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A Study of Mechanical Properties and Fractography of ZA-27/Titanium-Dioxide Metal Matrix Composites

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This paper reports an investigation of the mechanical properties and the fracture mechanism of ZA-27 alloy composites containing titanium-dioxide (TiO_2) particles 30-50 µm in size and in contents ranging from 0-6 wt.% in steps of 2 wt.%. The composites were fabricated by the compocasting technique. The results of the study revealed improvements in mechanical properties such as Young's modulus, ultimate tensile strength, yield strength and hardness of the composites, but at the cost of ductility. The fracture behavior of the composites was influenced significantly by the presence of titanium dioxide particles. Crack propagation through the matrix and the reinforcing particles resulted in the final fracture. Scanning electron microscopy (SEM) analyses were carried out to furnish suitable explanations for the observed phenomena.

Keywords fractography, mechanical properties, titanium dioxide, ZA-27 alloy

1. Introduction

In recent years there has been considerable interest in metal matrix composites (MMCs). This is because of the potential for improvements in mechanical properties such as tensile strength, compression strength, and hardness, and also an increase in high temperature properties. Such improvements are countered by reduction in ductility and toughness. Fiber-reinforced composites enhance properties to a greater extent. However, they are anisotropic and cannot be formed by conventional mechanical processing. Particulate-reinforced composites are more isotropic, modest improvements in properties can obtained, and the composites can be processed conventionally.[1]

Among the zinc-based foundry alloys, the zinc-aluminum (ZA) family of alloys has been used increasingly during the past few years. Considerable industrial applications have been found, mainly due to their good mechanical properties, excellent fluidity, and castability.[2] These alloys present advantages in comparison with copper- and aluminum-based alloys, especially high strength with a low casting temperature. Studies on ZA alloy matrix composites reinforced with different ceramic powders and short fibers showed that the composites exhibit excellent wear resistance, superior hardness and modulus, and a greatly reduced creep rate compared with the parent matrix alloys.

Of the three alloys, namely ZA-8, ZA-12, and ZA-27, belonging to the family of zinc alloys, ZA-27 has shown good wear resistance and a tensile strength substantially higher than that of ordinary cast aluminum alloys. Recently, these alloys have been considered for a number of commercial applications and are competing effectively with copper, aluminum, and iron-based foundry alloys because they exhibit good mechanical, machinability, bearing, and wear properties.[3] These properties are attributed to a favorable multiphase structure produced by the formation of alumina and zinc oxides on the bearing surface.[4-6]

It has been observed that the ZA alloys including ZA-27 suffer from a lack of high-temperature stability and creep resistance. As the temperature increases above ambient temperature, the ZA alloys lose their strength very rapidly, and there is, consequently, a very great need to improve the properties. However, in the present study, the mechanical properties of the composites were evaluated at room temperature alone and compared with those of the unreinforced alloy to establish the effect of ceramic reinforcement on metal matrix alloy.

2. Experimental Procedure

2.1 Material Selection

ZA-27 was used as the base alloy. The material can be either sand cast or die cast. The chemical composition of the ZA-27 alloy is given in Table 1.

Titanium dioxide has a Moh's hardness of 7-7.5, which is nearly equal to that of SiC. It does not react in many chemical solutions and does not have a sharp melting point, although it softens at a temperature range of 1140-1280 °C.

2.2 Preparation of Composite

The ZA-27-titanium dioxide composites were prepared by the vortex method of casting using particles of size 30-50 µm. The titanium dioxide contents used for the preparation of the composites were 0%, 2%, 45%, and 6%. The addition of titanium dioxide into the molten zinc alloy above its liquidus temperature at 500 °C was carried out by creating a vortex in the melt using a mechanical stainless steel stirrer coated with aluminite. The stirrer was rotated at a speed of 450 rpm in order

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Table 1 Chemical Composition of Za-27 Alloy in Weight Percent (ASTM B669-82)

Element	Aluminum	Magnesium	Copper	Zinc
Percentage Composition (wt.%)	25-28	0.01-0.02	2.0-2.5	Balance

to create the necessary vortex. The titanium dioxide particles were preheated to 400 °C and added to the melt through the vortex at a rate of 100 g/min. A small amount of magnesium, which improves the wettability of the titanium dioxide particles, was also added; the melt was thoroughly stirred and subsequently degassed by passing nitrogen through at a rate of 2-3 l/min. The molten metal was then poured into permanent molds for casting.

2.3 Testing of Mechanical Properties

All tests were conducted in accordance with ASTM standards. Tensile tests were conducted at room temperature using a universal testing machine (UTM) in accordance with ASTM E8-82. The tensile specimens of diameter 8.9 mm and gauge length 76 mm were machined from the cast composites with the gauge length of the specimen parallel to the longitudinal axis of the castings. Five specimens were tested, and the average values of the ultimate tensile strength (UTS) and ductility (in terms of percentage elongation) were measured.

The compression tests were conducted on specimens of 12 mm diameter and 20 mm length machined from the cast composites. In these tests, the compressive loads were applied gradually, and corresponding strains were measured until failure of the specimen occurred. This test was conducted according to ASTM E9 standard in the UTM at room temperature.

The hardness tests were conducted in accordance with ASTM E10 standard using a standard Brinell hardness testing machine (Vebwerkstoftprufmaschinen, Leipzig, Germany) with a ball indentor of diameter 2.5 mm and load of 31.25 kg. The load was applied for 30 s. Five readings were taken for each specimen at different locations to circumvent the possible effects of particle segregation.

3. Results and Discussion

3.1 Microstructure

Samples for microscopic examinations were prepared by standard metalographic procedures etched with Keller's agent and examined under optical microscope. The optical microstructures of die-cast ZA-27 alloy and ZA-27/titanium dioxide composite are shown in Fig. 1(a) and(b). Optical microscopy investigations showed that the titanium dioxide particle remained well bonded to the matrix despite the high residual thermal stresses induced by the large thermal expansion coefficient mismatch between the two phases,[7] and a uniform distribution of the reinforcement phase exists.

Microstructures play an important role in the overall performance of the alloys as well as composites. As a result, there were large clusters of titanium dioxide within some areas of the matrix while other areas were entirely titanium dioxide depleted. The segregation was more pronounced in the 4% titanium dioxide composites. When analyzed at higher magnifications (Fig. 1b), the structures reveal that the relatively colder particle chills the metal and unitized nucleation. The dendrites grow away from the particle due to the restriction caused by the particle to solute enrichment. Thus, the grains grow outwards from the particle, and the last remaining eutectic liquid solidifies around the particles. However, no gap is observed between the particle and the matrix, and the particles are seen well bonded with the matrix.

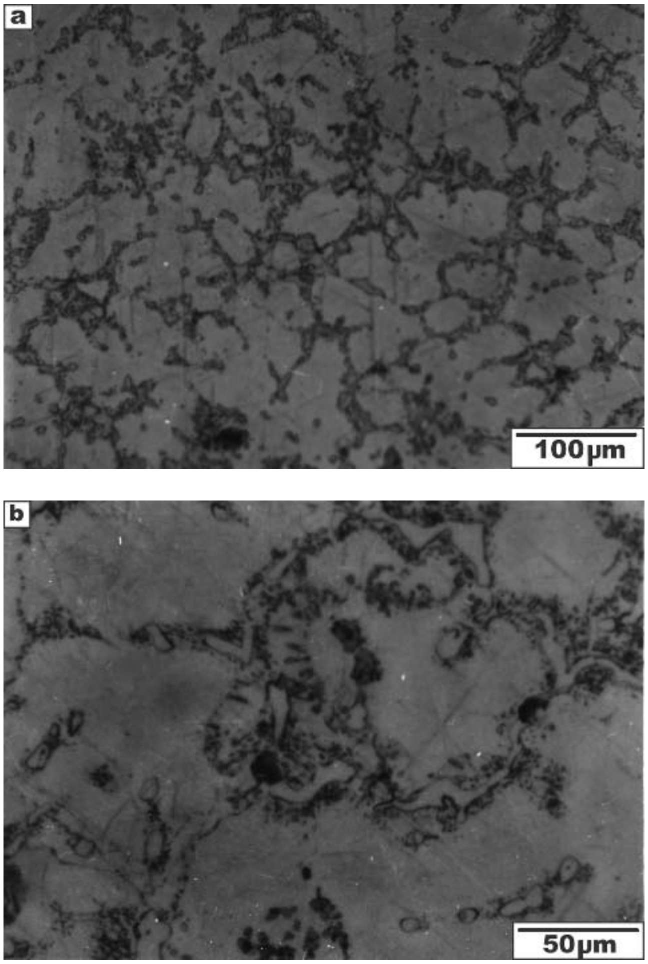

Fig. 1 Microstructure of **(a)** ZA-27 alloy and **(b)** ZA-27/6%-titanium composite

3.2 Ultimate Tensile Strength

Figure 2 shows the effect of addition of titanium dioxide on the UTS of composites. It can be seen that as the titanium dioxide content increases the UTS of the composite material. There is an increase of 26% for an addition of 6% titanium dioxide to ZA-27. It has been reported that the addition of titanium dioxide particulate to ZA-27 alloys improves the yield strength and the UTS of the composites, whereas the strain to failure decreases as the weight percentage of titanium dioxide

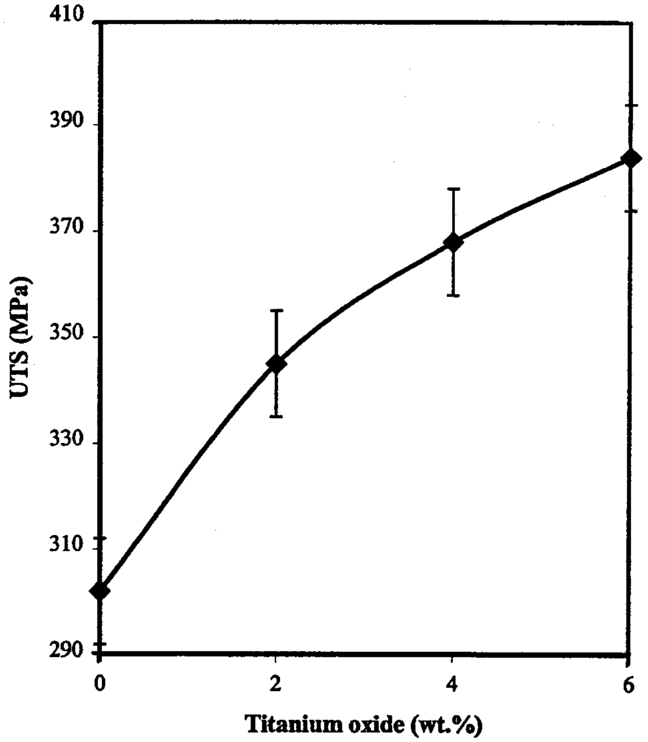

Fig. 2 Effect of titanium dioxide on ultimate tensile strength of ZA-27 alloy composites

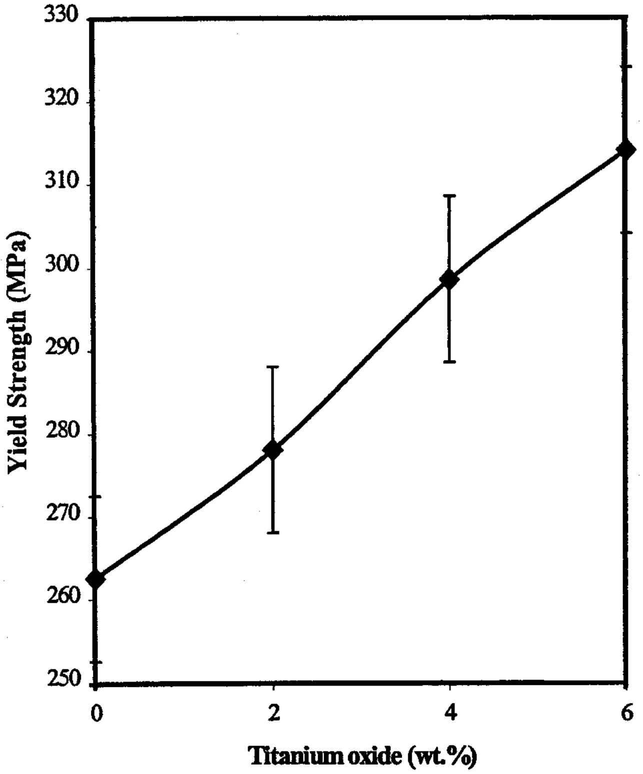

Fig. 3 Effect of titanium dioxide on ultimate tensile strength of ZA-27 alloy composites

particulate increases. Various investigators[8-10] also have reported that the addition of a hard ceramic particulate in metal alloys can lead to improved strength of the MMCs. Interphase bonding in the region of the reinforcement side wall promotes void nucleation and growth in the matrix between the side walls of the reinforcement because the shear lag transfer of load will be hindered by interphase bonding, causing more load to be carried by the matrix in this region.

3.3 Yield Strength

Figure 3 is a graph of yield strength of the composite specimen against titanium dioxide content. The graph shows an increase in the yield strength of the material, and an increase of 20% is observed for an addition of 6% titanium dioxide to ZA-27. The increase in yield was similar to the results obtained by another investigator who has worked on alumina reinforced aluminum alloy MMCs.[8] Here the reasons for the improvement in strength have been attributed to the concurrent and mutually interactive influences of residual stresses generated as a result of the intrinsic behaviors in thermal expansion coefficients between the constituents of the composites and to the constrained plastic flow and triaxility in the soft and ductile alloy matrix as a consequence of the presence of the hard and brittle particle reinforcement. However, the results obtained are in contrast with those of Dellis et al.,[11] who have observed a decrease in the strength of the composites with increasing particle content, and the reason for the same has been attributed to interface debonding between the particles and the matrix.

3.4 Hardness

Figure 4 is the graph of hardness of the composite specimens and the base alloy as a function of the titanium dioxide reinforcement. It follows from the graph that the specimens show an increase in hardness by about 10% as the content of titanium dioxide in the composite increases from 2-6%. Hardness is a measurement of resistance of the material to indentation under standards conditions. The resistance of the material is actually localized plastic deformation. The increase in hardness is quite obvious and expected since titanium dioxide is a hard dispersoid and contributes positively to the hardness of the composites. This dispersion strengthening effect is expected to remain even at elevated temperature and for extended periods of time because the particles do not react with the matrix phase. Increase in the hardness of the composite with hard dispersoids has been reported by several researchers.[12-14]

3.5 Ductility

The values of ductility, in terms of percentage elongation, measured for the as-cast composites are shown in the Fig. 5. It follows from the graph that the specimens show a decrease in ductility by about 42% as the content of titanium dioxide in the composite is increased from 2-6%. The ductility of any composite material is a complex interaction of parameters. Any variation in ductility of the resultant materials is mainly because of these parameters, and the prime factors affecting them are the matrix, the reinforcement, and their distribution.

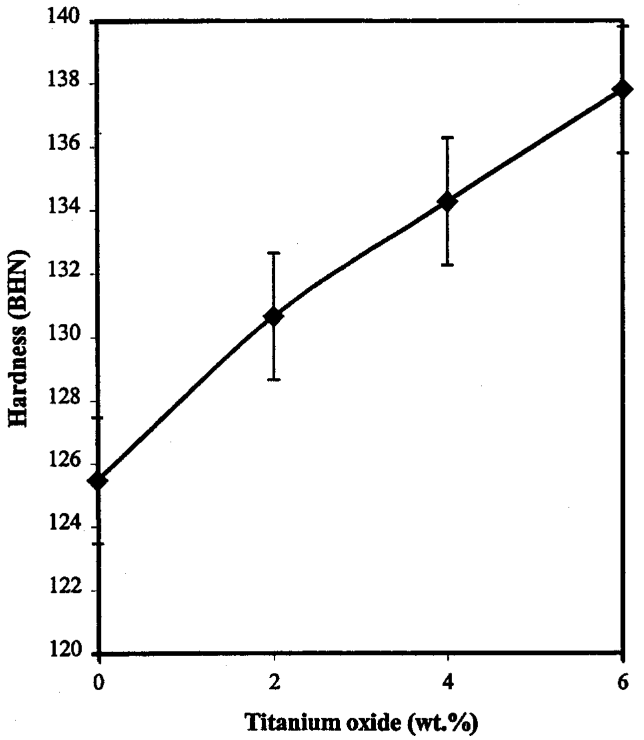

Fig. 4 Effect of titanium dioxide content on hardness of strength of ZA-27 alloy composites

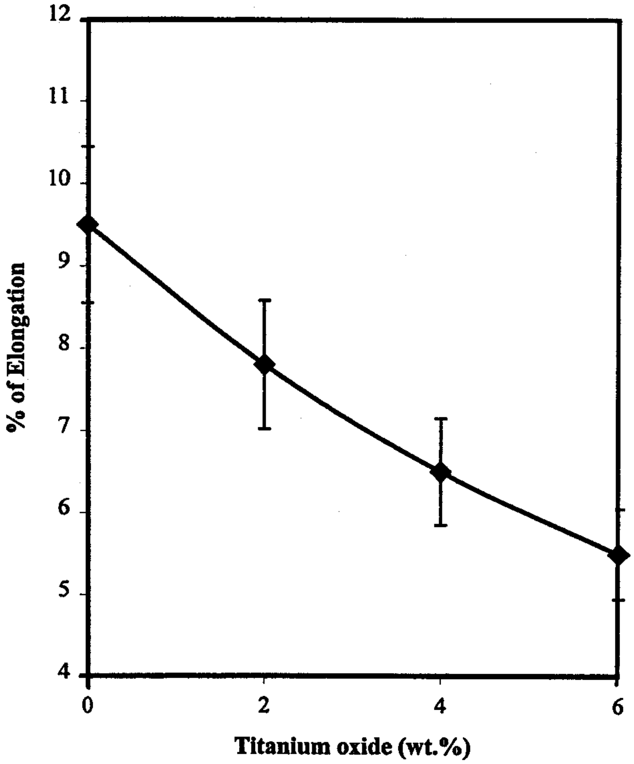

Fig. 5 Effect of titanium dioxide content on ductility of ZA-27 alloy composites

The decrease in ductility of particle-reinforced MMCs has been reported by various researchers. The observation made in the present case reveals that the fracture follows a ductile process.[14,15] The results and the behavior trends observed in the present case are similar to those obtained by various other researchers who also share the opinion that the ductility of the composite decreases with increasing reinforcement content. [16] This decrease in ductility can be attributed to the embrittlement effect that is observed as a result of the presence of hard titanium dioxide particles, which cause increased local stress concentration sites. These reinforcing particles resist the passage of the dislocations either by creating stress fields in the matrix or by inducing large difference in the elastic behavior between the matrix and the reinforcement. A few researchers[14,17] are of the opinion that this behavior may be due to void nucleation during plastic straining at the reinforcement, either by reinforcement fracture or by the de-cohesion of the matrix/dispersoid interface. Nucleation begins during the early stages of the straining and continues until final fracture. The voids grow, and coalescence occurs exactly as would be expected by a ductile-fracture mechanism. Various other workers[18,19] have also demonstrated that composite failure is associated with particle cracking and void formation in the matrix within the clusters of the particles.

3.6 Fractography and Fracture Analysis

Figure 6(a) shows the fractograph of fracture of as-cast matrix alloy, and Fig. 6(b) and (c) are fractographs depicting fracture of the as-cast composites (6%) for lower and higher magnification, respectively. Many dimples on the ZA-27 alloy are observed on some de-bonded particles seen in the fracture surface, which proves that relatively strong bonding is present between the matrix and the particle. The fracture surface of the matrix alloy has large dimples and heavy shear deformation prior to failure. However, in the case of the composite, it can be seen that the extent of ductile dimpling has decreased with the inclusion of titanium dioxide particles. The dimple size has been reduced significantly and the nature of failure of the interconnecting ligaments is by ductile tearing. Fine dimples occur in the region of matrix between the particle and those that have undergone ductile tearing.

The ceramic fails via transgranular fracture, with the fracture occurring through the particulate on the same place as the propagating cracks. The fractured specimen surface revealed a number of fractured particles; the particle fracture was often associated with the more elongated particles, which were aligned with the tensile direction and no pullout of the particulate was observed. The ZA-27 matrix fails in a ductile manner by normal void nucleation and growth.

The nature of the interface between the ductile matrix and the brittle reinforcement is shown in Fig. 6(c), a SEM micrograph of a tensile fracture surface of the composite containing 6 wt.%. This shows that there is an excellent bond between matrix and reinforcement. The strong bond allows load transfer between the matrix and reinforcement.

Researchers[20,21] studying deformation and failure mechanisms of composites have observed that the composites failed by the progressive fracture of the reinforcing particles present

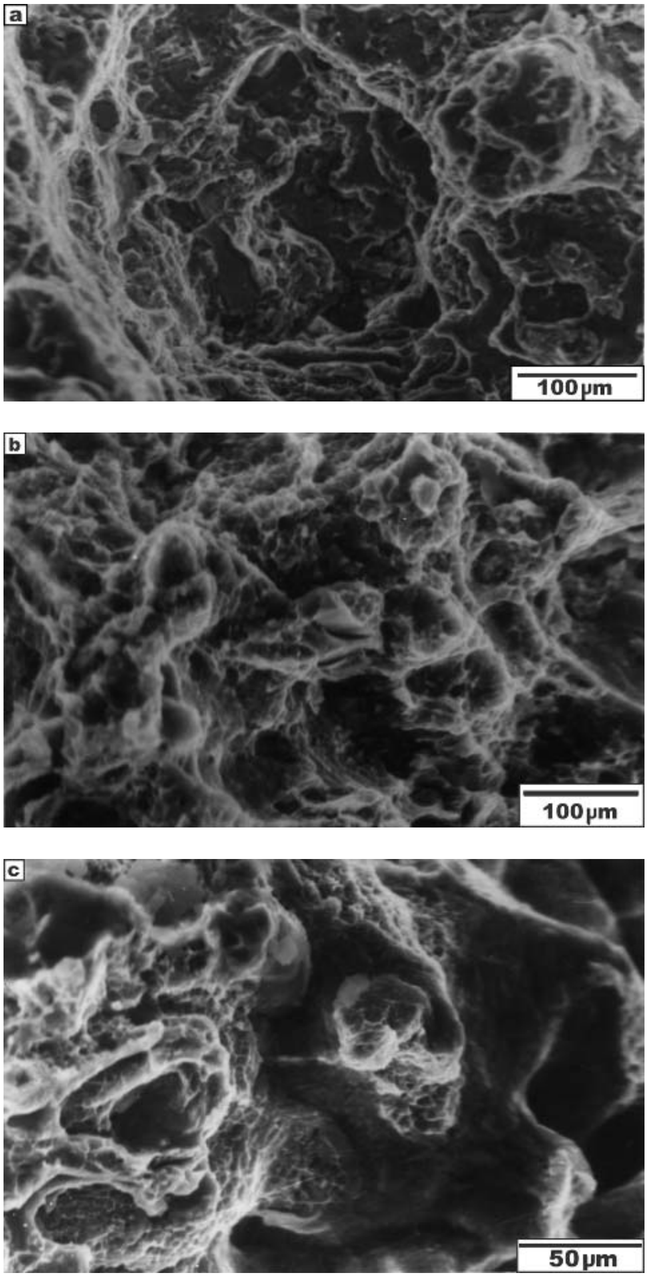

Fig. 6 Fracture surface of **(a)** as-cast ZA-27 matrix alloy, **(b)** 6% titanium dioxide reinforced ZA-27 composites with lower magnification, **(c)** fracture surface of 6% titanium dioxide reinforced ZA-27 composites with higher magnification

in the microstructure, and the final fracture of the composite results from the crack propagation through the matrix between the particles. The same observations have been made here also. The SEM provided in Fig. 7 clearly shows that the final fracture of the composites results from crack propagation through the matrix and between the reinforcing titanium dioxide particles. It is interesting to note that the fracture surfaces at high magnification reveal fracture-suggestive features of a locally ductile mechanism, even though the composites exhibited limited ductility on a macroscopic scale. The failure resulting from the uniaxial straining of the composites, such as particle checking, de-cohesion at the particle/matrix interface, and matrix-damage-like dislocations, coupled with residual stress effects may be due to the damage associated with the reinforcement. Cracks during tensile straining may be caused by the hard titanium dioxide particles, voids, or any other coarser intermetallics associated with the matrix. Such cracks produced by voids or by particle fracture then link together by ductile failure of the matrix. Hence, it becomes very essential to limit particle segregation or clustering, voids associated with particles clusters, and also to control the alloy composition so that no coarse intermetallics are included in the microstructure. Also, the observation of the tensile fracture surface clearly depicts that the fracture plane of the cracked particles is perpendicular to the loading axis, indicating the importance of the tensile stresses in inducing particle fracture. All the above observations clearly insinuate the complexity of the fracture mechanism of the composite materials as it involves several different phenomena.

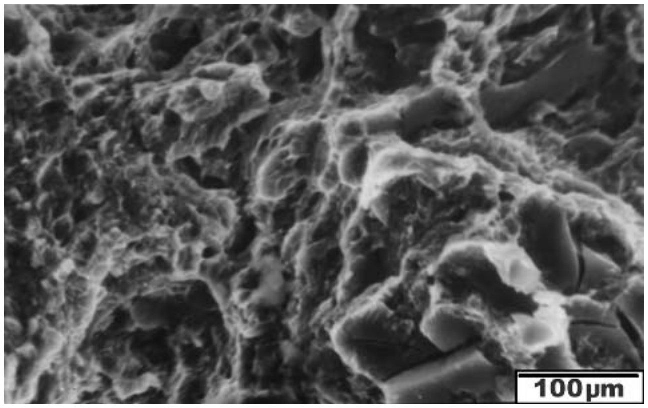

Fig. 7 The final fracture of the composites results from crack propagation through the matrix and between the reinforcing titanium dioxide particles.

4. Conclusion

The mechanical properties of the cast ZA-27/ titanium dioxide composites were considerably influenced by the inclusion of titanium dioxide particles. It was found that with an increase in percentage of titanium dioxide reinforcement from 2-6%, mechanical properties such as UTS, yield strength, and hardness increased significantly but at the cost of ductility and toughness. Therefore, in an attempt to increase the mechanical properties of the composites, a compromise is essential in deciding the content of titanium dioxide to be added so as not to sacrifice too much of its ductility and toughness. The fracture mechanism examined on a microscopic scale revealed features suggesting ductile failure. Segregation of reinforcing particles and cracking of individual particles present in the microstructure are responsible for initiation of fracture in the composites. Particle cracking obviously increases with the reinforcement content in the matrix. The final fracture of the composites is mainly because of the propagation of cracks through the matrix and the particles.

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