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Effect of Al_2O_3 Particles on the Microstructure and Sliding Wear of 7075 Al Alloy Manufactured by Squeeze Casting Method

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Aluminum (Al) alloy 7075 reinforced with Al_2O_3 particles was prepared using the stir casting method. The microstructure of the cast composites showed some degree of porosity and sites of Al_2O_3 particle clustering, especially at high-volume fractions of Al_2O_3 particles. Different squeeze pressures (25 and 50 MPa) were applied to the cast composite during solidification to reduce porosity and particle clusters. Microstructure examinations of the squeeze cast composites showed remarkable grain refining compared with that of the matrix alloy. As the volume fraction of particles and applied squeeze pressure increased, the hardness linearly increased. This increase was related to the modified structure and the decrease in the porosity. The effect of particle volume fraction and squeeze pressure on the dry-sliding wear of the composites was studied. Experiments were performed at 10, 30, and 50 N with a sliding speed of 1 m/s using a pin-on-ring apparatus. Increasing the particle volume fraction and squeeze pressure improved the wear resistance of the composite compared with that of the monolithic alloy, because the Al_2O_3 particles acted as load-bearing constituents. Also, these results can be attributed to the fact that the application of squeeze pressure during solidification led to a reduction in the porosity, and an increase in the solidification rate, leading to a finer structure. Moreover, the application of squeeze pressure improved the interface strength between the matrix and Al_2O_3 particles by elimination of the porosity at the interface, thereby providing better mechanical locking.

Keywords 7075 Al alloy, Al_2O_3 particles, composites, microstructure, squeeze casing, stir casing method, wear mechanism

1. Introduction

Metal matrix composites (MMCs) have proved their viability as good alternatives to conventional alloys in high-strength and stiffness applications,[1,2] but they are still a long way from high-volume commercial production. Cost is the key factor for the wider application of MMCs in modern industry. Particle-reinforced MMCs offer moderate improvements in stiffness and strength, accompanied by serious ductility and fracture toughness reductions, but are attractive due to their relatively low cost and ease of fabrication. MMCs are generally fabricated either by casting process or powder metallurgy. Some of the processes commonly used in casting, which is more economical than powder metallurgy, are stir casting, compocasting, and squeeze casting. Relatively few studies have investigated the use of advanced solidification techniques, such as squeeze casting, which tends to have a high level of process controls, to fabricate particle-strengthened MMC components. Squeeze casting is a versatile processing method for the fabrication of Al- and Mg-based MMCs. As an industrial process, squeeze casting is attractive because it allows the rapid production of near-net-shaped MMC components, with good shape tolerance and surface finish.[3] However, to eliminate defects in the final components, squeeze-casting conditions need to be carefully controlled, and optimum conditions vary depending on the matrix alloy and reinforcement type.[4]

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The present work was undertaken to manufacture 7075 Al matrix composites reinforced with Al_2O_3 particles of different volume fractions using the vortex method followed by squeeze casting. Microstructural characterization studies were carried out to establish the feasibility of the squeeze-casting parameters. Moreover, the microstructures of the composites were correlated with wear properties. Finally, the wear mechanisms that are operative in the composites were investigated to aid in the correlation of the microstructure and properties of the composites.

2. Experimental

7075 Al was used as a matrix throughout the course of this investigation. The chemical composition of the matrix alloy is as follows: 5.8% Zn, 1.9% Cu, and 2.4% Mg, with the balance Al. The reinforcement used was Al_2O_3 particles in the size range of 60-80 μm. Pre-treatment of the Al_2O_3 particles before adding them to the melt using the vortex method was essential to introduce the reinforcements into the molten matrix. Also, the addition of 1% Mg to the melt improved wetting between the reinforcement and matrix. The composite melt was poured into a preheated tool steel die, usually via a founder system, with the ram driven vertically downward to apply different squeeze pressures, which were maintained until solidification

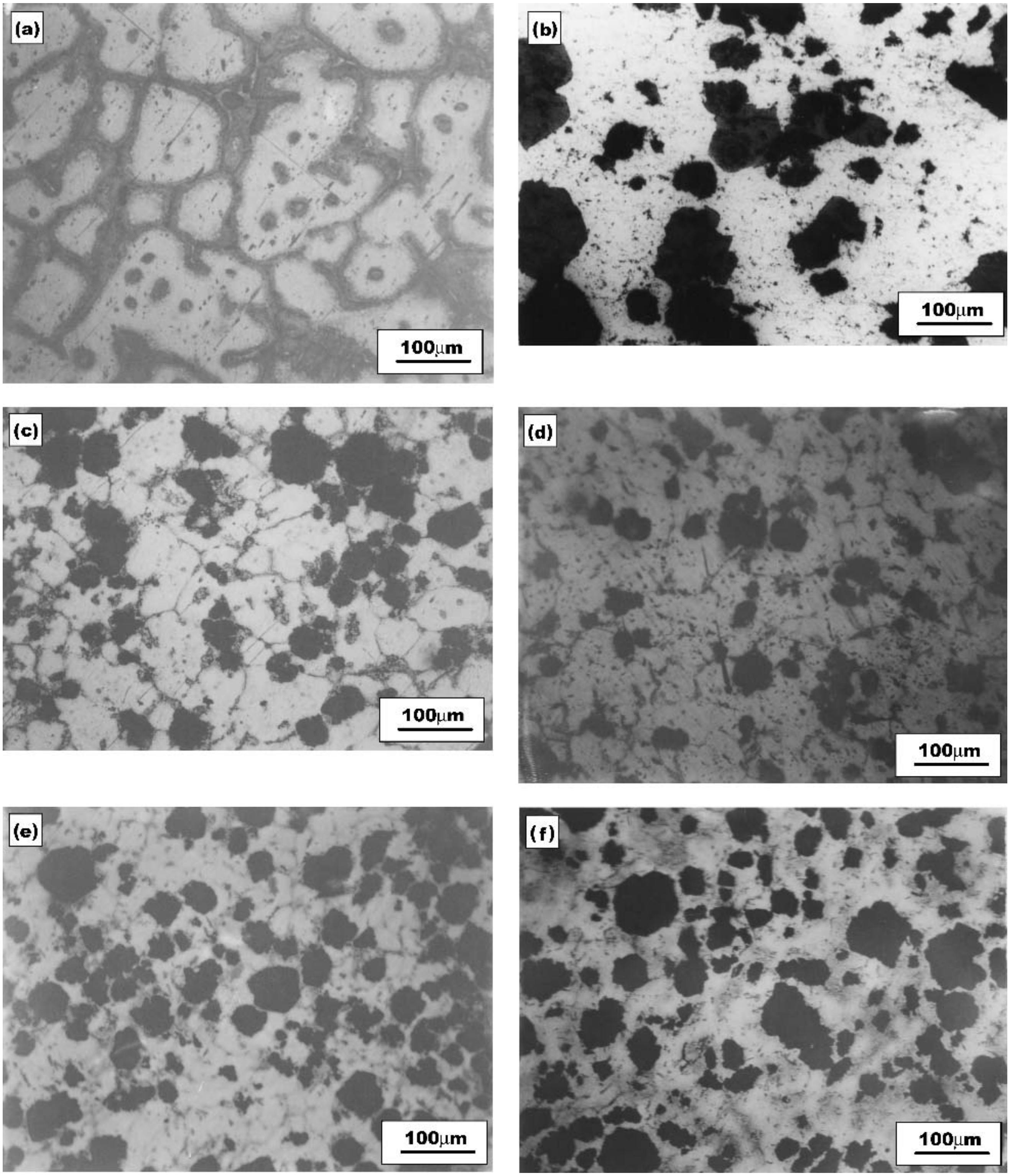

Fig. 1 Microstructure of the 7075 Al alloy reinforced with Al_2O_3 particles and squeeze cast at different pressures. **(a)** matrix 25 MPa; **(b)** matrix 50 MPa; **(c)** 5% Al_2O_3 25 MPa; **(d)** 5% Al_2O_3 50 MPa; **(e)** 20% Al_2O_3 50 MPa; **(f)** 20% Al_2O_3 25 MPa

was complete. The process conditions used for the alloys having 5-20 vol.% Al_2O_3 particles were as follows: melt temperature (T_m) = 750 °C; die temperature = 300 °C; ultimate squeeze pressure = 25 or 50 MPa; and holding time = 2 min. The cast composites were cut to suitable specimen sizes for experimentation and examination. Optical microscopy was used to reveal the microstructural features and the distribution of the particles.

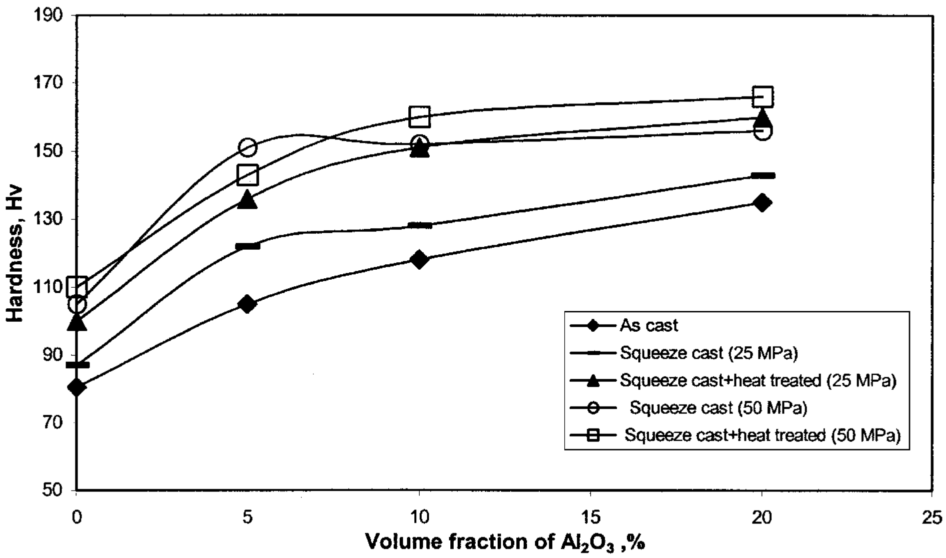

Fig. 2 Hardness vs volume fraction of Al_2O_3 particles of squeeze-cast and heat-treated 7075 Al-Al_2O_3 composites

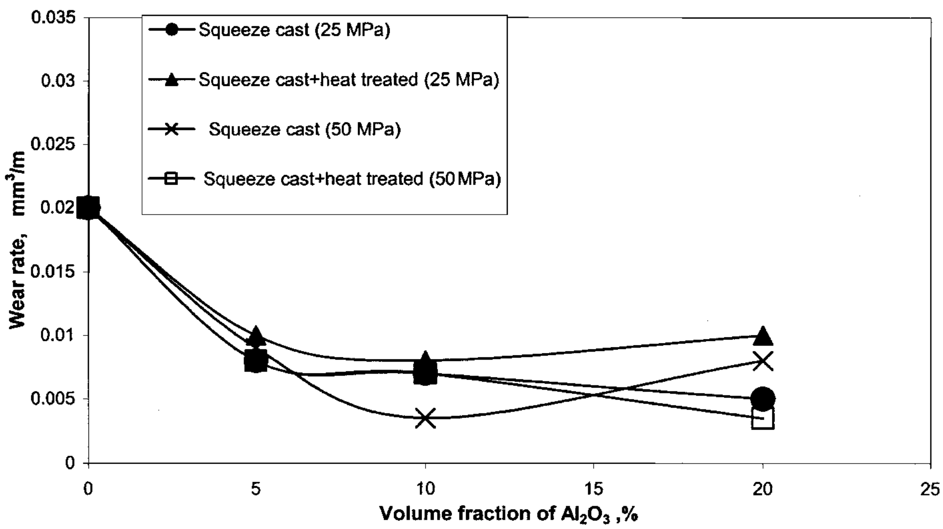

Fig. 3 Wear rate of the squeeze-cast 7075 Al-Al_2O_3 composite as a function of particulate volume fraction at different squeeze pressures (test load, 10 N)

Some specimens were heat treated after machining. The heat treatment consisted of a solution heat treatment at 490 °C for 2 h followed by quenching to room temperature (RT). The samples were then artificially aged for 8 h at 120 °C. The hardness of the alloys was measured using a Vickers hardness tester.

The wear tests were performed on a tribometer of the pin-on-ring type. Wear pins 8 mm in diameter by 15 mm in length were rubbed against the curved surface of an SAE1045 steel ring, 73 mm in diameter with its surface hardened to 62 Rockwell hardness (Rc). The surface roughness (R_a) values for the specimens and ring before the test were 0.4 μm and 0.2 μm, respectively. The rotational speed of the ring was always 265 rotations per minute, which corresponded to a linear velocity at the friction interface of 1 m/s. The applied test loads were 10, 30, and 50 N. All wear tests were carried out without any lubrication at a relative humidity of approximately 65% and at RT. The tests were carried out without interruption for 1 h. The reduction of pin height against sliding distance was continuously recorded during the test. The worn surfaces of the pins after the wear tests were examined using a scanning electron microscope (SEM) to characterize the nature of the surfaces. Finally, the worn samples were mounted and then sectioned into two halves lengthwise using a low-speed saw. The sectioned samples were prepared for metallographic investigation.

3. Results and Discussion

3.1 Microstructure

Representative microstructures of the as-cast and squeeze-cast 7075 Al and composites are shown in Fig. 1. In the case of

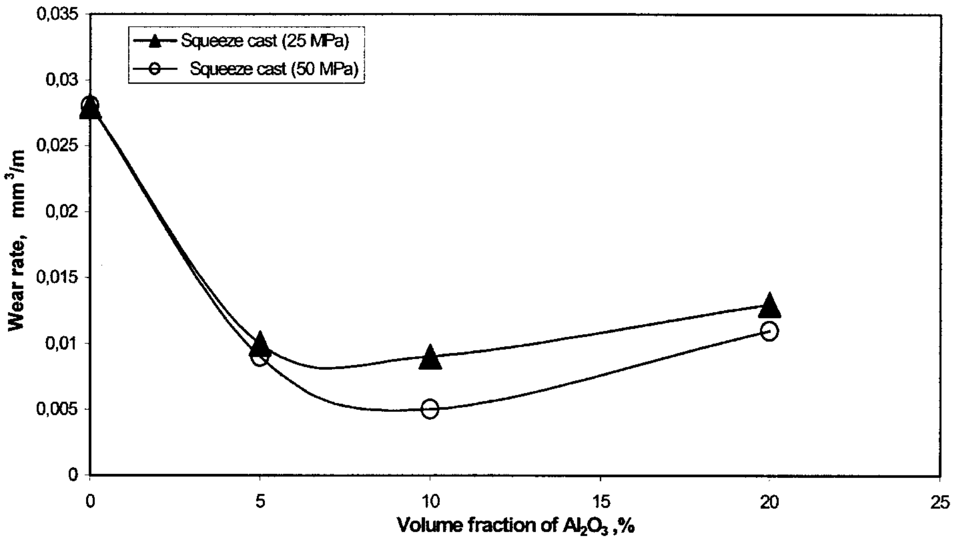

Fig. 4 Wear rate of the squeeze-cast 7075 Al-Al_2O_3 composite as a function of particles volume fraction at different squeeze pressures (test load: 30 N)

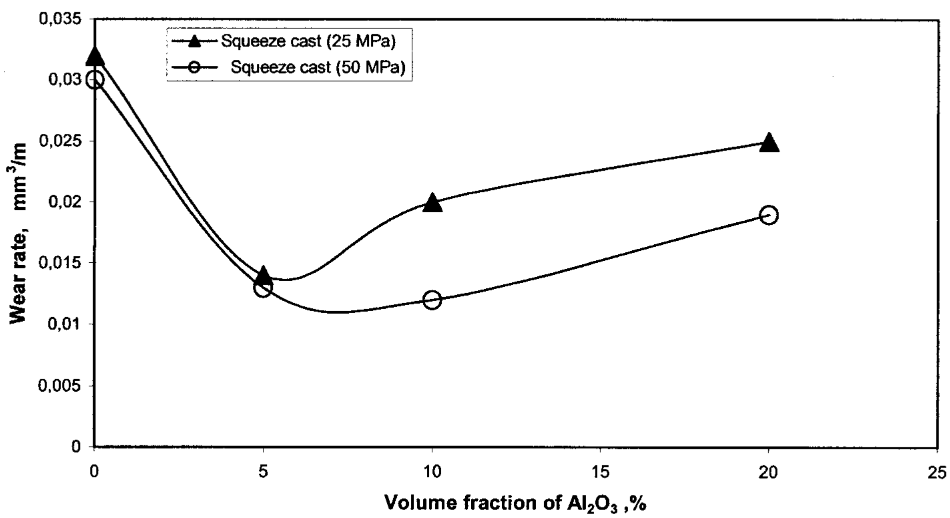

Fig. 5 Wear rate of the squeeze-cast 7075 Al-Al_2O_3 composite as a function of particle volume fraction at different squeeze pressures (test load, 50 N)

the as-cast composites (Fig.1b), particle agglomeration and porosity can be seen. This is due to imperfect wetting and vortex creation during the addition of particles, in which air gets trapped in the melt without being able to escape due to the increased viscosity of the melt due to the particle additions. The presence of particles in the 7075 Al affects the dendrite structure, which is refined compared with the as-cast 7075 Al.[5-7] This refinement may be caused by the accumulation of Al_2O_3 particles in the liquid between the growing dendrites, which seems to inhibit continued dendritic growth, and by the smaller amount of latent heat per unit volume of the composites compared with the matrix Al, which leads to a higher cooling rate during solidification, which in turn reduces the solidification time. The distribution of the Al_2O_3 particles in the solidified microstructure indicates that the nucleation of α-Al appears to occur away from the Al_2O_3 particles. The α-Al dendrite pushes the particles into the last regions of freezing liquid and traps them in the interdendritic regions. It appears that with an increase in the squeeze pressure, the microstructure becomes finer due to a higher cooling rate. Also, the microstructure shows the absence of porosity, which indicates that the squeeze parameters selected in the current study were adequate in closing any pores present in the casting. Moreover, the microstructure of the squeeze cast samples reveals an improvement in the particle dispersion even though there is some damage to the particles (Fig. 1c-f).

3.2 Hardness

Figure 2 shows the relationship between hardness and the particle volume fraction in the case of the as-cast and squeeze cast materials at pressures of 25 and 50 MPa. The hardness

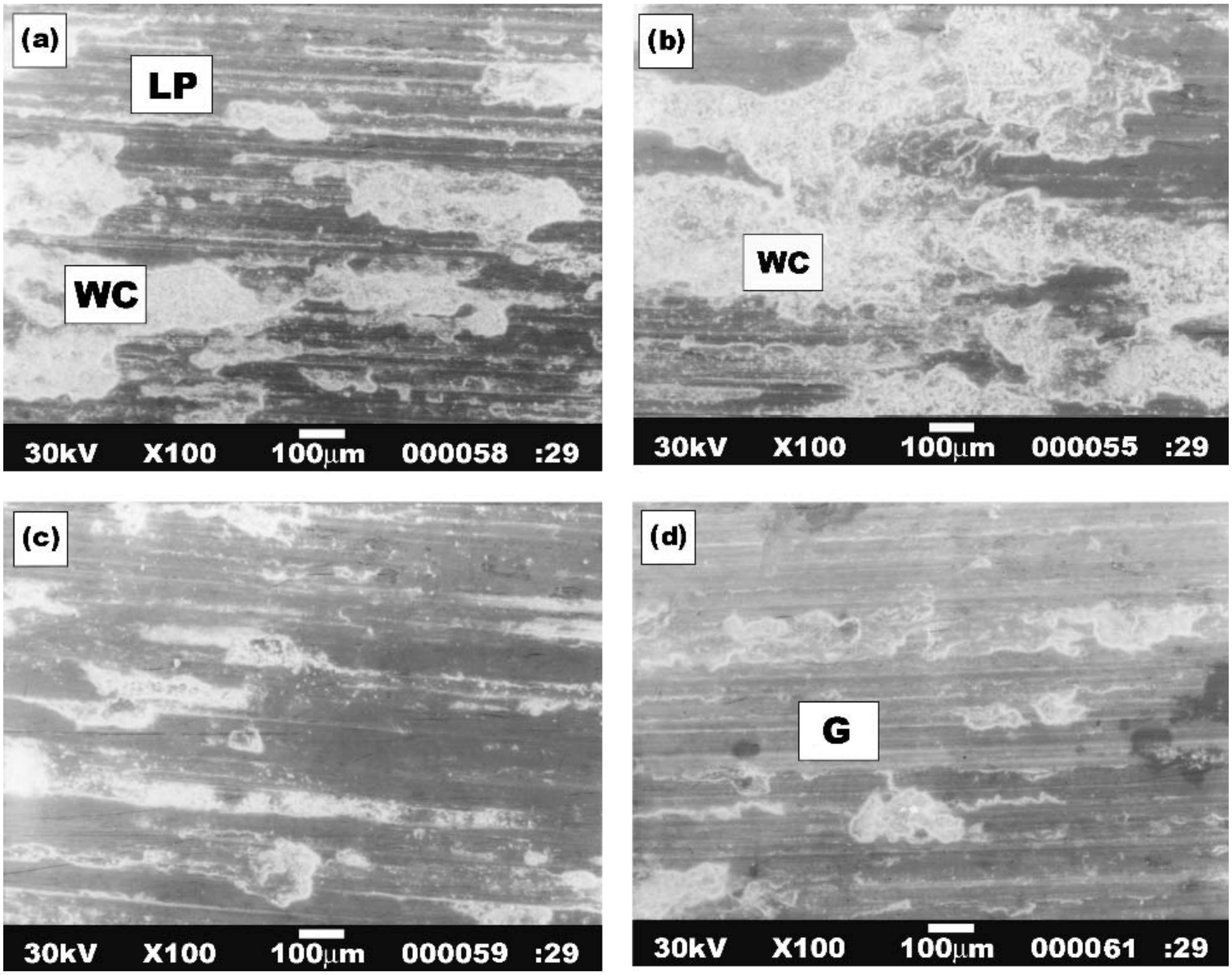

Fig. 6 SEM of the worn surfaces of squeeze cast 7075 Al matrix alloy and 7075 Al-5% Al_2O_3 composites at squeeze pressure of 25 MPa and different test loads. **(a)** matrix, test load: 30 N; **(b)** matrix, test load: 50 N; **(c)** composite, test load: 30 N; **(d)** composite, test load: 50 N

values of the composites increase with increasing Al_2O_3 particle volume fraction. The results also reveal that as the applied pressure increases, the hardness of the matrix alloy increases. The same trend also occurs in the composites. It can be seen that a T6 heat treatment has a significant effect on hardness for a composite cast at a pressure of 25 Mpa but has a lesser effect on the hardness of the composite cast at a pressure of 50 MPa.

3.3 Wear Behavior

Figure 3 shows the effect of Al_2O_3 particle volume fraction on the wear rate of materials that have been squeeze cast (25 and 50 MPa squeeze pressures), and squeeze cast and heat treated at a load of 10 N. Generally, increasing the volume fraction of the particles or the squeeze pressure improves the wear resistance of the composites. However, the effect of increasing volume fraction of the particles from 10-20 vol.% on the wear rate is less notable. However, heat treating of the composites to the T6 condition has a marginal effect on the wear resistance. Figures 4 and 5 show the effects of different loads, namely, 30 and 50 N, on the wear rate of the investigated composites. In comparing Fig. 3 and 4, it was noticed that, as the applied load increased from 10-50 N, the wear rate significantly increased. Thus, it can be concluded that the wear rate of the composites depends on the applied squeeze pressures, the applied load, and the particle volume fraction.[8,9]

3.4 Morphology of Worn Surfaces

The morphology of the worn surfaces of the unreinforced 7075 Al and the cast composites at different loads are presented in Fig. 6 and 7. The wear surfaces of the unreinforced alloy (Fig. 6a,b) consist of long smooth patches (marked as “LP” in Fig. 6a) interspersed by white large craters (marked as “WC” in Fig. 6a). Fine grooves and flow marks in these smooth patches can be seen. A cracked region in the middle suggests that a crater is formed when material is removed from such spots and these craters are filled by wear debris generated during the test. An increase in the magnitude of the test load from 10-50 N increases the number and size of the wear craters. Generally,

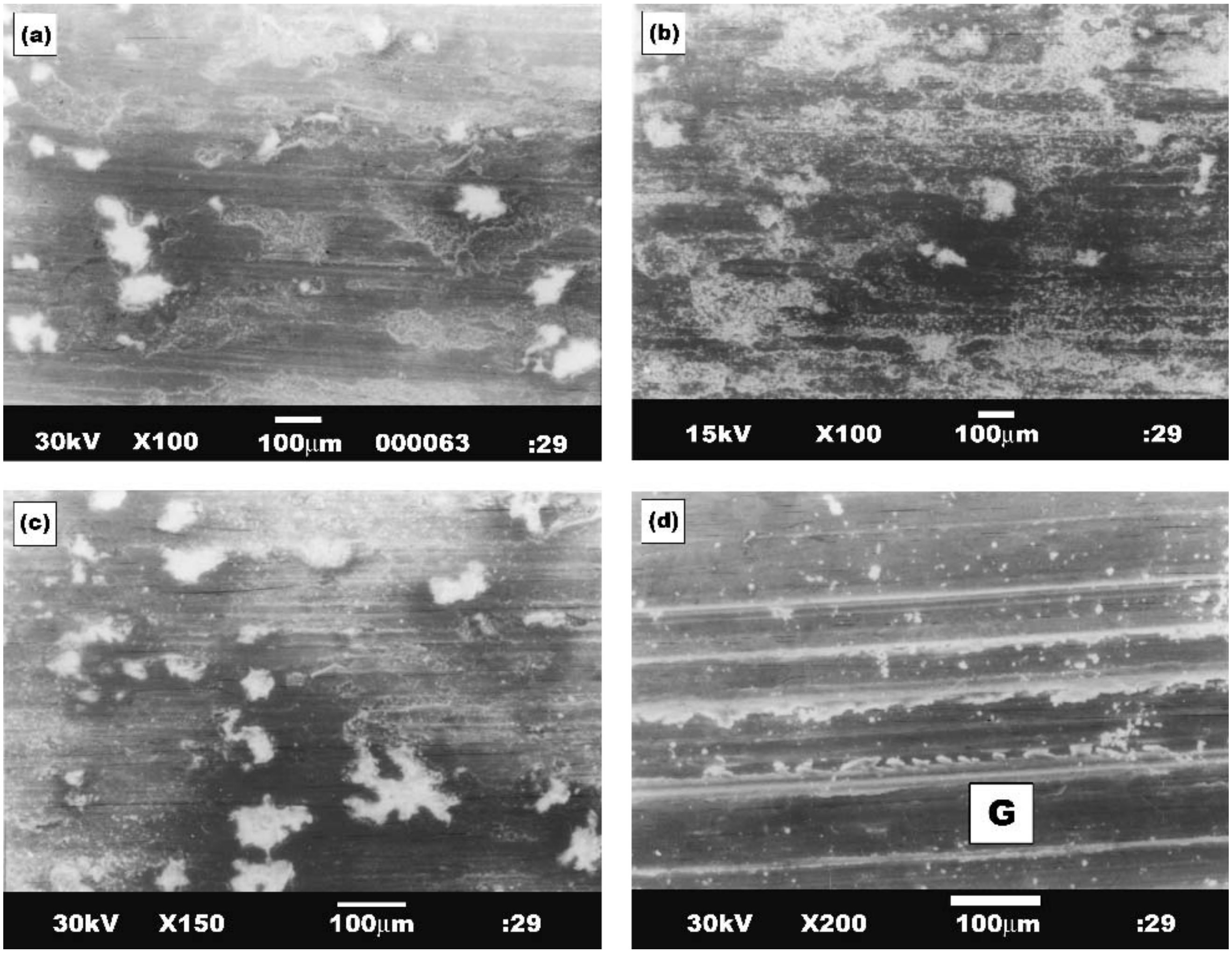

Fig. 7 SEM of the worn surfaces of squeeze-cast 7075 Al-20vol.% Al_2O_3 composites at different squeeze pressures and test loads. **(a)** squeeze pressure: 25 MPa, test load: 30 N; **(b)** squeeze pressure: 25 MPa, test load: 50 N; **(c)** squeeze pressure: 50 MPa, test load: 30 N; **(d)** squeeze pressure: 50 MPa, test load: 50 N

the worn surfaces of the unreinforced 7075 Al alloy tested at loads of 30 and 50 N are characterized by severe plastic deformation and other damage in the form of wear craters. In the case of 7075 Al-5vol.% Al_2O_3 tested at loads of 30 and 50 N (Fig. 6c,d), the worn surfaces predominantly reveal grooves (marked as "G" in Fig. 6d) in the sliding direction with extensive lip formation along the groove walls. The presence of grooves in the sliding direction and white patches on the worn surface can be observed. Scattered, very small wear craters can be observed, which increase in number with increasing load from 10-50 N (Fig. 7c,d). However, at a load of 30 N, analysis of the worn surface of the 7075 Al-Al_2O_3 composite shows the presence of higher Fe content in comparison to that of the matrix alloy and composites tested at a load of 50 N (Fig. 8b,c). The presence of a high Fe content on the surface of the composite pin can be explained as follows: the Al_2O_3 particles create a local milling action on the steel disk and cause formation of longitudinal microgrooves on its surface. The detached wear fragments from the steel disk are transferred onto the contact surface of the composite, which leads to an increase in the Fe content on the worn surface of the composite pins. Increasing the squeeze pressure during composite casting significantly reduces the damage and plastic deformation on the worn surface, as shown in Fig. 6. Also, it can be seen that small holes are created by the dislodged Al_2O_3 particles. At a load of 50 N, the morphology of the composite wear surface reveals more fractured particles, and, in addition, micro-grooves, which were formed by the fractured Al_2O_3 particles rubbing against the matrix (Fig. 7), also were found on the matrix material. An analysis of the wear surfaces of all the tested composites showed the presence of high Fe content for all squeeze pressures (i.e., 25 and 50 MPa) and test loads (i.e., 10, 30, and 50 N).

3.5 Subsurface Features

The features associated with the region just beneath the worn pin surface in the case of the 7075 Al alloy and the composites are presented in Fig. 9. At a load of 50 N, the unreinforced matrix shows a degraded layer of material as the

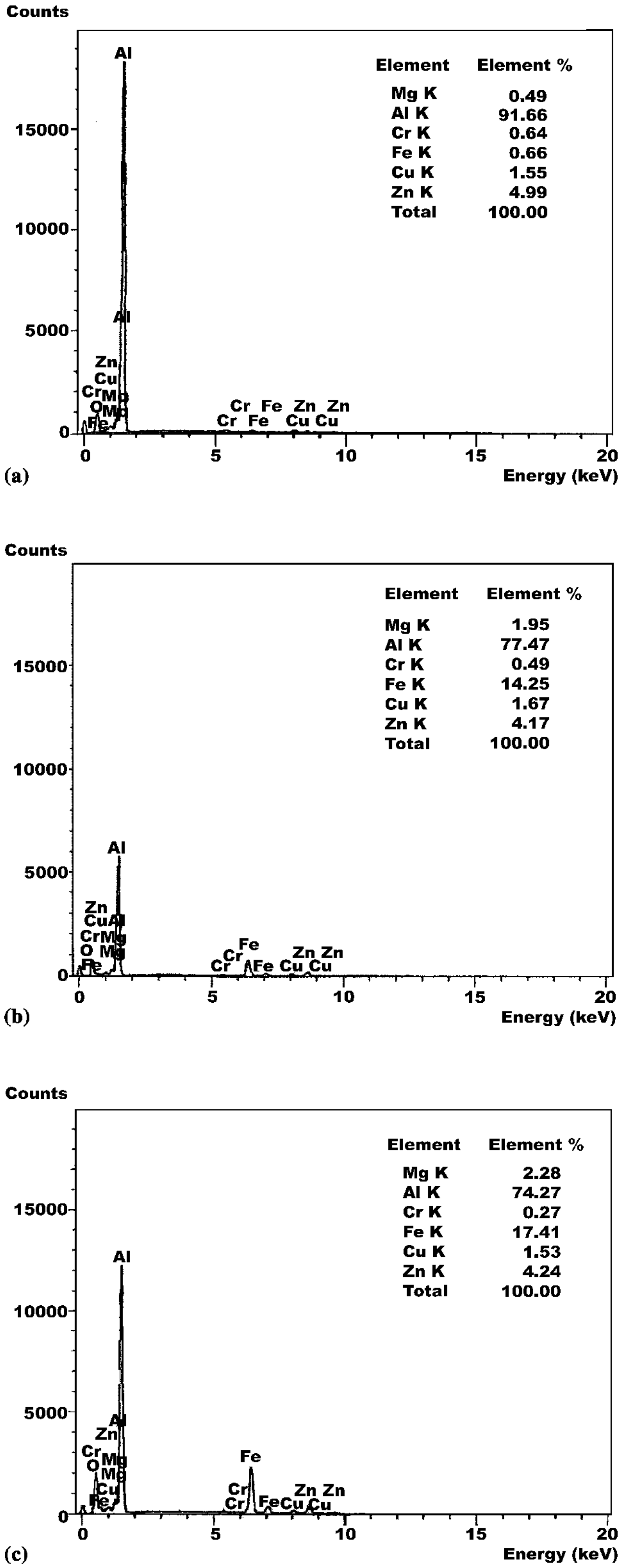

Fig. 8 Analysis of the worn surfaces of the unreinforced alloy and composites: **(a)** 7075 Al test load, 30 N; squeeze pressure, 25 MPa; **(b)** 7075-20vol.% Al_2O_3 Al test load, 30 N; squeeze pressure, 25 MPa; **(c)** 7075-20 Al_2O_3 Al test load, 50 N; squeeze pressure, 25 MPa

matrix undergoes plastic deformation, indicating that matrix deformation plays a key role in the wear behavior of this material (Fig. 9a). Also, severe cracking in the subsurface region can be seen. On the other hand, the layer of degraded material is not present in all composites, and the matrix does not appear to be damaged by the wear test. The Al_2O_3 particles are intact, even those very close to the sliding surface. No interfacial de-bonding between the particles and the matrix was observed as a result of the good interfacial strength developed in these composites. The incidence of subsurface cracking appears to be noticeably lower in the composites when compared with the unreinforced 7075 Al.[10] Thus, the combined effect of increasing the Al_2O_3 particle volume fraction in the composite and applying high squeeze pressures during solidification of the composites tends to reduce the extent of plastic deformation in the subsurface region of the matrix, thereby delaying the nucleation and propagation of subsurface microcracks (Fig. 9b-e).

In summary, the hardness and wear tests performed at loads of 10, 30, and 50 N indicate that the composites possess higher hardness and better wear resistance than the unreinforced alloy. The higher hardness and wear resistance of the composites can be attributed to the presence of Al_2O_3 particles, which act as load-bearing elements. The particles should maintain their structural integrity during sliding wear to remain effective load-bearing elements. At loads up to 50 N, the local stresses generated beneath the slider appear to be lower than the fracture strength of the particles. The surface of the composite is suitable to facilitate the transfer of the applied load directly onto the particles, because the Al_2O_3 particles stand proudly from the contact surface. Hence, the particles are considered to be useful in preventing the softer matrix from becoming directly involved in the wear process. Also, the exposed portions of the particles create a local milling action against the steel disk, resulting in iron oxides covering the wear surface, thereby providing a type of in situ lubrication. Once these layers have formed, they spread almost continuously over the wear surfaces of the composite samples (Fig. 8), and, therefore, the steel counter-face is in contact with a mixture of Fe and its oxides. Wear proceeds by the spalling and reformation of these layers. The Fe oxides have low coefficients of friction and, thus, provide in situ lubrication, which reduces the overall wear of the composites (Fig. 4-6).

Also, these results can be attributed to the fact that the application of squeeze pressure during solidification leads to the reduction in porosity by excellent feeding of shrinkage areas during solidification. An increase in the solidification rate results in a finer structure.[11,12] Moreover, the application of squeeze pressure improves the interfacial strength between the matrix and Al_2O_3 particles by eliminating the porosity at the interface, which leads to better mechanical locking of the particles.

4. Conclusions

1) The presence of Al_2O_3 particles in the 7075 Al alloy and the application of squeeze pressure during the solidification of the composites lead to a finer structure for the composites.

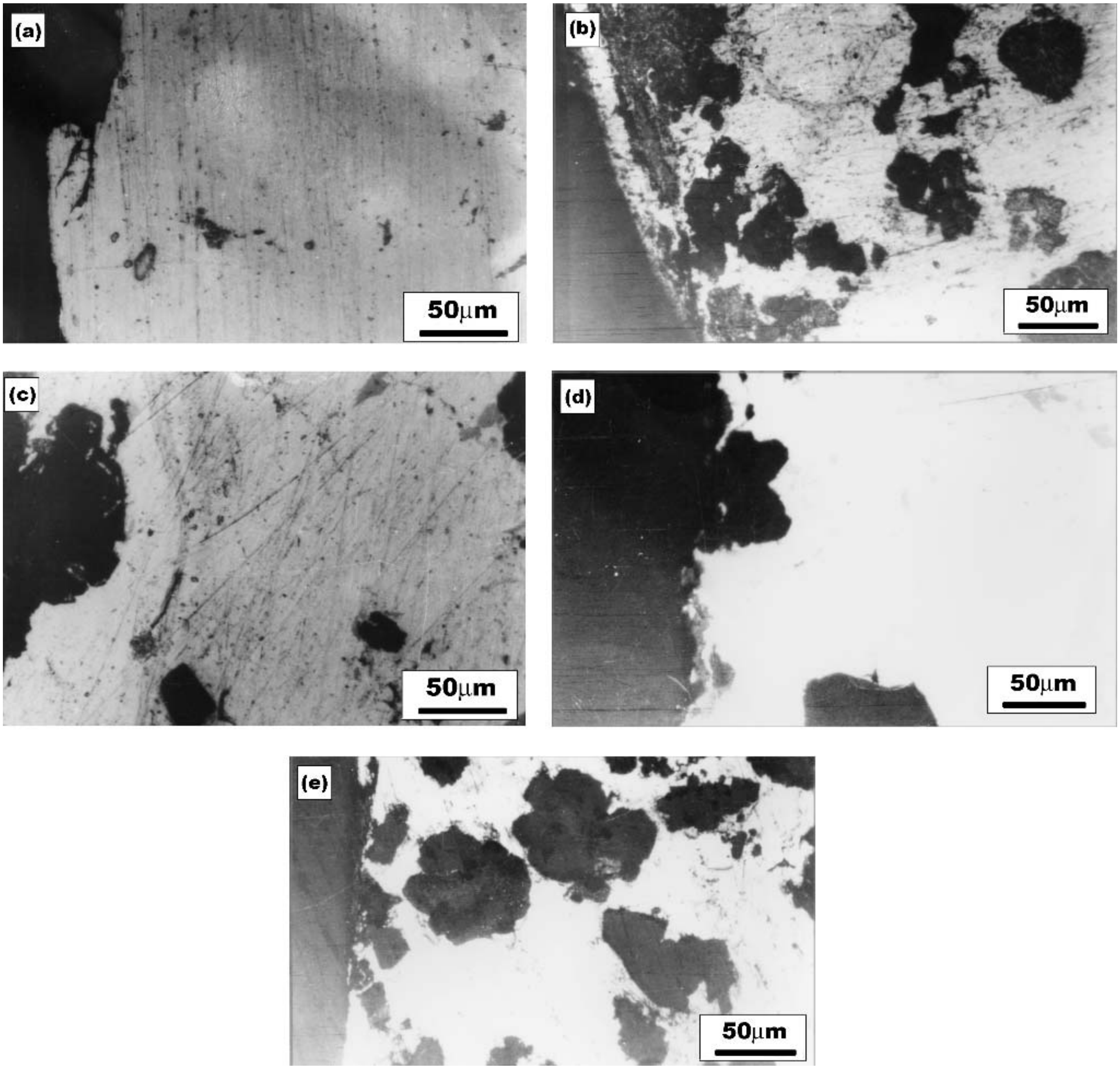

Fig. 9 Micrographs of the subsurface features obtained beneath the worn surfaces of squeeze-cast 7075 Al matrix alloy and 7075 Al-Al_2O_3 composites at different squeeze pressures and test loads. **(a)** matrix, 25 MPa; **(b)** 5% Al_2O_3, 50 MPa; **(c)** 5% Al_2O_3, 25 MPa; **(d)** 20% Al_2O_3, 25 MPa; **(e)** 20% Al_2O_3, 50 MPa

2) The application of squeeze pressure also improves the interfacial strength between the matrix and Al_2O_3 particles by eliminating excess porosity at the interface, thereby improving the mechanical locking of the particle to matrix.
3) The hardness increases linearly with an increasing volume fraction of particles and/or the applied squeeze pressure due to the finer structure and decreased porosity of the squeeze cast composites.
4) The squeeze cast composites exhibit better wear resistance than that of the unreinforced alloy, due to the application of squeeze pressure and the presence of the Al_2O_3 particles, which act as load-bearing elements during sliding wear.

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