FRACTURE ANALYSIS OF Mg-ALLOY METAL MATRIX COMPOSITES

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Abstract: This work is aimed at understanding the role of short-fiber reinforcements discontinuously dispersed through the metal-matrix of magnesium alloy on tensile deformation and fracture behavior. In particular, the role of volume fraction of the reinforcing phase on impact energy and fracture behavior is presented and discussed. Magnesium alloy (Mg-10Al-0.13Mn) was reinforced with (Al_2O_3) short-fibers. Three different volume fractions of the reinforcement phase (15, 20 and 25 vol. %) were chosen and the influence of volume fraction of alumina and tensile load were studied. The mechanism of fracture that appeared in the specimens was established from the SEM micrographs of the replicas taken from different zones of the fracture surfaces. The results obtained from the finite element analysis were compared with the experimental results. It was observed that the stress intensity factor and crack growth increased with increasing applied tensile load and volume fraction of alumina in the metal matrix composites.

1.0 INTRODUCTION

The metal matrix composites (MMCs) made up of Mg alloy and alumina finds critical applications in the industries of aerospace, automotive and even commercially related products as components of the aircraft engine (Polmear 1994, Chennakesava 2002,2004a, 2004b, 2004c). A few of the advantages are low density, good mach inability, dimensional stability and low power consumption, which makes alloys of magnesium potentially viable and economically affordable choice is preferred to aluminum alloys and titanium alloys for performance-critical applications (Mechter & Neil 1984; Das & Davis 1988; Froes 1989). Reinforced materials from pure magnesium and magnesium-based alloys, which can offer improvements in properties, such as stiffness, hardness, strength, fracture behavior, including wear resistance, similar to those observed in reinforced matrices of aluminum, copper and titanium. Reinforcing magnesium alloys either with ceramic particulates or ceramic fibers is likely to result in an improvement in certain mechanical properties, while also enhancing the thermal stability of materials with concomitant alteration of their responses to the chemical environment (Chennakesava, 1999, 2003).

This paper is aimed at understanding the role of short-fiber reinforcements discontinuously dispersed through the metal-matrix of magnesium alloy on tensile deformation and fracture behavior. In particular, the role of volume fraction of the reinforcing phase on impact energy and fracture behavior is presented and discussed.

2.0 METHODOLOGY

The material chosen was magnesium alloy (Mg-10Al-0.13Mn). The alloy was reinforced with (Al_2O_3) short-fibers. Both the un-reinforced and reinforced specimens were produced by squeeze infiltration technique. Three different volume fractions of the reinforcement phase (15, 20 and 25 vol. %) were chosen. The standardization of melting and casting parameters such as: (a) melt temperature, (b) melt holding time, (c) die temperature, (d) pre-form temperature, (e) pressure applied during squeezing, and (f) pressure holding time was initially optimized. The necessity for such standardization comes in the wake of their influence in governing the overall quality of the final casting.

Both the un-reinforced alloy and the reinforced composite counterparts were heat-treated. The heat treatment sequence essentially involved an interrupted solution heat treatment of the product at 410^0C for 18–24 hours. This was broken up into several intervals with intervening cooling periods: (a) 410^0C for 6 h, (b) 350^0C for 2–3 h, and (c) 410^0C for 12–14 h. Quenching followed this. The quenched samples were then artificially aged at 225^0C to facilitate improvement in properties.

The tensile tests were conducted on flat specimens. The mechanism of fracture that appeared in the specimens was established from the SEM micrographs of the replicas taken from different zones of the fracture surfaces. The mechanism of fracture was also studied using Finite Element Analysis Software (ANSYS). The results obtained from the FEA were verified with experimental results.

3.0 FINITE ELEMENT MODELING

3.1 Two-Dimensional Fracture Models

The recommended element type for a two-dimensional fracture model is PLANE-2, the six-node triangular solid. The first row of elements around the crack tip should be singular. The PREP7 KSCON command (GUI path Main Menu>Preprocessor>-Meshing-Shape & Size>-Concentrate KPs-Create), which assigns element division sizes around a key point, is particularly useful in a fracture model. It automatically generates singular elements around the specified key point. Other fields on the command allow controlling the radius of the first row of elements, number of elements in the circumferential direction etc.

3.2 Modeling Guidelines for 2-D Models
Take advantage of symmetry wherever possible as shown in Fig.1. In many cases, only one half of the crack region, with symmetry or anti-symmetry boundary conditions is to be modeled. For reasonable results, the first row of elements around the crack tip should have a radius of approximately a/8 or smaller, where 'a' is the crack length. In the circumferential direction, roughly one element for every 30 or 40 degrees is recommended. The crack tip elements should not be distorted, and should take the shape of the isosceles triangles.

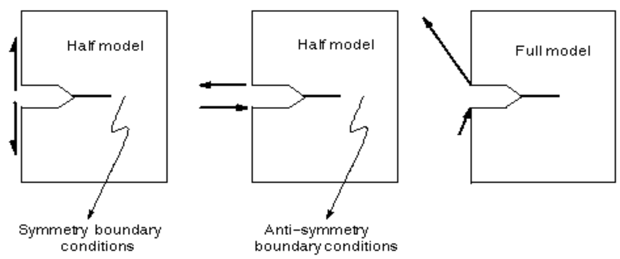

Fig.1 Advantage of Symmetry

3.3 Calculating Fracture Parameters
Once static analysis is completed, POST1, the general post processor is used to calculate fracture parameters. Typical fracture parameters of interest are stress intensity factors & the energy release rate.

3.3.1 Stress Intensity Factors
The POST1 KCALC command (GUI path Main Menu > General Postprocessor > Nodal Calculations > Stress Intensity Factors) calculates the mixed-mode stress intensity factors KI. This command is limited to linear elastic problems with a homogeneous, isotropic material near the crack region. To use KCALC properly, following steps in POST1 should be followed:

- Define a local crack-tip or crack-front coordinate system, with X parallel to the crack face (perpendicular to the crack front in 3-D models) and Y perpendicular to the crack face.
- Define a path along the crack face. The first node on the path should be the crack-tip node. For a half-crack model, two additional nodes are required, both along the crack face. For a full-crack model, where both crack faces are included, four additional nodes are required: two along one crack face and two along the other.
- Calculate KI. The KPLAN field on the KCALC command specifies whether the model is plane-strain or plane stress. Except for the analysis of thin plates, the asymptotic or near-crack-tip behavior of stress is usually thought to be that of plane strain. The KCSYM field specifies whether the model is a half-crack model with symmetry boundary conditions or a full-crack model.
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3.3.2 Energy Release Rate
Energy release rate is a concept used to determine the amount of work (change of energy) associated with a crack opening or closure. The crack length is extended by Δa for the second analysis by selecting all nodes in the vicinity of the crack and scaling them in the X direction [NSCALE] (GUI path Main Menu> Preprocessor> -Modeling-Operate. Scale) by the factor Δa.

4.0 RESULTS AND DISCUSSION

4.1 Deformation and Stress Analysis
It is observed that the deformations increase with increase of tensile loading. This is a common phenomenon. The interesting phenomena are: (1) the deformations in the base alloy are higher than that in the metal matrix composites and (2) the deformations decrease with increasing content of alumina. The reason could be the increase of elastic modulus with increase of volume fraction of alumina in the metal matrix composites. The increase in elastic modulus increases the stiffness in the composites. The Von Mises's stress is not influenced by the addition of alumina. The tensile load variation influences the stress induced in the base metal and metal matrix composites. The Von Mises's stress increases with increase in tensile loading.

4.2 Strain Intensity Factor

Fracture-resistant design has two significant components. The first, which considers the applied stress state and the likelihood of flaws being present in the structure, allows for estimating service stresses in terms of flaw size and the material property, K_I. There is a general trend of increasing strain intensity factor with increasing applied tensile load. It is also observed that the strain intensity factor increases with increasing volume fraction of alumina in the metal matrix composites. This is in fact true, because the number of sites for strain intensity increase with increase addition of alumina. Ideally, the curves should go zero stress intensity for zero applied loads.

4.3 Strain Release Energy

Under all the test conditions, the strain energy increases with increasing applied tensile load and volume fraction of alumina. Crack extension can occur when crack-driving force is equal to the energy required for crack growth. The energy required for a crack to grow in a metal is much larger than the surface energy to create the new free surfaces. In metals plastic deformation occurs in front of the crack and during crack extension energy is expended by the formation of a new plastic zone at the tip of the advanced crack. For a particular stress the energy release rate is proportional to the crack size. As the tensile load and the size of the initial increase, there is an increased crack growth in the Mg alloy and metal matrix composites. It is observed that the energy release rate is maximum at the crack tip. This indicates that the crack opening is accelerated with increase of tensile load and initial crack size.

4.4 Experimental Analysis of Fracture Mechanism

Microstructures of Mg-alloy, in the as-cast condition, produced by gravity die-casting and squeeze casting are shown in Fig.2. When compared to its gravity die-cast counterpart, microstructure of the squeeze-cast Mg-alloy reveals an overall refinement in grain size coupled with absence of porosity. These features are attributed to the high-applied pressure used in the squeeze-casting process. Under the influence of an applied pressure, there is no air gap formation between the solidifying metal and die-wall interface. This aids in dramatically enhancing the local heat transfer rate across the die surface, resulting in rapid solidification of the liquid metal. The applied pressure also aids in increasing the solubility of gases in the melt thus trapping the gases in solution. This helps in preventing the nucleation of bubbles in the melt with concomitant elimination of micro-porosity.

A representative microstructure of the squeeze-infiltrated Mg-alloy reinforced with 20 vol. % of alumina fibers is shown in Fig.3. A near-uniform distribution of the alumina short-fibers through the magnesium alloy metal-matrix with no distinct evidence of clustering, or agglomeration is observed. This proves the effectiveness of the squeeze-infiltration technique for producing composite microstructures. No visible compression of the pre-forms occurs during the application of pressure. Presence of compression leads to the occurrence of fiber clustering and eventual damage through breakage, thereby lowering the mechanical properties of the composite.
In the as-cast condition, aluminum is present both in solid solution with the matrix and precipitated as the $Mg_{17}Al_{12}$ phase that is present both at and along the grain boundaries. Fig.4 is a SEM of Mg-alloy showing fine precipitates dispersed along the grain boundary.

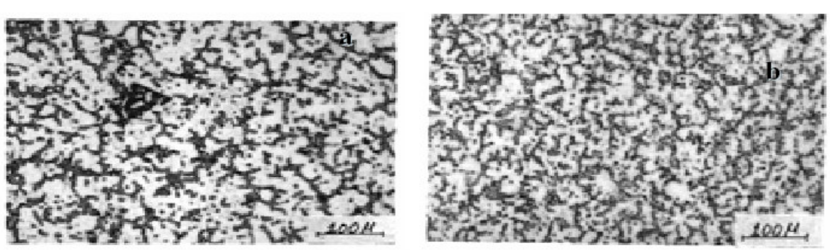

Fig.2 Optical micrographs showing microstructure of (a) Die cast (b). Squeeze cast

The composite material reveals evidence of micro cracking through the reinforcing fibers as seen in Fig. 5(a). As the volume fraction of the fiber reinforcement in the metal-matrix increases to 25 vol. %, failure occurs through a combination of partial breakage and total rupture as seen in Fig.5 (b). For notched test specimen, governing microscopic fracture mechanisms of the composite are intensified as seen in Fig.6. In the composite, a large percentage of the reinforcing short alumina fibers have fractured. This is evident as protruding lips observed as the broken ends of the fiber. As volume fraction of the reinforcing fibers in the magnesium alloy metal-matrix increases, the fracture surfaces reveal intense slicing of fibers (both across and along the length) along the impact plane as seen in Fig.6(b).

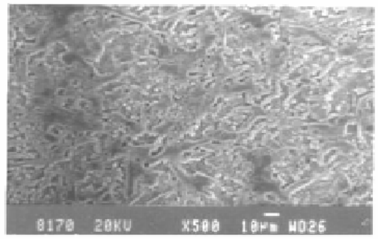

Fig.3 SEM of the Mg alloy (20vol% Al_2O_3) composite produced by the squeeze infiltration technique.

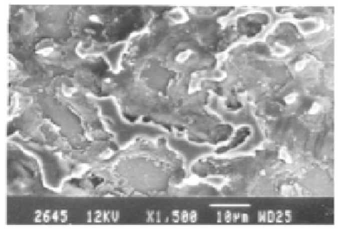

Fig.4 SEM of Mg alloy showing the region of matrix, eutectic and presence of $Mg_{17}Al_{12}$ precipitates along the grain boundary.

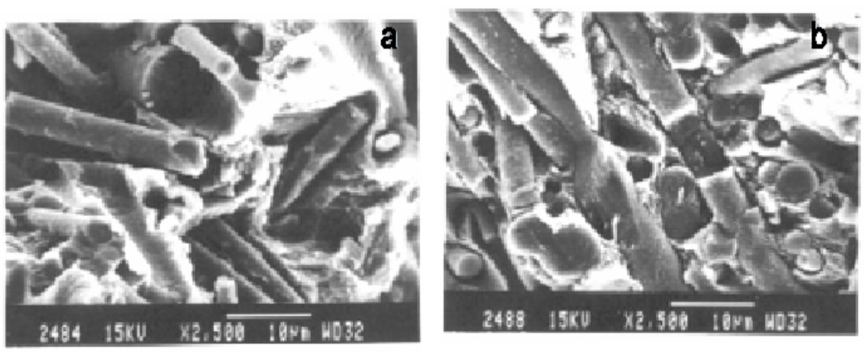

Fig.5 SEM of the Mg-alloy (25 vol% Al_2O_3) in the un-notched condition, showing (a) fine microscopic cracking through the fibers, (b) fiber failure by rupture and de-cohesion at the interface.

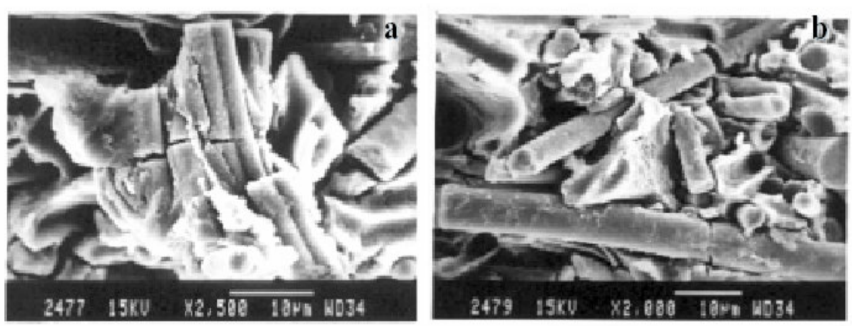

Fig.6 SEM of the Mg-alloy (25 vol% Al_2O_3) in the notched condition, showing: (a) fiber rupture or breakage, (b) slicing and de-cohesion of the fibers.

5.0 CONCLUSIONS

- Fracture-resistant design has two significant components. The first, which considers the applied stress state and the likelihood of flaws being present in the structure, allows for estimating service stresses in terms of flaw size and the material property, K_I.

- There is a general trend of increasing strain intensity factor with increasing applied tensile load. It can also be observed that the stress intensity factor increases with increasing volume fraction of alumina in the metal matrix composites.
- Under all the test conditions, the strain energy release increases with increasing applied tensile load. Crack extension can occur when crack-driving force is equal to the energy required for crack growth. For a particular stress the energy release rate is proportional to the crack size. As the tensile load and the volume fraction of alumina increase, there is an increased crack growth in the composites.
- The technique of squeeze casting facilitates overall refinement in grain structure while concurrently eliminating porosity and ensuring that the resultant casting is sound and suitable for heat treatment. In reinforced magnesium alloy, the fibers are near-uniformly distributed through the matrix.
- The presence of hard, brittle and essentially elastically deforming precipitates [$Mg_{17}Al_{12}$] both at and along grain boundaries makes the metal-matrix intrinsically hard.
- On reinforcing with short alumina fibers, the fiber–metal interfaces provide nucleation sites for precipitation, which enhances composite hardness while concurrently decreasing the aging time to peak strength.
- Density of reinforced metal-matrix is higher than that of the unreinforced counterpart (Mg-alloy). Density increases with volume fraction of the reinforcing phase and is attributed to the higher density of the reinforcing short-fibers.
- Modulus of elasticity of the reinforced metal-matrix is twice that of the unreinforced counterpart (Mg-alloy). While the presence of short-fibers in the soft metal-matrix enhances load-carrying capability of the composite microstructure, concomitant decrease as compared to the un-reinforced counterpart. Further, the presence of hard and brittle fibers degrades the ability of the composite microstructure to deflect.

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