CHAPTER-5

MECHANICAL BEHAVIOR OF AS-CAST Al-MG_2Si FUNCTIONALLY GRADED COMPOSITES

5.1. Introduction

The present chapter describes the mechanical behavior of FG-composites in as-cast condition with varying wt.% of Mg. The mechanical properties have been evaluated in three zones – inner, middle and outer peripheral of the functionally graded composites. The measurement of Vickers hardness values along outer to inner zones of FG composites and zone-wise tensile properties at room and elevated temperatures are presented. The microstructural features are correlated with hardness variation profile and room and high temperature tensile properties at 25°, 150°C and 300°C. Since the populations of Mg_2Si particles are highest at the inner zones, the hardness and tensile strengths at these zones are maximum among the three zones. The mechanism of tensile fracture has been explained based on the features in the tensile fractographs.

5.2. Hardness profile across the cross-sections

The values of hardness along the radial directions of the composite FGM tubes fabricated are shown in Fig. 5.1. The hardness of the composites shows nearly the same trend; maxima at the inner zone, gradually decreasing and then increasing to some extent near the outer zone. On the other hand, the base alloy shows a little decrease in hardness near the inner surface then becomes steady and again increasing a bit near periphery. These trends could be explained as a combined effect of Mg_2Si volume fractions and the solidification time.

Although, inner zones are having coarser SDAS, which yields lower hardness, in the case of composites the inner zones have maximum hardness due to the high volume fraction of Mg_2Si particles. These are absent in base alloy inner zone. However, near the outer periphery the hardness of base alloy increases due to finer SDAS as a result of mold chilling effect. This result is in agreement with the earlier results obtained by Chirita et al. [124]. In the case of composites, as the surface chilling effect causes some entrapment of Mg_2Si particles plus the finer SDAS result in the hardness increase near the periphery. The tendency of entrapment of Mg_2Si particles near the outer zones are more intense with higher wt.% of Mg composites. A large number of primary Mg_2Si are formed initially just beside the surface of the tube. The majority of these particles are moved to the inner zone initially so long the zone is in a liquid state. When the zone becomes in a semi-solid viscous state, movement of primary particles are difficult by centrifugal force and Mg_2Si particles are entrapped.

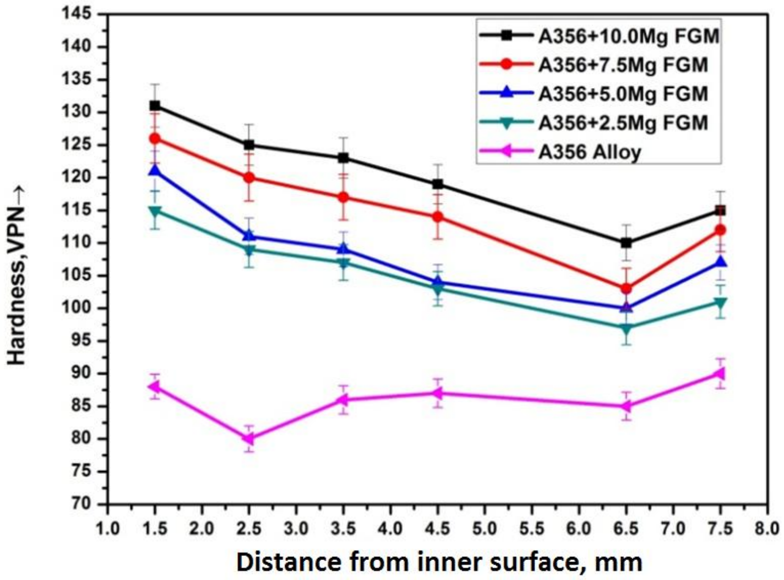

Fig. 5.1 Vickers hardness profile of A356 Alloy, A356+2.5Mg, A356+5.0 Mg , 356+7.5Mg and A356+10Mg FG-Composites

5.3. Effect of test temperatures on as-cast tensile properties

The engineering stress-strain diagrams of FG-composites obtained from the test data at room temperature (25°C), 150°C and 300°C are shown in Figs.5.2 to 5.6 respectively. The ultimate tensile strengths of different wt.% Mg FG composites at three zones are compiled and are shown in the Fig.5.7-5.8. It is evident that, at room temperature (25°C), composite with higher volume% of Mg_2Si exhibits an increased tensile strength at the inner zone. But irrespective of wt.% Mg the inner zones of all the composites are highly brittle. The ductility of the base alloy as well as the composites, are considerably low ranging from 3% to 6%; as expected higher ductilities are mostly obtained at higher the test temperatures.

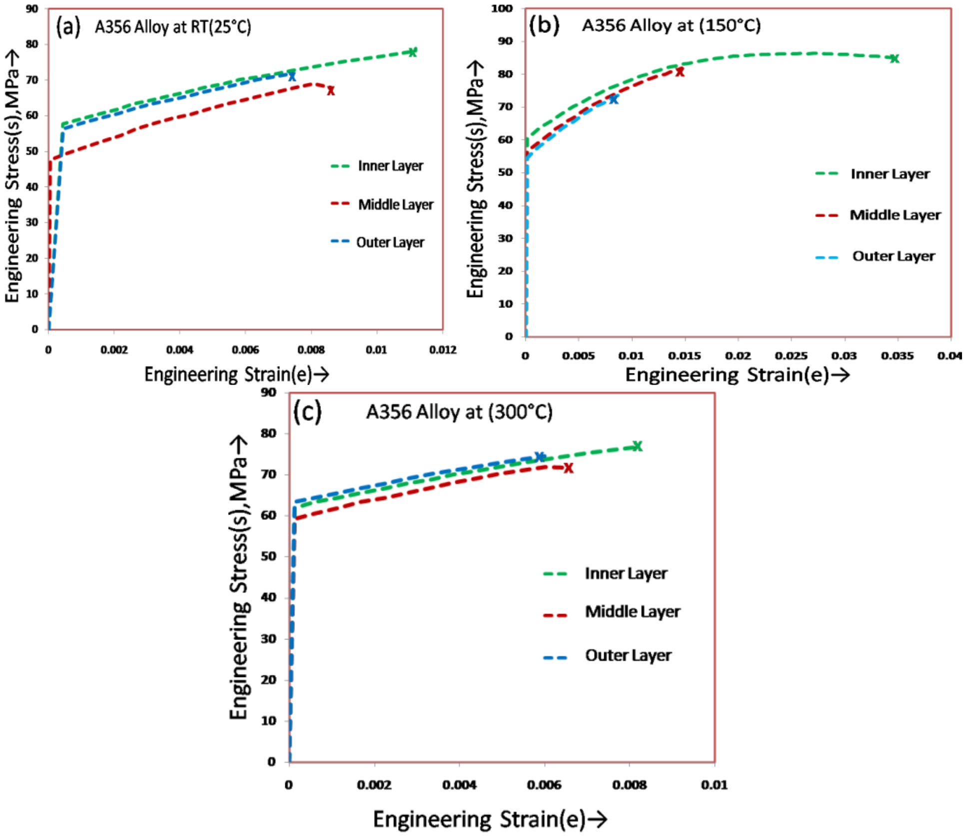

Fig.5.2 Stress-strain diagrams for different zones at; (a) RT (25°C), (b) 150°C and (c) 300°C of A356 base alloy

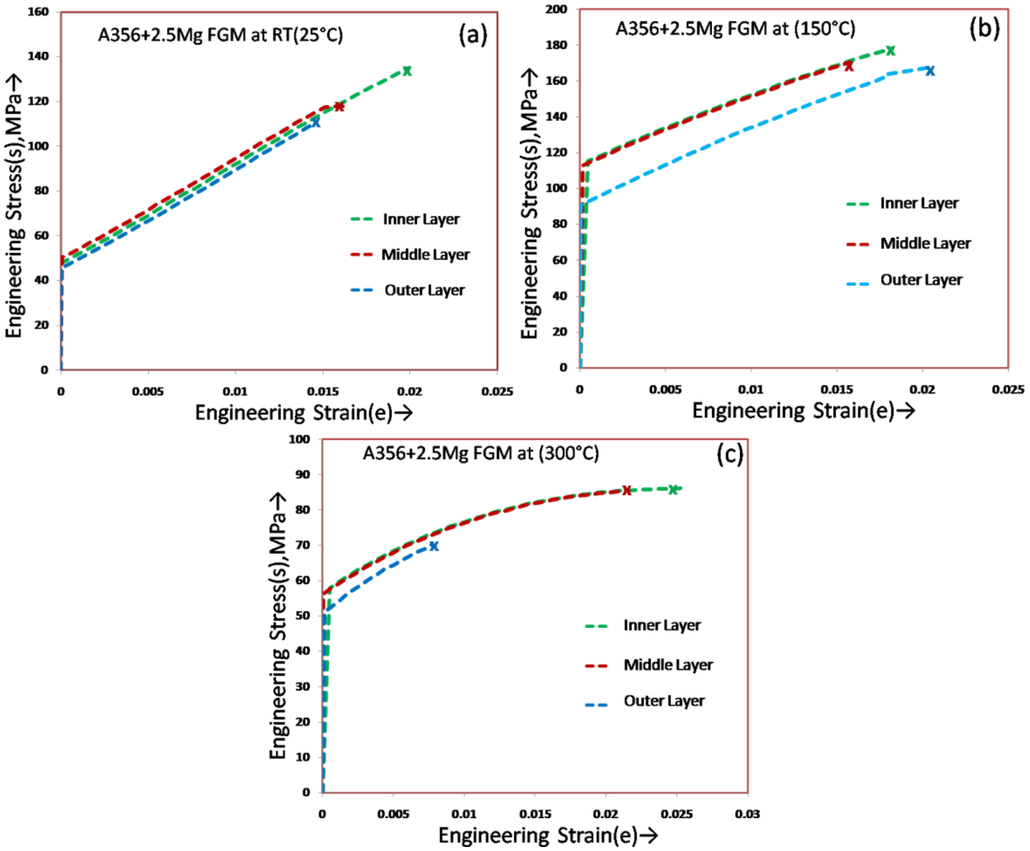

Fig.5.3 Stress-strain diagrams for different zones at; (a) RT (25°C), (b) 150°C and (c) 300°C of A356-2.5%Mg FG-composite

This is the consequence of inhibition of plastic flow of the matrix by the hard reinforcing particles. All three zones of the cross-sections of the composites show a common trend of attaining a peak UTS at about 150°C and then decreases with further increase in test temperature. This is because of the hard particles easily crack under the tensile load with increasing test temperature. Besides, with increasing testing temperature, the dynamic recovery of reinforcement free matrix becomes dominant in the process of tensile deformation, which results in decreasing the stress levels of UTS and YS. When the test temperature exceeds 150°C, the Al-matrix becomes soft and as such the strength of the matrix is too low to inhibit the strengthening effect of Mg_2Si particles. In contrast, at 150°C, slight softening of the matrix is able to accommodate the reinforcing Mg_2Si

particles effectively. As a consequence, the loads acted on reinforcements and the matrix is uniform. Beside this, incipient matrix precipitation at the test temperature of 150^0C can account for the enhanced tensile strength. A356 alloy shows some degree of precipitation strengthening specifically if Cu is present in the cast alloy. With increasing test temperature due to facilitated dislocation movement, the UTS are decreasing [125]. The yield strengths (0.2% offset method) are calculated for base alloy and FG-composites (three for each temperature, 25°C, 150°C and 300°C). The yield strength and ultimate strength of centrifugally as-cast base alloy remains relatively constant between room-temperature to 300°C as shown in Fig.5.11. Moreover, at outer zone of centrifugally cast base alloy, the ultimate strength was slightly increased due to chilling effects of mold wall. In contrast, the yield strength and ultimate strength of fabricated FG-composites are increases from room temperature to 150°C; the ultimate strength of FG-composites consistently increases at inner zones at 150°C and significantly decreases beyond 150°C of alloy and composites.

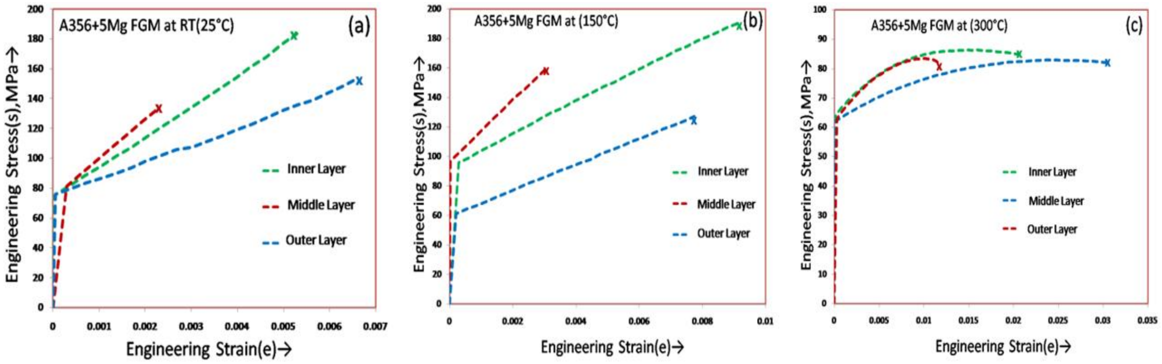

Fig.5.4 Stress-strain diagrams for different zones at; (a) RT (25°C), (b) 150°C and (c) 300°C of A356-5%Mg FG-composite

While increases the test temperature above 150°C, yield strength linearly decreases above until reaching a minimum. Although, the pure A356 commercial alloys has UTS value around 77MPa and YS 64MPa respectively. Thus the strength of centrifugally cast components is gradually enhanced due to introducing the hard Mg_2Si reinforcements.

The movement of dislocations through a lattice is supported by thermal vibrations. Consequently, resistance to dislocation slip increases as the temperature falls. As the temperature increases, the potential for dislocation climb and dislocation slip increases. The strain hardening exponent is another parameter characterizing plastic deformation of material. The values of strain hardening exponent n have been determined from the equation $\sigma=K(\varepsilon_p)^n$ where σ is the true stress and ε is the corresponding true plastic strain and K is strain hardening coefficient (Fig.5.9).

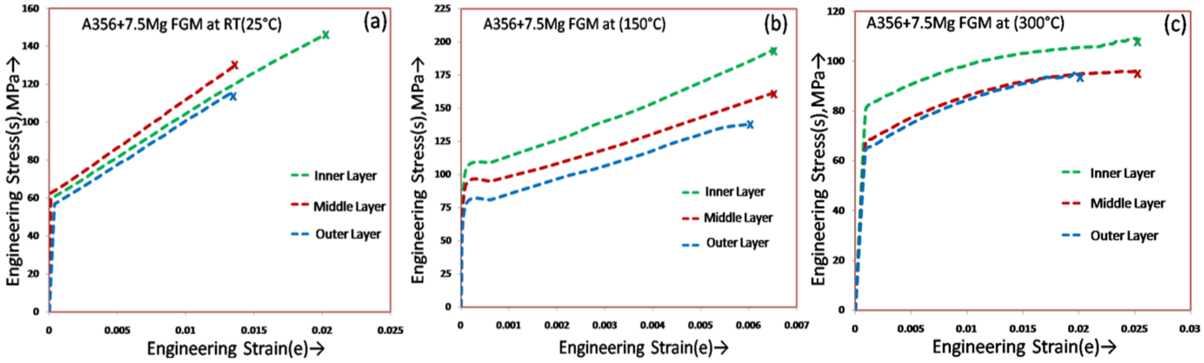

Fig.5.5 Stress-strain diagrams for different zones at; (a) RT (25°C), (b) 150°C and (c) 300°C of A356-7.5%Mg FG-composite.

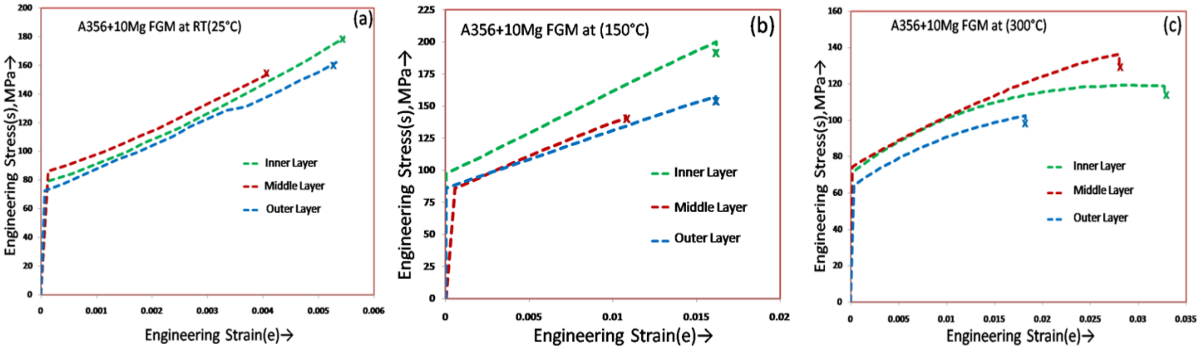

Fig.5.6 Stress-strain diagrams for different zones at; (a) RT (25°C), (b) 150°C and (c) 300°C of A356-10%Mg FG-composite

As the test temperature increases the strain hardening exponent value should decrease since with increasing test temperature, the movement of dislocations increases causing annihilation and reduce their accumulation/pile up at grain boundaries. The rate of work hardening reduces, and thermal softening of materials enhances which results in the decrease of the n values [126]. The decreasing strain hardening rate with increasing temperature is due to particle cracking as the material is deformed. At lower temperatures, strain hardening severely limits the amount of strain that will be generated at a constant stress. However, in the present study some deviations are observed perhaps due to the presence of casting porosity and the variable Fe content in the base metal. The contribution from the cracking of intermetallic is not consistent (Fig. 5.9).

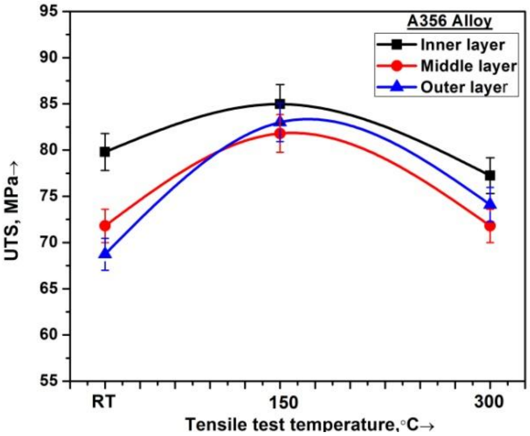

Fig. 5.7 UTS graphs for base alloy (A356) at inner zone, middle zone and outer zone at different temperature

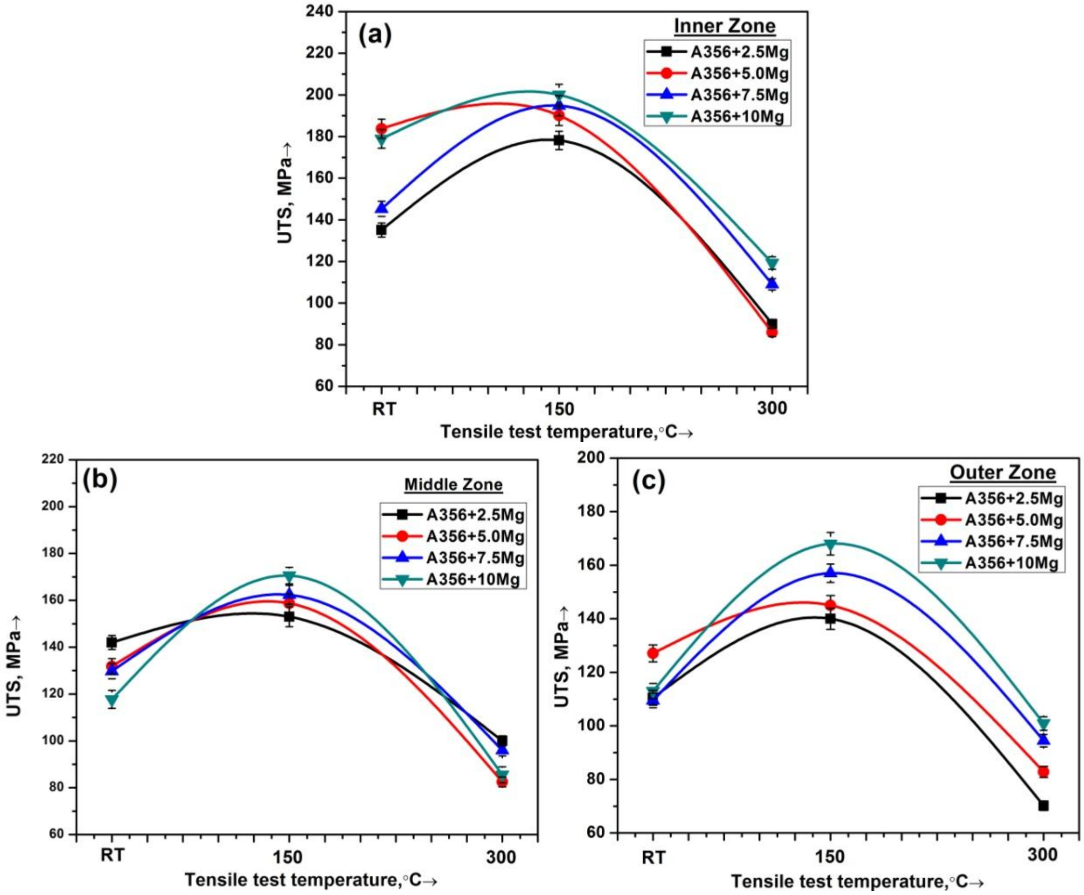

Fig. 5.8 Tensile properties in different zones along the radial direction of the FGM composites with varying Mg content

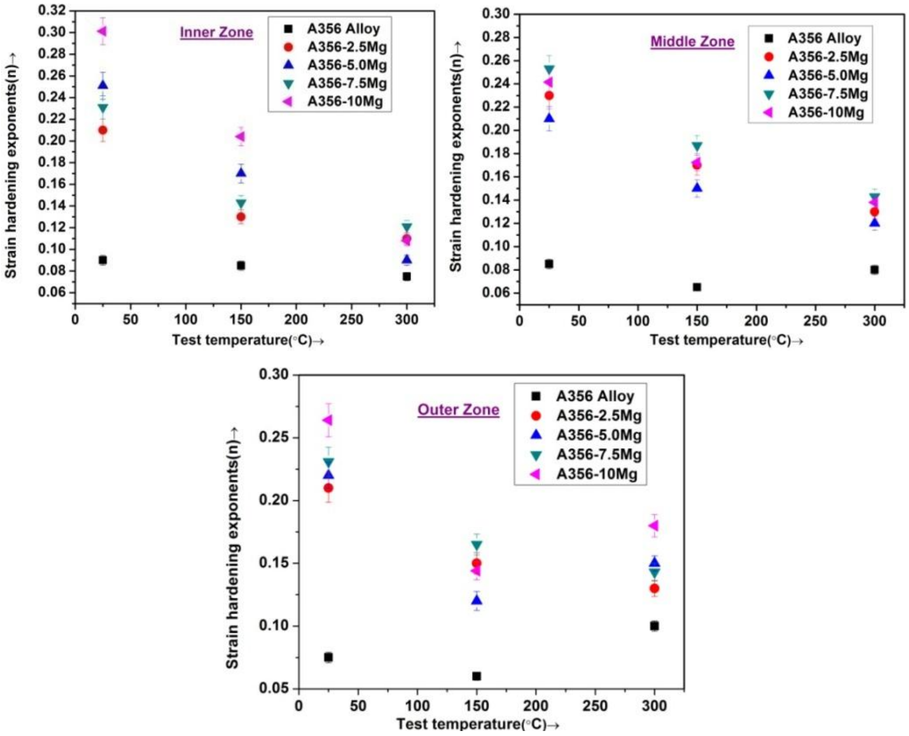

Fig. 5.9 Strain hardening exponents (n) of various zones of A356 and composite FGMs at different test temperatures.

The tensile ductility of FG composites in the outer zone are observed to be reduced with increase in wt.% Mg in the composites (Fig. 5.10). This can be attributed to a higher volume fraction of primary Mg_2Si and specifically β-Fe intermetallics in the higher Mg-content composites. A large fraction of damaged intermetallic particles favors failure. Microcracks originating from intermetallic particles propagate through the α-Al matrix and eutectic Si and subsequently combine to generate the main crack. Increase in the tensile test temperature influences the failure process in two ways: i) the softened α-Al dendrites reduce the matrix instability between the fractured particles and ii) the stress induced in particles during matrix deformation is intensified. This results in an increased fraction of damaged particles [127]. The fracture strain is determined by the balance between these two factors. In general, the tensile ductility values were observed to be lower at the temperature of around 150°C than those at room temperature and increased with further increase in temperature to 300°C. The matrix instability appears to be less pronounced at 150°C while the number of cracked particles was already increased. As a consequence, the plasticity was reduced a little bit. This trend was not observed in the middle transition zone, as the microstructures are not homogeneous; it is partly with higher segregation of Mg$_2$Si and partly almost precipitates free (Fig.5.10). Inconsistency in the ductility values observed is also probably due to presence of porosity which was not quantitatively assessed. Incipient matrix precipitation near 150^{0}C test temperature might be another probable cause for lowering of ductility.

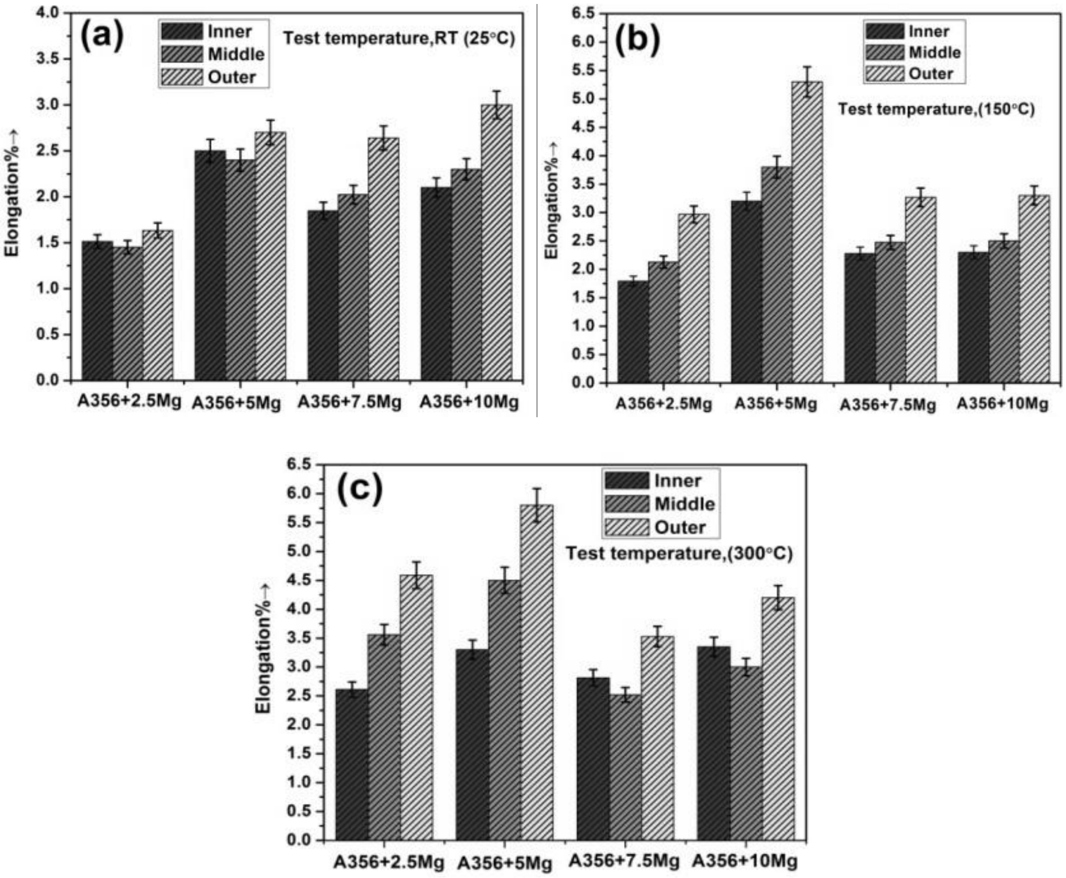

Fig.5.10 Tensile ductility (elongation %) of different zones at various test temperatures.

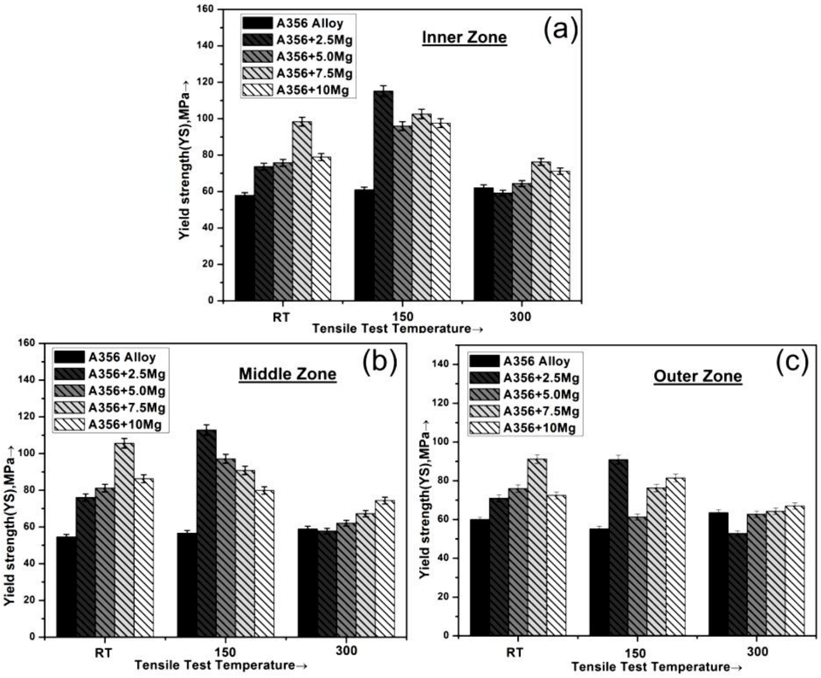

Fig.5.11 Yield strength of base alloy and FG-composites at (a)inner,(b)middle zone and (c) outer zones at 25°C,150°C and 300°C respectively.

5.4. Tensile fracture characteristics

The fractographs shown in the Fig. 5.12 indicate that the fracture characteristics are changing from mixed mode to ductile mode with increase the test temperature from room temperature (25°C) to 300°C. The fracture surface corresponding to room temperature test exhibits considerable portion of cleavage type of fractures. Cracking of some eutectic silicon is prominent which have been subsequently de bonded from the matrix. Although porosities are least probable in centrifugally cast materials because of fast solidification time, some porosities are observed in fracture surfaces surrounded by dendrites of α-Al and blades of Fe-intermetallic (Fig.5.12a).

In the inner zones of the FG-composites populated with a huge amount of reinforcements, the phenomenon of interface debonding and nucleation of voids at higher test temperature can be identified in Fig. 5.12. At lower test temperatures, the particle/

matrix interface is strong enough, and the stress can be transferred from the matrix to the reinforcing particles. Besides this, the strength of Mg2Si and intermetallics is usually controlled by flaws, and the probability of a strength-limiting flaw present increases with material volume. The particle cracking features depend on the localized condition including particle size, particle shape, particle orientation, activation of dislocation source, etc.

With increasing test temperature, the strength of the particle/matrix interface decreases with simultaneous softening of the Al matrix. Thus, it is easier to accommodate the reinforcing particles. Cracks are initiated at the matrix interface and propagate along the interface. Different modulus and thermal expansion of the reinforcing particles and the matrix and simultaneous softening of the Al-matrix are also supposed to be responsible for high temperature fracture characteristics. On increasing the testing temperature, the thermal expansion of the matrix and the particles generates a gradient which increased the interfacial stress leading to fracture and decohesion of the particles. In addition, under these conditions the brittle intermetallic particles were found to shatter into multiple pieces as a result of the increasing stress build-ups at the particle/matrix interfaces (Fig.5.13) in contrast with a single dominant cleavage crack observed at low temperatures. For samples tested at 300°C (Fig.5.13c), micro-voids with dimples and tear ridges increased while the secondary cracks are decreased. This is an indication of softness of the matrix and reduction of alloy strength.

The outer zones of the FG-composites are almost reinforcement free and are predominantly the matrix alloy A356. Plastic deformation in these zones results in the cracking of a significant fraction of eutectic Si particles and intermetallics. With increasing strain, the cracking of Si particles occurs gradually, and cracks in the particles become voids that grow and link forming larger cracks in the Al matrix. These microcracks eventually become unstable, causing ultimate failure. Microstructures containing small dendrite cells and Si particles develop damage at a low rate consequently requiring a large strain to reach the critical level of damage for fracture. In contrast, coarser microstructures with large cell sizes, large and elongated Si particles are prone to crack at low strains, lowering the ductility. When the porosity is present in the load bearing area is reduced. As a consequence, the defective region will yield first, concentrating the strain. As to the fracture of intermetallics, it is the stress field at the tip of a crack that breaks up the blocking intermetallic particles.

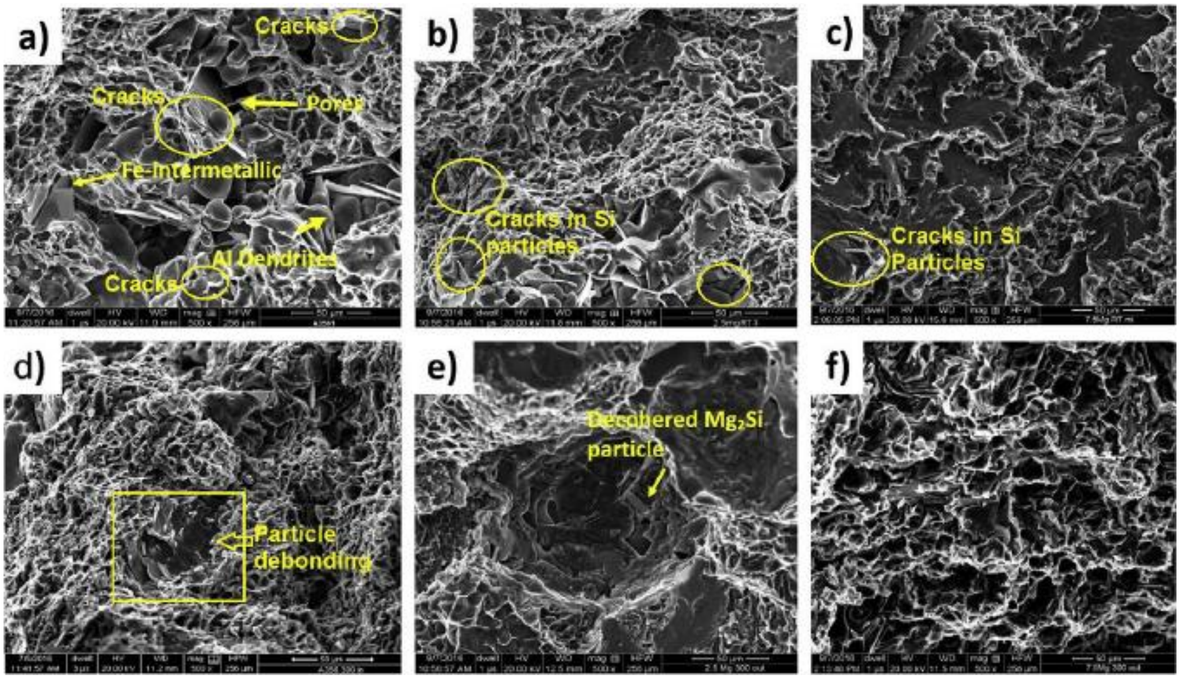

Fig.5.12. Fractographs of a) A356 alloy (inner zone), b) A356 +2.5%Mg (outer zone) and c) A356 + 7.5%Mg (middle zone) FGMs, respectively at room temperature and d) A356 alloy (inner zone), e) A356 +2.5%Mg (outer zone) and f) A356 +7.5%Mg (outer zone) respectively at 300 °C.

The fracture mechanism involved in outer zone matrix alloy at temperatures higher than 200°C is void nucleation and growth. The nucleation might be occurring at the coarse constituent particles or other second-phase present in the microstructure. The fracture initiates with nucleation of small discontinuities which is taken place on the interfaces between dispersed precipitates and the matrix. The mechanism of fracture in the middle transition zones of the FG-composites might be the combination of those involved in the failure of inner and outer zones.

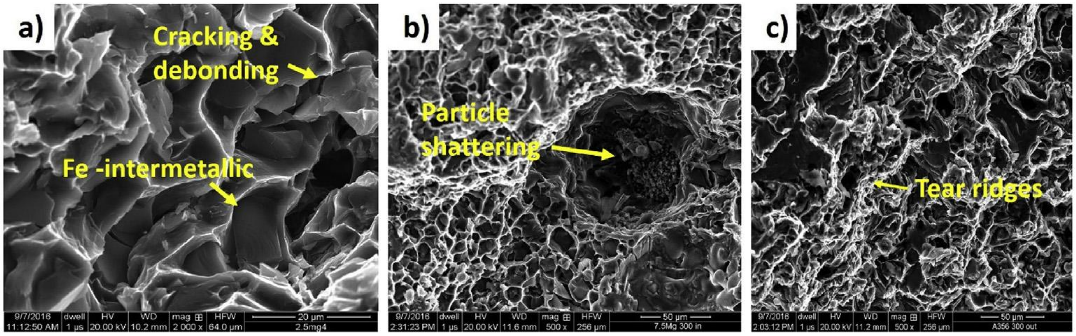

Fig. 5.13. Fractrogrphs illustrating typical features at high temperature (300°C) fracture, a) cracking and debonding of particles, in the inner zone of A356-2.5 Mg FG composite; b) particle shattering in the inner zone of A356-7.5 Mg FG composite and c) tear ridges in outer zone of A356

5.5. Chapter summary

The effects of varying Mg contents on room temperature and elevated temperature mechanical properties of in-situ A356-Mg_2Si composite functionally graded material in as-cast conditions have been investigated. The microstructural features are correlated with hardness profile, high temperature tensile properties and fracture behavior of different zones of FG composites. From analysis of the results, the following conclusions can be drawn:

- From the hardness-distance profile, the maximum hardness are obtained at the inner zone and this again increases with increasing wt.% of Mg. The hardness values are gradually decreasing from inner zones towards outer zones. However, at the vicinity of outer zones the hardness values are showing increasing trend. This trend is due to the combined effect of mold wall chilling and entrapment of some fine primary Mg_2Si particles. In the base alloy A356, outer zone is showing highest hardness because of chilling at the mold wall.

- In FG-composites, the ultimate tensile strength (UTS) at room temperature are also maximum at the inner zone and UTS values are increasing with increasing Mg content. While the test temperature is raised to 150°C, A356-2.5%Mg FGM shows a maximum peak value of 178 MPa and a further increase in test temperature to 300°C causes softening. Similarly, the UTS of FG-composites with higher Mg% were consistently increases at 150°C at inner zones. A356-5%Mg FGM shows a maximum peak value of around 188 MPa and a further increase in test temperature to 300°C causes softening. The peak UTS values at 150°C are 194.4MPa and 200.5MPa for A356-7.5Mg and A356+10Mg respectively. The consistent values of UTS in others zones were not observed with higher Mg% because of gradient distribution of reinforcements. The more or less values of tensile strength in respective zones depend on volume fractions of particles and voids or porosities present.
- The fracture behavior reveals a change in the mode of fracture from mixed mode to ductile mode as the test temperature is increased. At lower test temperatures, cracking of eutectic Si and Fe-intermetallics as well as porosities are responsible for failure while at higher temperatures due to softening of the Al-matrix the strength of the particle/matrix interfaces decrease. Cracks are initiated at these interface regions. This results in decohesion of the particles and void nucleation. In addition, under these conditions the brittle intermetallic particles were found to

shatter into multiple pieces as a result of the increasing stress build-ups at the particle/matrix interfaces.