

# Corrosive Wear Behavior of 7075 Aluminum Alloy and Its Composite Containing Al<sub>2</sub>O<sub>3</sub> Particles

S.K. Varma and Gustavo Vasquez

(Submitted 19 March 2002; in revised form 20 September 2002)

Corrosive wear behavior of 7075 aluminum alloy and a composite containing 0.10 volume fraction of alumina particles (VFAP) has been evaluated. Transient current (TC) generated as a result of impacting a rotating cylindrical electrode immersed in a 0.1M NaCl solution with a Vickers diamond hardness indenter has been used to measure the corrosive wear response. Age hardenable 7075 alloy shows TC values that are sensitive to prior solutionizing time. The effect of alumina particles in a 7075 aluminum alloy matrix has been studied by comparing the TC values of a monolith along with composites under almost identical experimental conditions. The role of microstructural features associated with composites, such as dislocations generated after solutionizing treatment and during the corrosive wear process, has been observed with the help of near surface microstructures through transmission electron microscopy (TEM). Deformation induced dislocations, as well as those that are due to differences in the coefficient of thermal expansion (CTE) values between the particles and the matrix during solutionizing, have been attributed to the experimentally observed TC values. They may also be affected by the aging response of the monolith and composites, depending on solutionizing time.

**Keywords** 7075 aluminum alloy, Al<sub>2</sub>O<sub>3</sub>, ceramic particles, wear behavior

## 1. Introduction

Composites of aluminum alloys reinforced with ceramic particles are the materials that can show high strength-to-weight ratio and may be very desirable for many applications. A loss of ductility with gain in strength is usually one of the sacrifices one has to consider when using composites. However, corrosive wear is another property of interest when selecting materials that are suitable for many engineering design criteria.

The combined action of corrosion and wear is a complicated process since they may interfere with each other in a very destructive manner and reduce the useful life of a component. Corrosive wear in 6061 and 2014 aluminum alloys in the monolith form as well as composites reinforced with alumina particles have been investigated<sup>[1,2]</sup> by using a modified scratch technique. It was initially developed<sup>[3-9]</sup> for new experimental Fe-Cr-Ni alloys. It consists of dropping an indenter, from a known height, onto a rotating cylindrical electrode immersed in an electrolyte and measuring the transient current (TC). This technique is a very effective and convenient method of measuring magnitude of corrosive wear. It has been used to determine the correlation of corrosive wear characteristics to microstructural features such as grain size,<sup>[6]</sup> dislocations in the homogeneously distributed and cellular forms,<sup>[4]</sup> and annealing and deformation twins.<sup>[3]</sup>

Fang et al.<sup>[10]</sup> reported the effect of reinforcement with 10, 15, and 20 vol.% alumina particles in 6061 aluminum alloy on

their corrosive wear behavior. Although reinforcing particles have a detrimental effect on corrosion, the authors found that the corrosive wear was decelerated.<sup>[10]</sup> This 6061 aluminum alloy is an age hardenable alloy, and the effect of solutionizing time on the TC values was investigated<sup>[2]</sup> by the scratch technique. Results indicate that the TC values almost remain constant as a function of solutionizing time in the composite reinforced with 0.10 volume fraction of alumina particles (VFAP), while the monolith undergoes a considerable amount of corrosive wear. However, similar experiments on 2014 aluminum alloy show that the composite exhibits rather high TC values and indicated an increasing trend with an increase in solutionizing time. It may thus be concluded that the alloying elements in the base metal may be a cause for the differences in the corrosive wear behavior of the two composites.

Solutionizing at an elevated temperature followed by the quenching operation in water can result in the generation of a large number of dislocations and vacancies in the matrix. It is considered to be due to the differences in the coefficient of thermal expansion (CTE) values between the matrix and the reinforcing particles. Thus the dislocations are known as CTE dislocations. Dislocations generated due to the plastic deformation by wear in the matrix and CTE dislocations formed due to the solutionizing treatment can both act as the anodic site for the corrosion to take place and thus result in higher TC values. Microstructural evidence has been presented<sup>[11]</sup> to indicate high dislocation density around the alumina particles, and the dislocation density increases with increase in solutionizing time, particle size, and VFAP.

**Table 1** Nominal Composition of 7075 Aluminum Alloy in wt.%<sup>[15]</sup>

Mg	Cu	Zn	Cr	Si	Fe	Mn
2.5	1.6	5.6	0.23	0.4	0.5	0.3

S.K. Varma and Gustavo Vasquez, Department of Metallurgical and Materials Engineering, The University of Texas at El Paso, El Paso, Texas 79968-0520. Contact e-mail: skvarma@utep.edu.

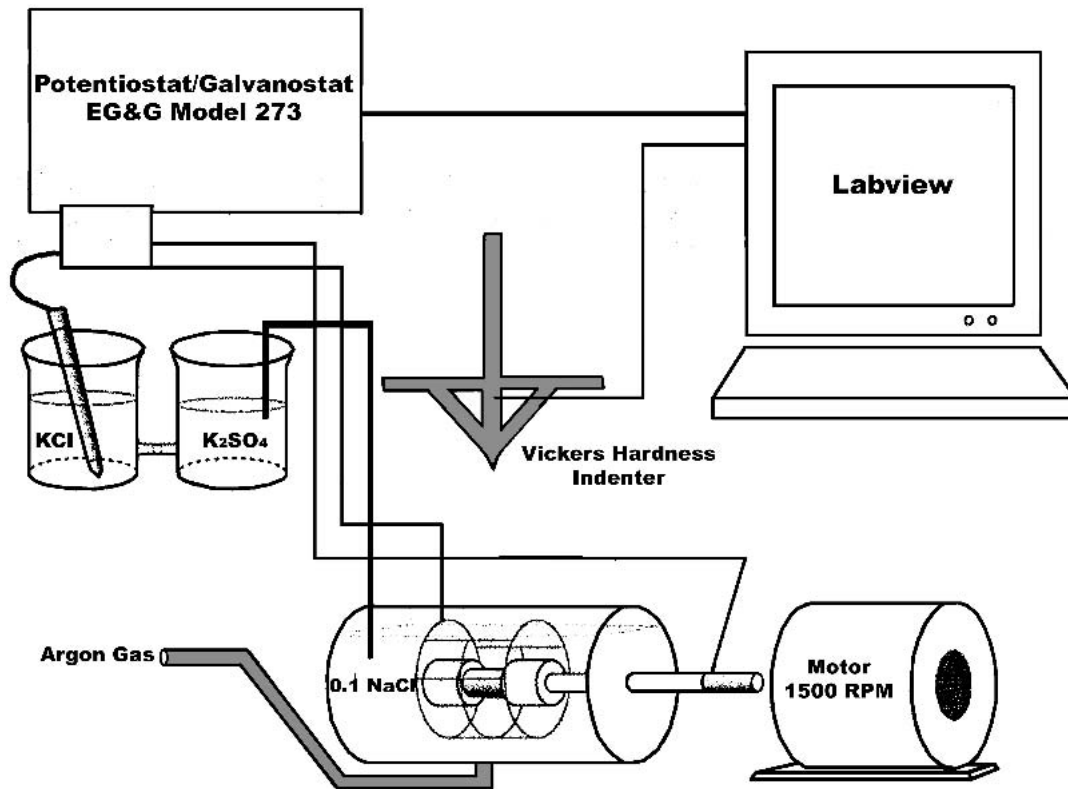


Fig. 1 A schematic diagram of the experimental setup of this study

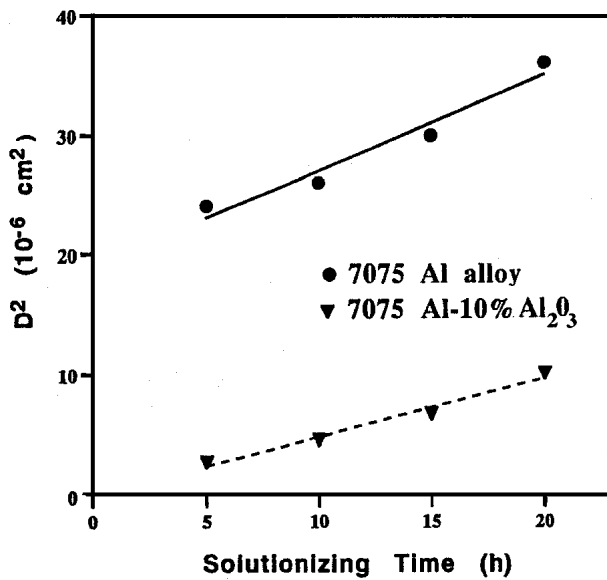


Fig. 2 Square of grain diameter as a function of solutionizing time for the monolith of 7075 aluminum alloy and its composite reinforced with 0.1 VFAP at a temperature of 520 °C

This article presents the results of a study that investigated the effect of solutionizing time on the corrosive wear behavior of a 7075 aluminum alloy in the monolith form as well as its composite reinforced with 0.10 VFAP. The results will be compared with those already published for 2014 and 6061 aluminum alloys under similar conditions. Changes in composition of the matrix alloy can signifi-

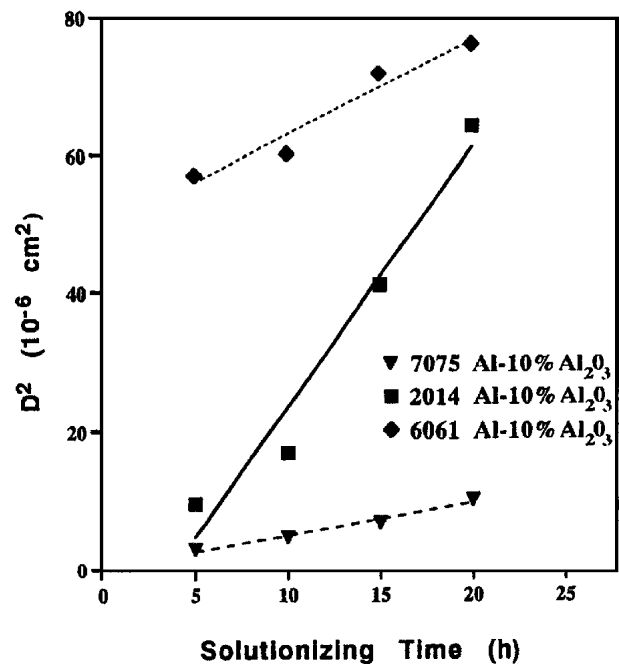


Fig. 3 Square of grain diameter as a function of solutionizing time for the composites of 6061, 2014, and 7075 aluminum alloys reinforced with 0.10 VFAP at 520 °C

cantly alter the TC values when subjected to the scratch tests. Near-surface microstructures will be examined to determine their correlation with corrosive wear in both monolith and composite.

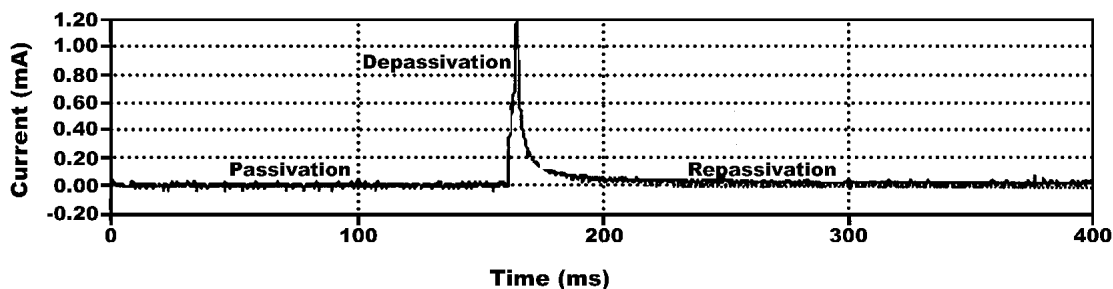


Fig. 4 Typical transient current response of a composite in a 0.1M solution of NaCl as observed by a scratch technique

## 2. Experimental Details

Monolith of 7075 aluminum alloy was purchased from a local store, while the composite with 0.10 VFAP was obtained from QED Extrusion Development, San Diego, CA, in a 19 mm (approximately 0.75 in.) rod form. A typical nominal composition of 7075 aluminum alloy is shown in Table 1.

Solutionizing was carried out in a box furnace in air at 500 °C for 5, 10, and 20 h, and samples were quenched in water and stored in a freezer. Samples had dimensions of 6.4 and 12.4 mm inner and outer diameters, respectively, while the length was 12.7 mm. A mirror polished surface was produced with 0.3 μm alumina particles before subjecting them to corrosive wear tests. The experimental setup may be divided into three units: electrochemical cell, potentiostat, and data acquisition system. It consists of an electrochemical cell made of Teflon containing 0.1M NaCl solution as an electrolyte. The sample was immersed in the cell, which could be rotated at a speed of 1500 rpm with the help of an electric motor. The noise signal from the sample was reduced by using silver brushes at the electrode. A standard calomel reference electrode was used and was separated from the main cell with the help of a bridge containing K<sub>2</sub>SO<sub>4</sub> solution to prevent the migration of chloride ions to the cell. The counter electrode was a platinum cage wound around the cell interior. Purified argon gas was bubbled through the solution 1 h prior to the experiment and also during the entire duration of testing. The rotating cylindrical electrode was allowed to be struck by a Vickers hardness indenter attached to a stylus, which was dropped from a known height to set the load on the specimen. The force was measured with the help of a transducer. The transients for both current and loads were simultaneously recorded on a computer using LABVIEW. Figure 1 shows a schematic diagram of the experimental setup for this study.

Wafers of samples with 0.5 mm thickness were cut from the composite rods and hand ground to a thickness of nearly 0.3 mm for transmission electron microscopy (TEM) sample preparation by ion milling. Some 3.0 mm discs were punched out using a mechanical hand punch and the thickness was reduced to 0.15 mm by hand grinding. A GATAN dimpler reduced the thickness to 50 μm with the help of 6 μm diamond paste. Finally, a GATAN ion mill with an accelerating voltage of 4 kV was used to perforate the sample. A beam current of 1 mA was allowed while the sample was inclined to the specimen at an angle of about 12°.

The monolith TEM sample preparation was carried out by

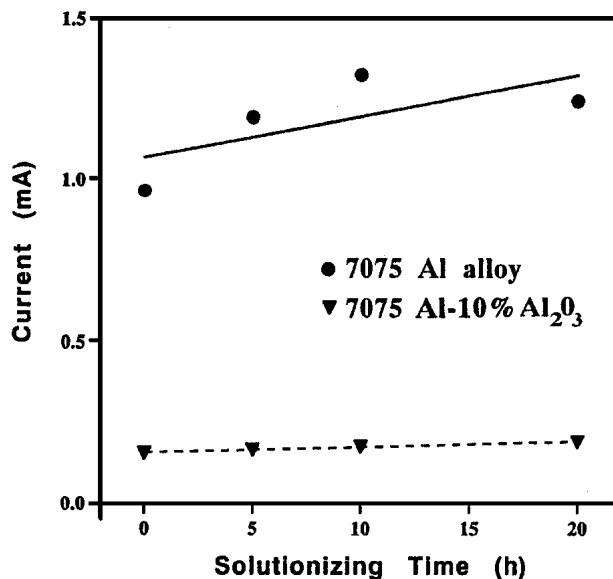


Fig. 5 Variation in the transient current as a function of solutionizing time for the monolith and the composite of 7075 aluminum alloy reinforced with 0.10 VFAP

the conventional dual jet electropolishing technique using Struer's Tenupol-3 unit. The solution was a mixture of 75% methanol and 25% nitric acid at 25 V and a temperature of -20 °C. A Hitachi H-8000 scanning transmission electron microscope (STEM) was used to observe the near-surface microstructure at a voltage of 200 kV.

## 3. Results and Discussion

Figure 2 shows the variation of the square of grain diameter (grain size was measured by linear intercept method) as a function of solutionizing time at 520 °C for 7075 aluminum alloy. It can be seen that the alloy does follow the grain growth law. Figure 2 also includes the grain sizes that are developed in 7075 aluminum alloy reinforced with 0.10 VFAP. Composites show significantly lower grain diameter values than the monolith. These results are consistent with the earlier data<sup>[3]</sup> presented for 6061 and 2014 alloys.

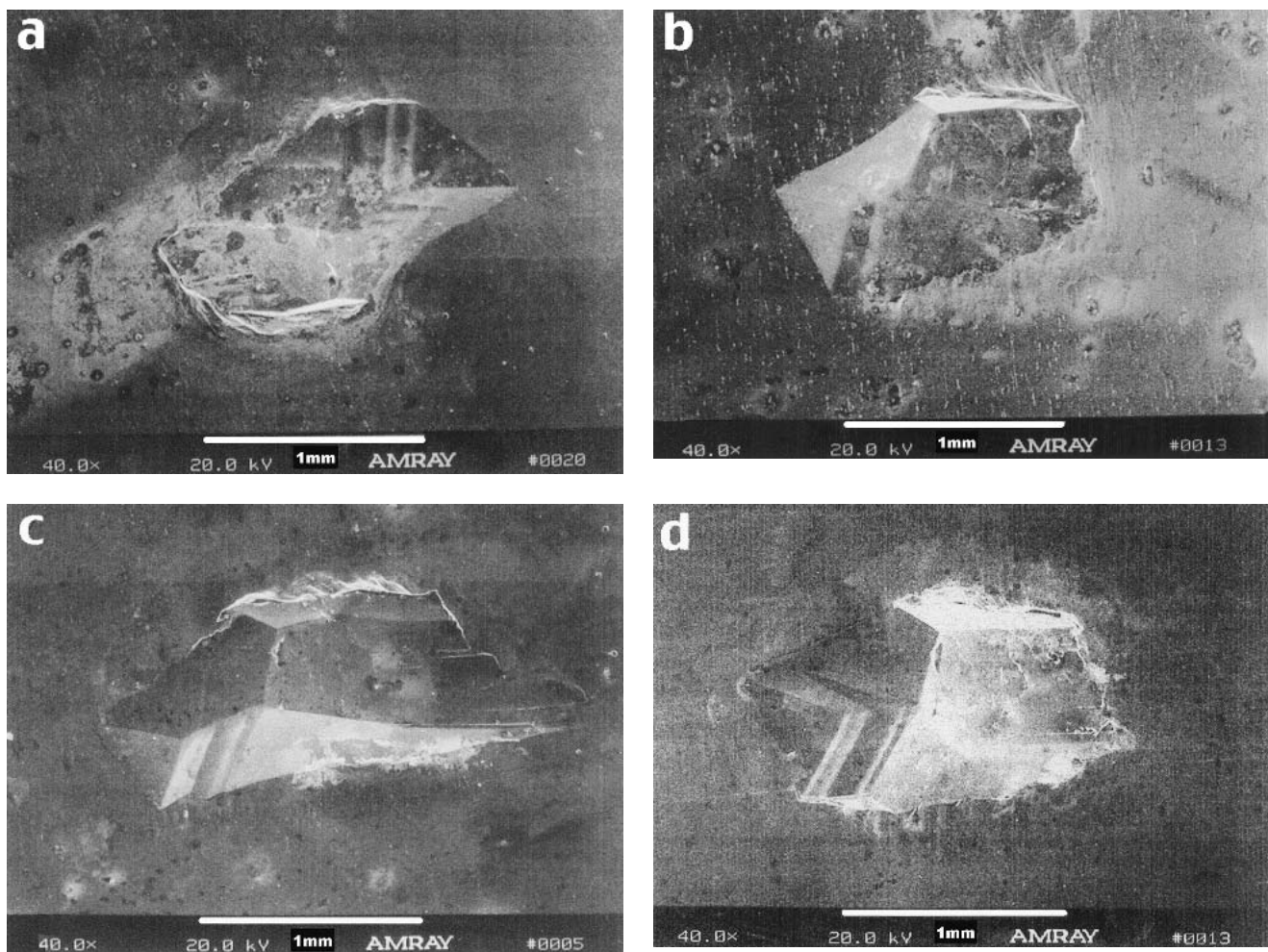
Grain growth (grain sizes were measured by the standard linear intercept method) during solutionizing in composites of 6061 and 2014 aluminum alloys reinforced with 0.10 VFAP is shown in Fig. 3, which also includes the data for 7075 alloy

composite reproduced from Fig. 2 for comparison. Although the rate of grain growth (slope of lines in Fig. 2 and 3) in the composite of 2014 alloy has been observed to be much higher than the composites of the other two alloys, the grain diameters achieved after solutionizing for a given time for the composites are lowest in 7075 alloy while they are largest in 6061 alloy. It follows the trend that grain diameters may be a function of the content of total alloying elements. Higher grain growth rate or larger range of grain diameters developed in 2014 aluminum alloy composite may be due to the extent of prior deformation.

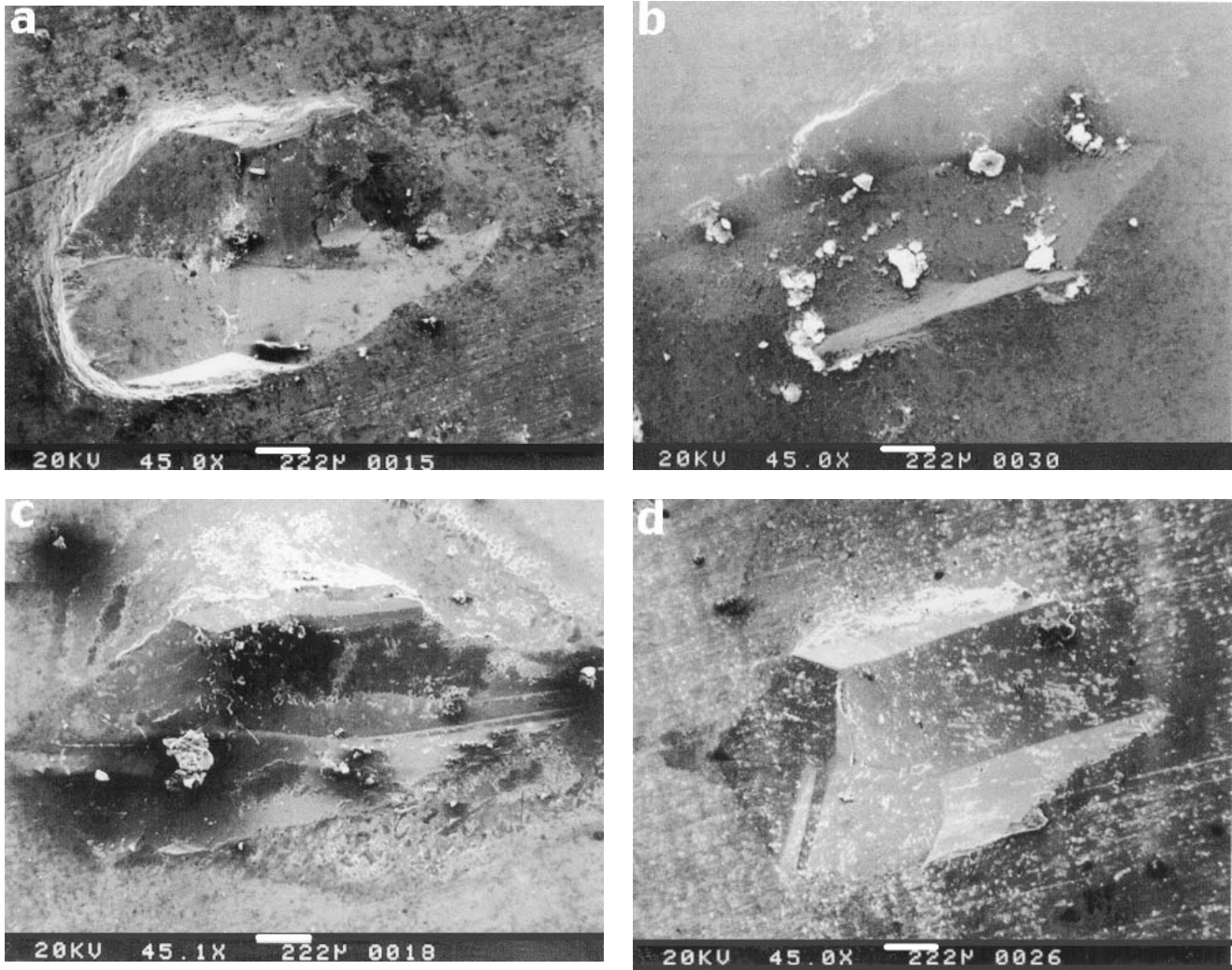
TEM results, not shown here, indicate that the dislocation density after the solutionizing treatment is higher in the composites compared with those observed in the monolith. It has been well established that the higher dislocation density in composites may be attributed to the differences in the values of CTE for the alloy matrix and the alumina particles. The volume fraction and size of the particles have also been shown to play an important role in determining the dislocation density values.<sup>[3]</sup> Volume fraction and size of the particles both increase the dislocation density due to CTE effect after the solutionizing treatment.

The scratch technique consists of dropping a Vickers hard-

ness indenter, from a known height, onto the surface of a rotating cylindrical electrode immersed in an electrolyte and measuring the transient current response. Figure 4 shows a typical transient current response in a given experiment. The electrode, while initially sitting in the electrolytic cell, develops a passive film, and a stable current value is observed. However, when the stylus containing the Vickers hardness indenter strikes the sample, it breaks the passive film and exposes the bare surface of the electrode to the electrolyte generating a transient current. This is known as the depassivation process, which continues until the stylus leaves the surface of the electrode when the repassivation process begins. The maximum current value reached during the depassivation region is a measure of corrosion, and obviously in this research, the value is expected to be influenced by the corrosive wear. It has been reported that better correlation between the transient current and other microstructural features may be accomplished by following the transient current density (obtained by dividing the peak current values by the area of the scratch as measured by scanning electron microscopy (SEM)) instead of peak current. However, the uncertainty in measurement<sup>[5]</sup> of the area can lead to some erroneous results.



**Fig. 6** Typical scratch morphology developed after scratch testing the samples of 7075 aluminum alloy solutionized for (a) as received, (b) 5, (c) 10, and (d) 20 h at 520 °C



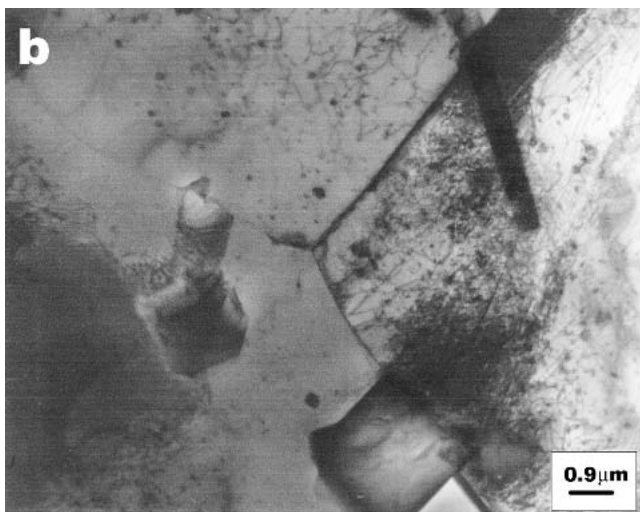
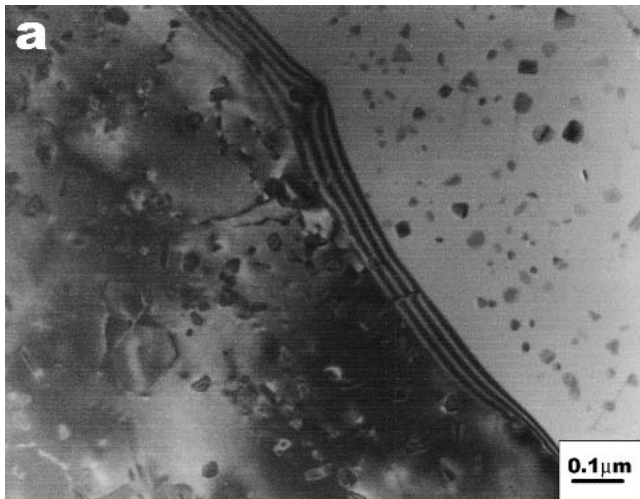
**Fig. 7** Typical scratch morphology developed after scratch testing the samples of 7075 aluminum alloy reinforced with 0.10 VFAP solutionized for (a) as-received, (b) 5, (c) 10, and (d) 20 h at 520 °C

Bare surface current density measured by the scratch technique has been criticized by Wei<sup>[12,13]</sup> and his group. According to them, two factors can be responsible for unreliable results by this technique: (1) positioning of the probe in the electrolytic cell and (2) the ratio of the passive film surface area to the scratch area. However, Burstein and Gao<sup>[14]</sup> have conducted experiments where the passive film to scratch area ratios of up to 1000 have been used. Observed current values were found to be independent of this ratio.

The effect of solutionizing on the corrosive wear behavior of the 7075 aluminum alloy has been compared with the composite containing 0.10 VFAP. Figure 5 shows that the transient peak current values are higher for the monolith, indicating that the composite may be a better material as far as the corrosive wear resistance is concerned. This result is rather surprising since both 6061 and 2014 alloys and their composites show<sup>[2]</sup> that the reinforcement with Al<sub>2</sub>O<sub>3</sub> particles results in more degradation due to corrosive wear. The interface between the particles and the matrix appears to be the main site at which the corrosion could initiate (perhaps, the interface acts as an anodic

site). Generally, composites are considered to have poorer corrosive wear resistance than their monoliths. However, it will be shown later that the alloy and the composites may be undergoing pitting corrosion.

SEM shows the morphology of the scratches that are developed, for a constant load, in the monolith and the composite of 7075 aluminum alloy reinforced with 0.10 VFAP in Fig. 6 and 7, respectively. The scratch size increases with an increase in solutionizing time, which is consistent with the increase in grain size during the heat treatment (Fig. 1). Presence of pits in the SEM pictures are noticeable. A careful examination shows that the density of pores or pits increases with an increase in solutionizing time for both the alloy and the composite. Grain growth during solutionizing takes place by grain boundary migration, which must decrease its surface area as it grows in diameter. The grain growth occurring by boundary migration involves absorption and release of vacancies, since the total number of vacancies at a solutionizing temperature must be assumed to be constant. Longer solutionizing time, resulting in larger grain diameter, could possibly develop higher vacancy



**Fig. 8** TEM of solutionized, for 20 h, samples of composite of 7075 aluminum alloy reinforced with 0.10 VFAP in the (a) undeformed and (b) deformed, near the scratch, conditions

concentration near the grain boundaries if it is assumed that the rate of absorption (due to boundaries acting as sinks) is lower than the rate of generation (due to reduction in total surface area of the grain boundaries). Coalescence of vacancies could give rise to the nucleation of pits, which may cause pitting corrosion to be the dominating mechanism of corrosion in this material. It supports the experimental observation of the pits observed both inside the scratched area as well as in the matrix. However, the area occupied by the ceramic alumina particles cannot develop the pits, at least, to the same extent as the alloy. This would explain the lower transient current values observed for the composite in Fig. 2 compared with the monolith. This observation is consistent with the results obtained by Fang et al.<sup>[10]</sup> in 6061 aluminum and composites reinforced with 0.10, 0.15, and 0.20 VFAP. However, earlier study<sup>[2]</sup> by our group shows that the composites of 6061 aluminum alloy reinforced with similar VFAP are less corrosive resistant than the monolith. It is possible that the contradictory results may be due to the combined effect of various microstructural features and minor differences in the compositions of the materials.

Possibility of dislocations providing anodic sites for corrosion to take place cannot be ruled out even though pitting corrosion is the dominating mechanism in the material. A higher dislocation density near the scratches in the material subjected to corrosive wear compared with the monolith can be seen in Fig. 8. Near surface microstructures as seen in TEM confirms the presence of a large number of dislocations in the scratches in the deformed samples.

Thus, two main factors are responsible for the corrosive wear of 7075 aluminum alloy and its composite reinforced with 0.1 VFAP: the dislocations generated due to wear deformation and the higher concentration of vacancies in the solutionized samples due to boundary migration taking place during solutionizing. It may be assumed that the latter occurs in a higher proportion when the two mechanisms are competing.

#### 4. Conclusions

- 1) Significant grain growth can occur in the composite of 7075 aluminum alloy as a function of solutionizing time at 520 °C.
- 2) The composite of 7075 aluminum alloy reinforced with 0.10 VFAP has a better corrosive wear resistance than its monolith.
- 3) Pitting corrosion appears to be the dominating mechanism of corrosion in both the alloy and the composite.

#### Acknowledgments

The authors wish to acknowledge the financial support of National Science Foundation for this research through grant number HRD-9353547. Dr. A. Bronson has been very helpful in the development of the electrochemical aspect of this research.

#### References

1. S.K. Varma and S. Andrews: "Solutionizing Effects During Corrosive Wear in 6061 Aluminum and Composites," *J. Mater. Eng. Processing*, 1998, 7, pp. 33-47.
2. S.K. Varma, S. Andrews, and G. Vasquez: "Corrosive Wear Behavior of 2014 and 6061 Aluminum Alloy Composites," *J. Mater. Eng. Processing*, 1999, 8, pp. 98-102.
3. S.K. Varma, M.M. de Lugo, A.H. Advani, and A. Bronson: "Influence of Near Surface Microstructures on the Transient Current Response in Fe-Cr-Ni Alloys During Scratch Tests," *Metall. Mater. Trans.*, 1994, 25A, pp. 1325-31.
4. S.K. Varma, M.M. de Lugo, and V. Caballero: "The Effect of Electrolyte Strength and Grain Size on the Transient Current Response in Fe-Cr-Ni Alloys During a Scratch Test," *Wear*, 1994, 178, pp. 101-08.
5. S.K. Varma, J.C. Arroyo, and A. Bronson: "The Effect of Indenter Shape on the Transient Current Response and Surface Microstructures in Fe-16wt.%Cr-16wt.%Ni Alloy," *Wear*, 1992, 154, pp. 49-63.
6. S.K. Varma and R.R. Romero: "The Effect of Impact and Continuous Scratches on the Corrosive Wear Behavior of Fe-18%Cr-5%Ni Alloy and 304 Stainless Steels," *Wear*, 1996, 201, pp. 121-31.
7. A.H. Advani, J.C. Arroyo, L.E. Murr, S.K. Varma, L. Montes, and C. Odegard: "Transmission Electron Microscopy of Scratched-Induced Surface Deformation Microstructures in Austenitic Fe-Cr-Ni Alloys," *Scripta Metall.*, 1992, 26, pp. 1181-86.
8. J.C. Arroyo, A. Bronson, and S.K. Varma: "The Surface Morphology and Transient Current Response of Fe-16wt.%Cr-16wt.%Ni in a Scratch Test," *J. Mater. Sci. Lett.*, 1990, 10, pp. 91-95.
9. J.C. Arroyo, A. Bronson, and S.K. Varma: "Effect of Microstructures

- on the Transient Current Response of Vacuum Processed Iron,” *Corrosion*, 1991, 47, pp. 177-78.
10. C.K. Fang, C.C. Huang, and T.H. Chuang: “Synergistic Effects of Wear and Corrosion for Al<sub>2</sub>O<sub>3</sub> Particulate-Reinforced 6061 Aluminum Matrix Composites,” *Metall. Mater. Trans.*, 1999, 30A, pp. 643-51.
  11. S.K. Varma, J. Ponce, M. Solis, S. Andrews, and D. Salas: “The Control of Grain Size and Distribution of Particles in a (6061 Alloy)<sub>m</sub>/(Al<sub>2</sub>O<sub>3</sub>)<sub>p</sub> Composite by Solutionizing Treatment,” *Metall. Mater. Trans.*, 1996, 27A, pp. 2023-34.
  12. R.P. Wei and M. Gao: “Further Observations on the Validity of Bare Surface Current Densities Determined by the Scratched Electrode Technique,” *J. Electrochem. Soc.*, 1991, 138, pp. 2601-06.
  13. R.P. Wei, M. Gao, and P.Y. Xu: “Peak Bare-Surface Current Densities Overestimated in Straining and Scratching Electrode Experiments,” *J. Electrochem. Soc.*, 1989, 136, pp. 1835-36.
  14. G.T. Burstein and G. Gao: “Verification of the Validity of Peak Bare Surface Current Densities Obtained From Scratched Electrodes,” *J. Electrochem. Soc.*, 138, pp. 2627-30.
  15. Anon: *ASM Metals Handbook*, 9th ed., Metals Park, OH, 1979, p. 129.