5 at.%Fe alloy. The contributing factors for softening is ascribed to the competing effects of mechanisms such as grain boundary sliding, decrease in interfacial excess volume and amorphous phase formation.

7.1.4 Inverse Hall-Petch effect in nanocrystalline Al_5Fe_2 intermetallic

Al_5Fe_2 resulted from Al-30%Fe alloy lead to formation of nanocrystalline intermetallic and found quite stable under the present experimental conditions and crystallite size of it decreases up to 10 nm with an increase in milling time. Microhardness measurements of single Al_5Fe_2 nanocrystalline intermetallic phase produced by mechanical milling resulted in Hall–Petch (HP) break down and showed two distinct behaviors. The hardness of the milled powders increased with decreasing grain size down to about 32 nm and decreased with further refinement, demonstrating the IHP behavior. The observed critical grain size was found larger compared to nanocrystalline alloys.

Possible factors and deformation mechanism leading to softening behavior was investigated in detail. The break-down of HP observed for the averaged microhardness mearsurements was due the transition of deformation mechanism from dislocation activity to grain boundary sliding and/or grain boundary shearing. Mesoscopic grain boundary sliding and thermally activated grain boundary shearing is ascribed to be a viable deformation mechanism resulting in softening behavior observed in this system.

7.2 Suggestions for future work

- EN AW6082 composites could be developed with varying amount of garnet and MWCNTs as reinforcements in more intensive grinding media for different length of time to enhance mechanical properties further.
- Garnet and MWCNTs have shown very promising reinforcement in both pure Al and Al-alloy matrix. So possibility to improve the strength of the Al-based composite by using heat treatable alloy matrix such as Al-2024, Al-7075 and other Al-alloy series.

- Consolidation of the composite powders could be carried out using advanced techniques like high pressure torsion (HPT) and spark plasma sintering (SPS) method to achieve nearest to theoretical density (>95%) retaining nano-features in the bulk specimens, as increase in the density would improved mechanical properties.
- Systematic investigation of the mechanical properties of the composites is worth pursuing in order to understand the nature of the Hall-Petch relation and to establish the structure property correlations.
- Al-Fe intermetallic alloy systems such as Al_3Fe, Al_5Fe_2 and Al_2Fe can be investigated for their microstructural evolution and stability using other non-equilibrium process namely rapid solidification and after mechanical milling and rapid solidification processing.
- Studies are required to ascertain the relative contribution towards softening from the effect of nanocrystallinity as well as amorphous phase formation in case of composite microstructures achieved in intermetallics.
- Investigation on the mechanical properties of intermetallics in terms of deformation mechanism is significant to ascertain structure-property-performance correlations.
- Thermodynamic calculations are to be extended considering modified approach based on CALPHAD and THERMOCALC which involves phase diagram.
- Detailed HRTEM study has to be carried out to understand the relationship between microstructure and macroscopic properties in particular inverse Hall-Petch effect by investigating grain boundaries.