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Mechanical Properties of As-Cast and Heat-Treated ZA-27 Alloy/Short Glass Fiber Composites

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This paper reports on the mechanical properties of as-cast and heat-treated ZA-27 alloy composites reinforced with glass fibers from 1 to 5 wt%. The composites were fabricated using the Compocasting method, in which short glass fibers were introduced into the vortex created in the molten alloy through an impeller rotated at 500 rpm. The molten mass was thoroughly stirred and poured into permanent molds and squeezed under pressure. The specimens were heat treated at 320 °C for 1, 2, 3, and 4 h. The tests on the as-cast composites revealed that as the glass content in the composites was increased, the ultimate tensile strength (UTS), compressive strength, and hardness of the composite increased, while the ductility and impact strength were decreased. Heat treatment was found to improve significantly the ductility, compressive strength, and impact strength, while the hardness and UTS were reduced. This paper discusses the behavior of these composites.

Keywords composites, E-glass, mechanical properties, zinc alloys

1. Introduction

Over the past four decades, there have been pioneering efforts to develop metal-matrix composites (MMCs) as new engineering materials having improved properties and light weight in comparison with traditional materials (Ref 1). The outstanding benefit of metal matrix composites (MMCs) is that they combine metallic properties with ceramic properties, thus yielding attractive physical and mechanical properties (Ref 2).

The matrix materials used in MMCs are usually popular alloys selected mainly on the basis of their already established superior properties (Ref 3). For good bonding and strength in composites, metal alloys are used as the matrix elements instead of pure metals (Ref 4). Ceramic reinforcements are generally used because of their combination of high strength and stiffness at both room and elevated temperatures (Ref 4). During the last few years several studies of the mechanical behavior of discontinuously reinforced composites have been reported (Ref 5, 6).

Composites reinforced with randomly oriented short fibers have become increasingly popular in recent years (Ref 7). In the design of such composites, it is essential to understand the strengthening mechanism and the relationship between the strength of the composite and the properties of the components (Ref 8). The short-fiber-reinforced MMCs have shown improved modulus of elasticity and tensile strength, whereas particle reinforcement improves the hardness and damping properties and also lowers the coefficient of thermal expansion (Ref 9). Moreover, short-fiber-reinforced composites are used because they tend to be less expensive and more amenable to mass production techniques than continuous fiber composites; they represent an economic compromise. The performance relationships and the ease of fabrication are influenced by the interface between the matrix and the reinforcing phase (Ref 10). Various studies on reinforcement interfaces have been made to determine the factors that dictate bonding and interface behavior (Ref 11, 12).

The zinc-aluminum (ZA) family of alloys, which are often the first choice to replace cast iron, brass, or aluminum alloys (Ref 13), are popular alloys for matrix materials. The ZA-27 alloy, which was developed by the Canadian Organization of Noranda Mines Limited, is a high-strength alloy whose properties can be equivalent to those of aluminum alloys (Ref 14). The ZA-27 alloys have been used in bearings, bushings, and other wear-resistant applications as a replacement for bronze bearings due to their lower cost and equivalent or superior performance (Ref 15). The present investigation evaluated the mechanical properties of the ZA-27/short glass fiber composites in both the as-cast and heat-treated conditions.

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2. Experimental Procedure

2.1 *Preparation of the Composites*

ZA-27 alloy (25 to 28 wt% Al, 0.01 to 0.02 wt% Mg, 2.0 to 2.5 wt% Cu, bal Zn) was used as the base matrix alloy. E-glass was used as the reinforcement. The diameter of the fibers was 4 to 5 μm and the length was 4 to 6 mm.

The ZA-27/glass-fiber composites were fabricated using the Compocasting technique, which is similar to the one used by Hosking et al. (Ref 16). This is the most economical method of fabricating composites with discontinuous fibers (Ref 17). The matrix alloy (ZA-27) was first superheated above its melting temperature, and stirring was initiated to homogenize the temperature. The temperature was then lowered gradually until the alloy reached a semisolid state. At this temperature (440 °C) the glass fibers were introduced into the slurry. During the addition of glass fibers the temperature was raised gradually and stirring was continued until the interface between the fibers and the matrix promoted wetting. The melt was then superheated above its liquidus temperature of 500 °C and was finally poured into the lower die-half of the press. The top die was brought down and high pressure was applied to solidify the composite.

The specimens were heat treated at 320 °C for 1, 2, 3, and 4 h and were subsequently air cooled. The durations and temperature were selected based on the reports of other researchers (Ref 14, 18).

2.2 *Testing of Specimens*

The tension tests were performed at room temperature using a universal testing machine.

The tensile test was conducted according to ASTM E 8-82. The specimens were machined from the cast composites with the gage length of specimens parallel to the longitudinal axis of the castings. As many as eight tensile specimens were tested for each case and the average values of the tensile strength and

Table 1 Effect of heat treatment on hardness of ZA-27/glass fiber composites

Hours of heat treatment(a)	Hardness (BHN) of composites containing:			
	0% glass fiber	1% glass fiber	3% glass fiber	5% glass fiber
0	125.61	129.98	132.42	137.08
1	100.46	107.96	110.64	114.21
2	89.55	96.49	100.41	103.56
3	79.03	84.31	92.80	98.77
4	72.71	76.89	81.26	87.52

(a) Temperature: 320 °C

Table 2 Effect of heat treatment on ductility of ZA-27/glass fiber composites

Hours of heat treatment(a)	Ductility (% elongation) of composites containing:			
	0% glass fiber	1% glass fiber	3% glass fiber	5% glass fiber
0	9.07	7.68	6.80	6.10
1	9.72	8.42	7.56	6.92
2	10.62	9.24	8.37	7.84
3	11.48	10.18	9.14	8.71
4	12.26	11.24	10.48	9.86

(a) Temperature: 320 °C

Table 3 Effect of heat treatment on ultimate tensile strength of ZA-27/glass fiber composites

Hours of heat treatment(a)	Ultimate tensile strength (MPa) of composites containing:			
	0% glass fiber	1% glass fiber	3% glass fiber	5% glass fiber
0	301.55	348.68	359.90	381.66
1	276.27	316.72	336.18	356.42
2	252.48	294.15	314.37	331.78
3	234.63	268.24	291.61	316.57
4	218.35	254.36	278.28	299.32

(a) Temperature: 320 °C

Table 4 Effect of heat treatment on impact strength of ZA-27/glass fiber composites

Hours of heat treatment(a)	Impact strength (J) of composites containing:			
	0% glass fiber	1% glass fiber	3% glass fiber	5% glass fiber
0	39.40	31.16	27.31	24.22
1	46.62	39.86	34.45	31.64
2	55.24	48.42	43.86	40.18
3	65.88	56.82	52.42	49.44
4	76.64	70.20	64.25	58.56

(a) Temperature: 320 °C

ductility in terms of elongation were calculated. The specimen was mounted on the machine using shackles and the load was applied gradually. The corresponding strain readings were noted. The procedure was continued until failure of the specimen.

Hardness tests were conducted according to ASTM E 10. Hardness was measured using a Brinell hardness testing machine with a ball indenter of 2.5 mm diameter and a load of 31.25 kg. The load was applied for 30 s. In order to avoid the segregation effect of the particles, as many as eight readings were taken for each sample.

The Charpy impact test was done according to ASTM E 23 on an impact testing machine. The specimens were held in the shackles and the torque was applied slowly. The readings of the torque and the twist were noted until failure of the specimens.

3. Results and Discussion

Tables 1 to 5 show the effects of heat treatment on the various mechanical properties evaluated. Each value represented is an average of eight measurements. Each value is repeatable in the sense that each individual value did not vary more than 5% from the mean value. All the results are represented graphically in Fig. 1 to 5.

3.1 *Hardness*

Figure 1 shows the effect of percentage increase of short glass fibers on the hardness of the composites. As the percentage of glass fibers was increased from 0 to 5 wt%, the hardness of the composite increased significantly by 10%. Zhu and Liu (Ref 19) have observed a similar increase in hardness when ZA alloy is reinforced with short alumina fibers. Various other workers also have reported that the addition of hard ceramic short fibers in metal alloys can lead to improved strength, wear resistance, and hardness (Ref 20, 21). The increase in hardness is attributed to the presence of hard glass fibers that act as barriers to the movement of dislocations within the matrix.

The homogenizing heat treatment at 320 °C decreased the hardness of the composites of various glass fiber contents. The percentage decreases in the hardness of the composites containing 0, 1, 3, and 5 wt% glass fibers were 42.11, 40.84, 38.63, and 36.15, respectively, after 4 h of heat treatment. A study of the Zn-Al phase diagram (Ref 13) shows that as the ZA-27 alloy is cooled from the melt to room temperature, it goes through several phases, namely (α + L), β, (α + β), and finally (α + η). Cooling in permanent molds may not be slow enough to allow the whole casting to reach the equilibrium room temperature phase of (α + η), or the β phase may still be present in the casting even at room temperature. It is probable that the conversion from the β phase to the α phase and η equilibrium phases during heat treatment is responsible for the decrease in hardness observed. It also appears that the increase in grain size due to heat treatment causes a drop in hardness. A compromise is essential in deciding the duration of the heat treatment in order to enhance the ductility, impact strength, and compressive strength of the composites but not sacrifice too much hardness. It follows from the results obtained that glass fiber content and duration of heat treatment conspire to aggravate this problem of decreasing hardness.

3.2 *Ductility (% Elongation)*

Figure 2 shows the effect of heat treatment on the ductility (in terms of percentage elongation) of the composites. The ductility of the composite specimens decreased with an increase in glass fiber content. The reduction in ductility was about 33% as the glass fiber content was increased from 0 to 5 wt%. The decrease in ductility in comparison with that of the base alloys is the most commonly encountered disadvantage in discontinuously reinforced MMCs (Ref 22). Flom and Arsenault (Ref 23) have related such reduction in ductility to an inhomogeneous distribution of the reinforcement and void initiation at the reinforcement-matrix interface during straining due to a weak interfacial bond.

The results and the behavior trend are on par with those obtained by other workers (Ref 16, 24). The reduced ductility in these specimens can be attributed to the fibers, which may get fractured and have sharp corners that make the composites prone to localized crack initiation and propagation. There may also be an embrittlement effect due to the presence of the hard glass fibers, causing increased local stress concentration sites. Moreover, the reinforcing fibers resist the passage of the dislocations, either by creating stress fields in the matrix or by inducing large differences in the elastic behavior between the matrix and the dispersoid. Mummery et al. (Ref 25) are of the opinion that this behavior is probably due to void nucleation during the plastic straining of the reinforcement, either by reinforcement interface or by the decohesion of the matrix-reinforcement interface.

Elongation is the parameter most sensitive to heat treatment (Ref 1). Heat treatment was found to improve the ductility of the composites. The percentage increases in ductility of the composites containing 0, 1, 3, and 5% graphite were 35.17, 46.35, 54.11, and 61.63, respectively, after 4 h of heat treat-

Table 5 Effect of heat treatment on compressive strength of ZA-27/glass fiber composites

Hours of heat treatment(a)	Compressive strength (MPa) of composites containing:			
	0% glass fiber	1% glass fiber	3% glass fiber	5% glass fiber
0	785.96	905.66	1010.91	1138.18
1	890.12	999.96	1070.35	1194.84
2	965.28	1028.81	1223.72	1332.72
3	1050.56	1202.38	1302.86	1401.27
4	1172.34	1281.11	1368.35	1489.21

(a) Temperature: 320 °C

ment. Barber et al. (Ref 14) reported similar findings where the heat treatment of the alloy at 320 °C for 3 h with subsequent slow cooling yielded increased elongation, which is a measure of ductility. Gervais et al. (Ref 18), who have also observed this phenomenon, have explained that by providing coarsening of the eutectoid phase, a homogenizing heat treatment of the ZA-27 alloy for 3 h at 320 °C with furnace cooling gives added ductility. In view of these results, it can be concluded that the homogenizing effect of heat treatment probably improves the ductility of the composites. It also appears that the heat treatment affects the zinc alloy mainly and not so much the reinforcing glass fibers in the composites. Moreover, the glass fibers do not react with the matrix material and hence do not affect its properties, even at elevated temperatures.

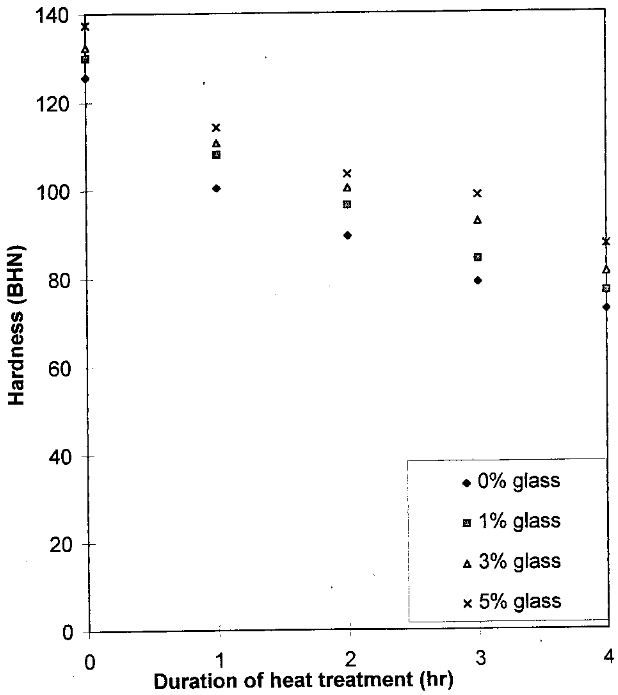

Fig. 1 Effect of heat treatment on the hardness of ZA-27/glass fiber composites

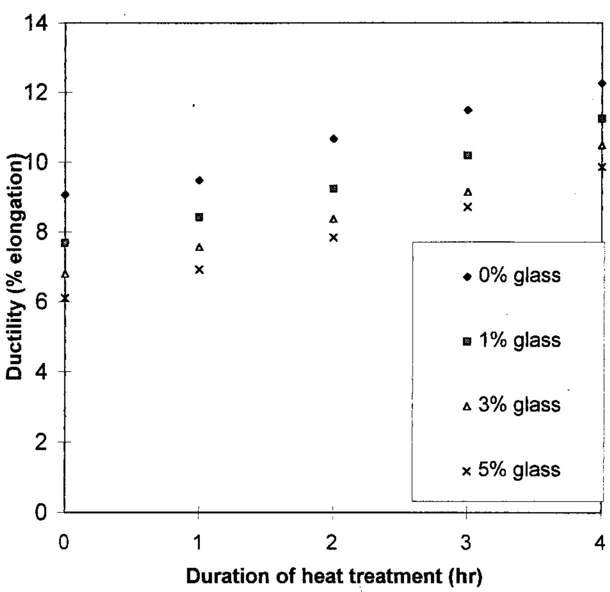

Fig. 2 Effect of heat treatment on the ductility of ZA-27/glass fiber composites

3.3 *Ultimate Tensile Strength*

Figure 3 shows the effect of heat treatment on the ultimate tensile strength (UTS) of the composites. As the glass fiber content in the composite was increased, the UTS of the composite material increased by significant amounts if other factors were kept constant. The UTS of the composite specimens increased by about 27% as the glass fiber content was increased from 0 to 5 wt%. The increase in UTS can be attributed to the presence of hard glass fibers that impart strength to the matrix alloy, thereby providing enhanced resistance to tensile stresses. A reduction in the distance between the hard glass fibers increases the dislocation pile-up as the fiber content is increased. There is also a restriction to the plastic flow due to the random distribution of the fibers in the matrix, thereby providing enhanced tensile strength to the composites.

Vogelsang et al. (Ref 26) believe that the improvement in UTS may be due to the matrix strengthening following a reduction in composite grain size, and the generation of a high dislocation density in the matrix as a result of the difference in the thermal expansion between the metal matrix and the glass fiber reinforcement.

Heat treatment decreased the UTS of the composites. The percentage decreases in the UTS of the composites containing 0, 1, 3, and 5 wt% glass fibers were 27.59, 27.05, 22.67, and

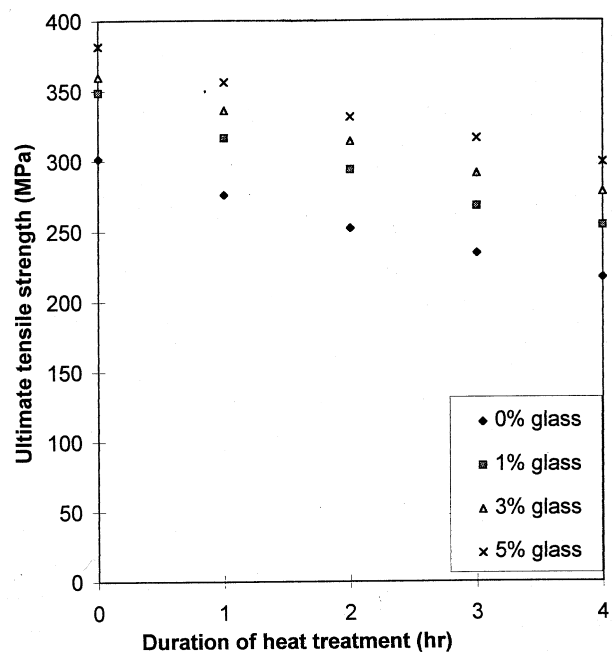

Fig. 3 Effect of heat treatment on the ultimate tensile strength of ZA-27/glass fiber composites

21.57, respectively, after 4 h of heat treatment. The homogenization heat treatment causes the matrix to be softened, allowing easier movement of the dislocations mentioned above. This homogenization also allows diffusion of segregated components, producing a more uniform composition. The overall result of this heat treatment is therefore a drop in the UTS of the composite.

3.4 *Impact Strength*

Figure 4 shows the impact strength of the composites in terms of impact energy absorbed during the Charpy impact test. The specimens showed a decrease in impact strength of about 39% as the glass fiber content was increased from 0 to 5 wt%. The reduction in impact strength can be attributed to the short glass fibers, which cause an embrittlement effect by acting as barriers to the movement of dislocations in the matrix, thereby increasing the number of local stress concentration sites. The effect of glass fibers is expected to be mechanical in nature because the fibers are not reactive with the matrix phase. These results for impact strength are to be expected, because it is generally true that the impact strength of a material has a positive relationship with its ductility. Hence, the impact strength of the composite is strongly influenced by the toughness of the matrix.

Homogenizing heat treatment at 320 °C improved the impact strength by significant amounts. The percentage increases in impact strength of the composites containing 0, 1, 3, and 5 wt% glass fibers were 94.51, 125.28, 135.26, and 141.78, respectively, after 4 h of heat treatment. Apparently, the heat treatment causes the matrix material to age and shift the stress-strain curve such that the area under the curve increases, resulting in an improvement in the impact strength of the composite.

3.5 *Compressive Strength*

Figure 5 shows the effect of heat treatment on the compressive strength of the composites. The compressive strength of the as-cast composite material increased significantly by 44.81% as the glass fiber content was increased from 0 to 5 wt% if other factors were kept constant. As in the case of UTS, the improved compressive strength may be attributed to the presence of hard glass fibers that impart strength to the matrix alloy, thereby providing enhanced resistance to the compressive stresses. A reduction in the distance between the hard glass fibers increases the dislocation pile-up as the fiber content is increased. Dutta et al. (Ref 27) explains that the reinforcement causes a high dislocation density in the matrix, resulting in improved compressive strength. The dispersion strengthening effect is expected to be retained even at elevated temperatures and for extended periods of time, because the glass fibers are unreactive with respect to the matrix phase (Ref 28).

Heat treatment increased the compressive strength by significant amounts. As the glass fiber content was increased from 0 to 5 wt%, the specimens heat treated for 1, 2, 3, and 4 h showed improvements in compressive strength of 49.16, 41.45, 35.35, and 30.84, respectively. The results are on a par with those obtained by Gervais et al. (Ref 18), who found that the heat treatment results in the microstructure became more homogeneous, causing the compressive strength to improve.

4. Fractography and Fracture Analysis

Evaluation of the mechanical properties of the composite materials is essential, but the failure/deformation mechanisms and fracture modes need to be investigated simultaneously.

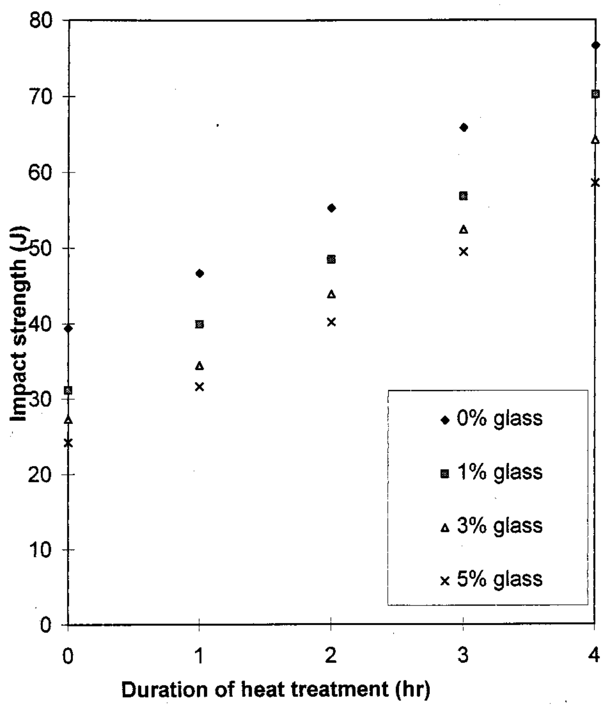

Fig. 4 Effect of heat treatment on the impact strength of ZA-27/glass fiber composites

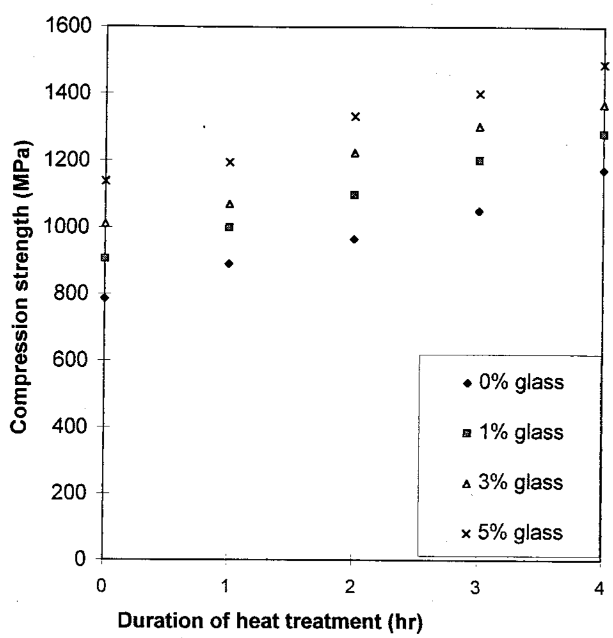

Fig. 5 Effect of heat treatment on the compressive strength of ZA-27/glass fiber composites

Hence, detailed scanning electron micrograph examinations were conducted on the tensile fracture surfaces of fractured specimens.

Figure 6(a) shows the fractography of fracture of as-cast unreinforced ZA-27 alloy, while Fig. 6(b), (c), and (d) are the fractographs of fracture of the as-cast composite materials containing 1, 3, and 5 wt% of short glass fibers, respectively. The fracture surface of the ZA-27 alloy has large dimples and heavy shear deformation, indicating a large amount of deformation prior to failure. But in the case of the composite materials, it can be seen that the extent of ductile dimpling has decreased with the inclusion of short glass fibers. The dimple size has been reduced significantly and the nature of failure of the interconnecting ligaments is by ductile tearing. The fine dimples occur in the region of matrix between the fibers that have undergone ductile tearing. The fracture occurring by ductile mechanism is largely controlled by void nucleation, growth, and coalescence in the matrix. In addition to voiding, some fibers and any intermetallics associated with them may crack during tensile straining. Cracks produced by voiding or by fiber fracture then link by ductile failure of the matrix.

The observation that the ductile fracture is controlled by void nucleation, growth, and coalescence has been made by other workers (Ref 29). The relative importance of each stage determines the ductility of the specimens. In ductile materials reinforced with a high content of hard second-phase fibers, it has been suggested that fracture nucleation events may dominate ductility, because the subsequent stages of void growth and coalescence may be extremely rapid once initiation has occurred. It follows from these observations that the fracture process in these materials is quite complex, involving several different phenomena.

The decrease in ductility of the as-cast composites in the present case is by about 33% as the content of reinforcement is increased from 0 to 5 wt%. Other investigators (Ref 30) have observed reduction in ductility by as much as 50% in 6061 Al

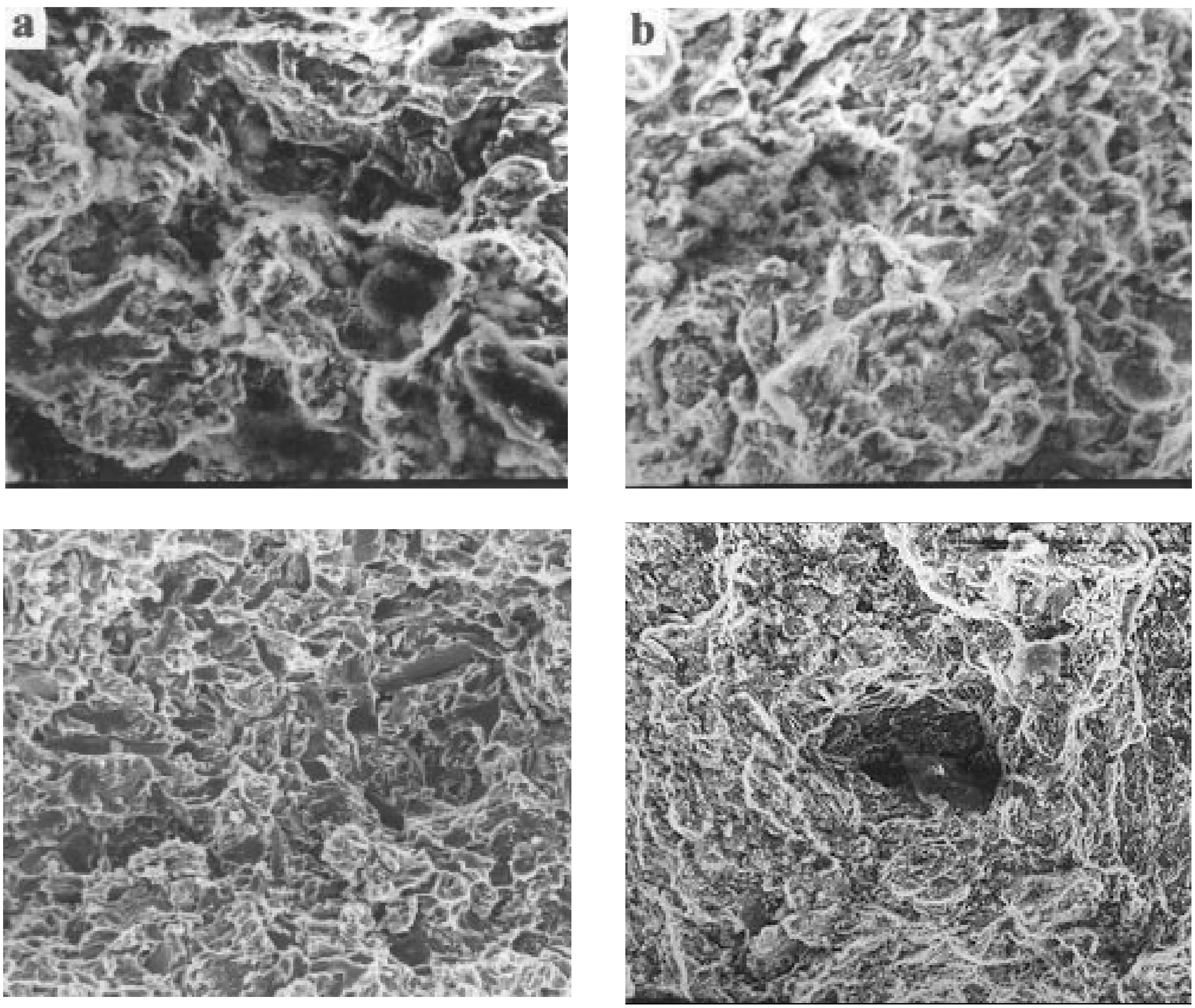

Fig. 6 Fractographs of the ZA-27 alloy with (a) 0%, (b) 1%, (c) 3%, and (d) 5% short glass fiber reinforcement. 300×

composites reinforced with short saffil fibers. Optimization of the tensile elongation requires the elimination of voids and any intermetallics that may be present in the microstructure.

4. Conclusions

The mechanical properties of the cast ZA-27 alloy/glass fiber composites were significantly changed by the varying amounts of glass fiber as well as by the heat treatment. Increasing the glass fiber content in the ZA-27 matrix resulted in significant increases in UTS, compressive strength, and hardness but decreases in ductility and impact strength. The heat treatment improved the ductility, compressive strength, and impact strength but reduced hardness and UTS. Hence, in an attempt to enhance the mechanical properties of the composites, a compromise is essential in deciding the amount of glass fiber to be added so as not to sacrifice too much ductility and impact strength, and in deciding the heat treatment duration so as not to sacrifice too much UTS and hardness and, hence, wear resistance.

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