



Experimental investigation of effect of specimen thickness on fracture toughness of Al-TiC composites

M. S. Raviraj

Department of Mechanical Engineering, Government Engineering College, Chamarajanagar 571313, India
ravirajsunkapur@gmail.com

C. M. Sharanaprabhu

Department of Mechanical Engineering, Bapuji Institute of Engineering and Technology, Davangere 577004, India

G. C. Mohankumar

Department of Mechanical Engineering, National Institute of Technology Karnataka, Surathkal 575025, India

ABSTRACT. In this paper, the macro and micro-mechanical fracture behavior was studied for aluminum (Al6061) alloy matrix, reinforced with various proportions of TiC particles such as 3wt%, 5wt% and 7wt%. The Al6061-TiC metal matrix composites were produced by stir casting method to ensure uniform distribution of the TiC particulates in the Al matrix. The compact tension (CT) specimens were machined according to ASTM E399 specifications to evaluate the fracture toughness for Al6061-TiC metal matrix composites. The CT specimens were machined for crack to width (a/W) ratio of 0.5 and thickness to width (B/W) ratios of 0.2 to 0.7 with an increment of 0.1. Load versus crack mouth opening displacement (CMOD) data was plotted to estimate stress intensity factor K_Q for various thicknesses of the specimen. The fracture toughness K_{IC} was obtained by plotting stress intensity factor versus thickness to width ratios of specimen data. The fracture toughness of these composites varied between 16.4-19.2 $\text{MPa}\sqrt{\text{m}}$. Scanning Electron Microscope (SEM) studies was made on the fractured surface of the specimens to understand the micro-mechanisms of failure involved in these composites. Void initiation is more significant in the matrix near the interface. The micro-cracks grow from these micro-voids and crack propagates by linking these micro cracks locating the crack path preferentially in the matrix adjacent to the interface indicating ductile fracture.

KEYWORDS. Fracture toughness; Titanium Carbide particulates; Aluminum matrix composites; Micro-mechanism.

INTRODUCTION

Nowadays Aluminum alloy Metal Matrix Composites (MMCs) are replacing their monolithic counterparts for having enhanced mechanical properties and extended reliability combined with ease of processing. The incorporation of ceramic particles into the Al alloy matrix significantly alters the mechanical behavior of the materials. Addition of Titanium Carbide (TiC) particulates into the aluminum alloy results in grain refinement [1] and

initiates and propagates by 2.5mm the fatigue loading would stop by the control options as given in the software to operate the testing machine.

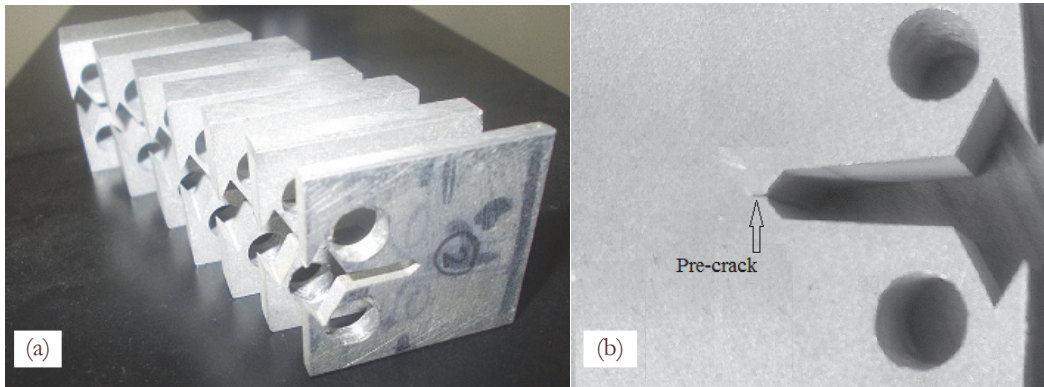


Figure 2: (a) Machined CT specimens of various thicknesses. (b) Fatigue pre-crack.

All fracture toughness tests were conducted using BiSS servo-hydraulic testing machine at room temperature. The machine capacity is of 100kN and is equipped with a load cell, Crack Mouth Opening Displacement (CMOD) gauge and a Linear Variable Differential Transformer (LVDT). All mentioned equipments associated with the test are calibrated. The CMOD gauge attached to a specimen was mounted in the loading system by the use of special grips as shown in Fig. 3.

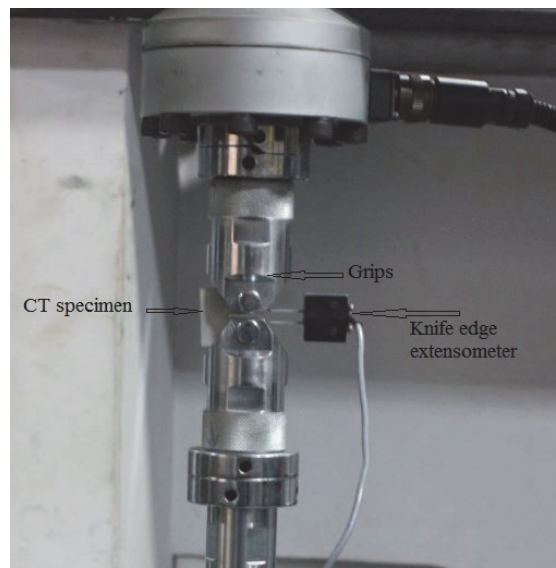


Figure 3: Test set up showing the mounted specimen in grips with COD gauge.

The fatigue pre-cracked CT specimens were tested under monotonically increasing tensile load using the commercial programme for determination of stress intensity factor. For the practical analyses, 5 identical CT specimens were considered for various Al6061-TiC composites and B/W ratios of $a/W=0.5$. Totally 90 specimens are considered for the practical analysis to estimate the fracture toughness of Al6061-TiC composite. All the test control was by stroke mode with a rate of 0.01667mm/sec. All the specimens were examined optically and by using Scanning Electron Microscope (SEM) to study the nature of the cracks and other details of bonding between matrix and particulates. The topography of fractured specimens and the microstructures were examined in detail using scanning electron microscope of ZEISS EVO18 make and an optical microscope (OM). This is done to characterize the fracture mechanisms of the composites. The particle and matrix interface details and the profile of crack propagation through the matrix and near the particles can



be assessed. Also by observing the fractographs the nature of fracture such as ductile and brittle fracture can be distinguished.

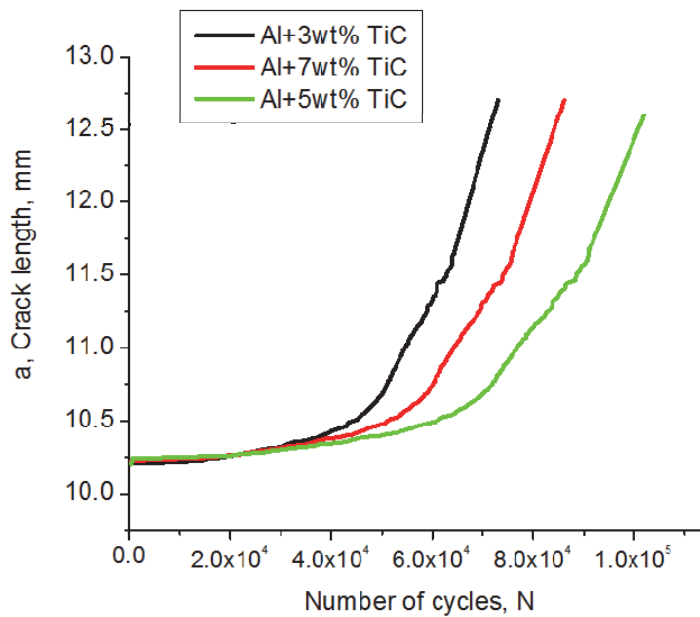


Figure 4: Crack length vs. Number of cycles for various Al6061-TiC composites typically for $a/W = B/W = 0.5$.

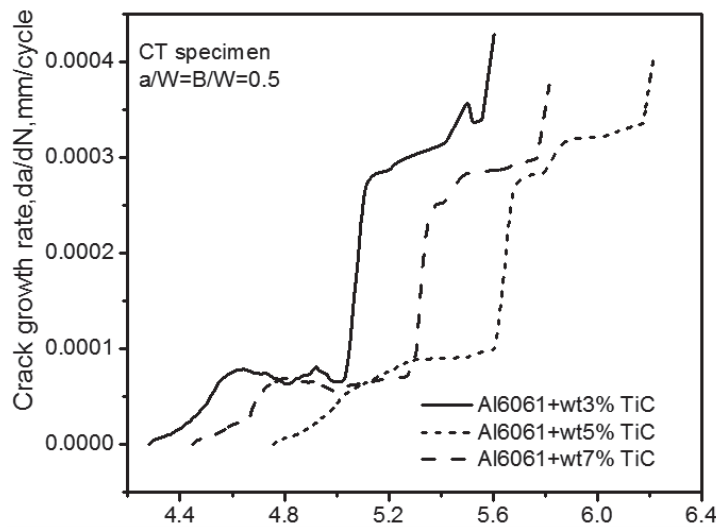


Figure 5: da/dN vs. ΔK for various Al6061-TiC composites with typically for $a/W = B/W = 0.5$.

RESULTS AND DISCUSSION

The fatigue pre-crack should provide the occurrence of cracking at right place for all CT specimens of various Al6061-TiC composites and B/W ratios of $a/W = 0.5$. During fatigue pre-cracking of the specimens, the increase in the crack length from 10.2mm to 12.7mm was measured with respect to the number of cycles for a load range (R) of 0.1. Fig. 4 shows the variation of crack length versus number of cycles for CT specimens of $a/W = B/W = 0.5$ with various wt% TiC particles. It is clearly seen from Fig. 4 that number of cycles (N) increased with weight percentage of TiC in the composites. The nature of variation of crack length versus number of cycles is similar to the earlier work of Mohanty *et.al.* [17], which was carried out for single edge notch specimen of Al7020-alloy. As the crack propagate in the

matrix, the reinforcing particles act as obstacles to reduce the local stress in the matrix and cause deviation of crack path as the crack deflects around the particles. This would increase the effect of roughness-induced closure and hence increase the threshold for crack propagation. Furthermore, the fatigue crack growth rates (da/dN) were measured with stress intensity factor range (ΔK) for various CT specimens of Al6061-TiC composite. Fig. 5 shows the variation da/dN vs. ΔK for CT specimens of $a/W=B/W=0.5$ with various wt% TiC particles. From Fig. 5, it is clear that Al6061+5 wt% TiC shows higher ΔK value compare to other two compositions of Al6061-TiC composites since Al6061+5 wt% TiC composite has higher Young's modulus as revealed in our earlier work, will increase ΔK value. The results shown in Fig.5 are similar to the earlier work of Harrison [16]. Subsequently, SEM micrograph shows clear distinction of the three regions *i.e.*, machined notch surface, fatigue pre-crack surface and fracture mode surfaces in Fig. 6 for CT specimen of Al6061+5 wt %TiC composite with $a/W=B/W= 0.5$. It is observed that that the fatigue crack growth results in curved crack front indicating the plane strain condition exists in the center where crack grows more and is subsequently arrested at the surface. The fatigue crack growth curve for various Al6061-TiC composites and B/W ratios of $a/W=0.5$ fall over a narrower stress intensity range. Hence, the composite may therefore, be considered as potential candidate materials for aerospace sectors [13].

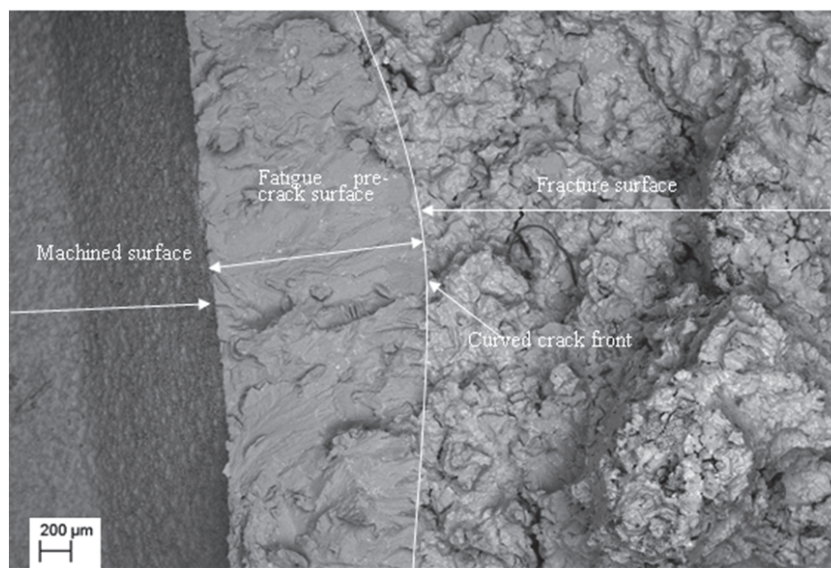


Figure 6: SEM micrograph of different surfaces for Al6061+wt5%TiC composite with $a/W=B/W= 0.5$.

Next, the CT specimens of various Al6061-TiC metal matrix composites and B/W ratios of $a/W=0.5$ were subjected to loading to estimate the critical load (P_Q) by plotting load vs. crack mouth opening displacement. The average value of five identical CT specimens of various Al6061-TiC composites and B/W ratios was considered to plot load vs. crack mouth opening displacement. Figs. 7-9 show the variation of load vs. crack mouth opening displacement for various Al6061-TiC composites and B/W ratios. It is observed from Fig. 7-9 that the maximum load increases with increase in B/W ratios. The specimens with $B/W \leq 0.4$ undergo plane stress fracture due to high plasticity and less stress triaxiality compared to the specimens with $B/W \geq 0.5$. The P_Q value was obtained by drawing the 5% of the secant line to the maximum load on experimental data using curve fitting phenomena, which is not shown in figure. The magnitude of stress intensity factor K_Q for CT specimens of various Al6061-TiC composites and B/W ratios were calculated experimentally by substituting the F_Q value and dimensions of CT specimen in Eq. (1) [14].

$$K_Q = \frac{P_Q}{B\sqrt{W}} \times f\left(\frac{a}{W}\right) \quad (1)$$

The $f\left(\frac{a}{W}\right)$ polynomial equation:



$$f\left(\frac{a}{W}\right) = \frac{2 + \left(\frac{a}{W}\right)}{\left[1 - \left(\frac{a}{W}\right)\right]^{3/2}} \left[0.886 + 4.64\left(\frac{a}{W}\right) - 13.32\left(\frac{a}{W}\right)^2 + 14.72\left(\frac{a}{W}\right)^3 - 5.60\left(\frac{a}{W}\right)^4 \right] \quad (2)$$

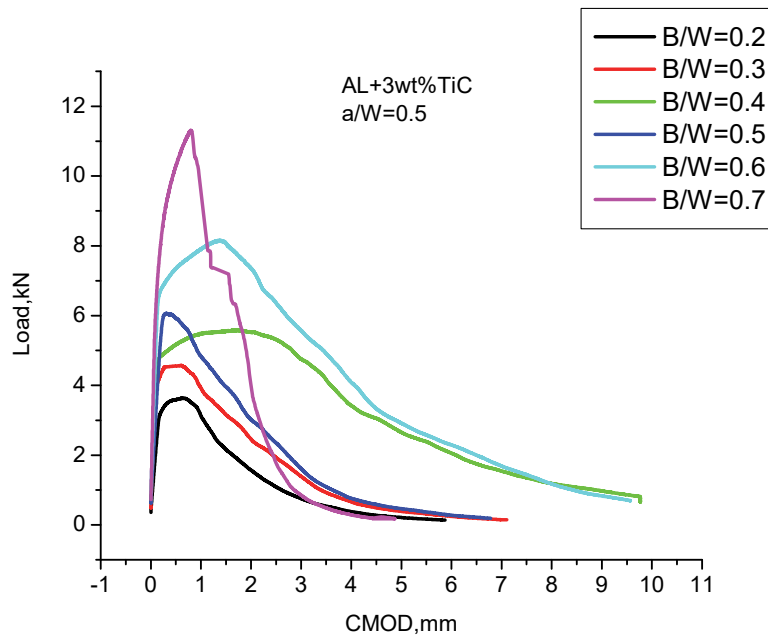


Figure 7: Load vs. crack mouth opening displacement curves for Al6061+wt3% TiC composite of various B/W ratios.

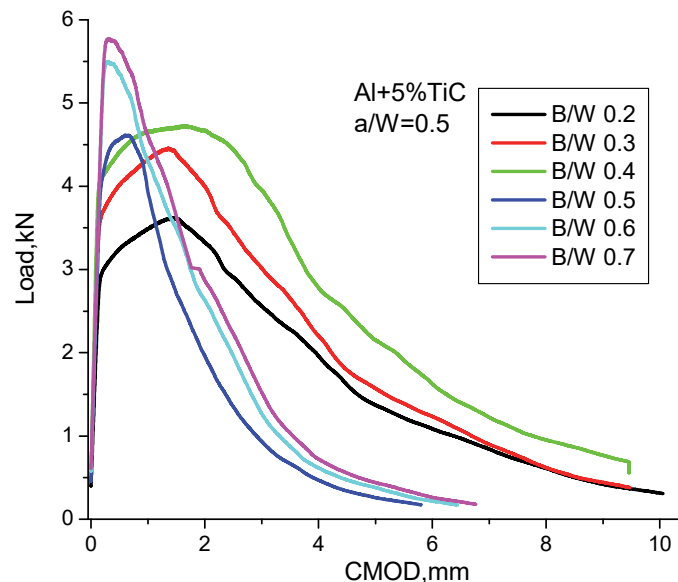


Figure 8: Load vs. crack mouth opening displacement curves for Al6061+wt5% TiC composite of various B/W ratios.

The calculated K_Q is plotted against various B/W ratios for various Al6061-TiC composites. Fig. 10 shows the variation of K_Q vs. B/W ratios for various Al6061-TiC composites. It is observed from Fig.10 that the K_Q decreases with increase in B/W ratios and found to remain constant for $B/W \geq 0.5$. This constant value of K_Q for $B/W \geq 0.5$ prevail the plane strain fracture toughness (K_{IC}) of the composite. For $B/W \leq 0.4$, the value of K_{IC} can be considered the real plane stress fracture toughness. It is analyzed from Fig. 10 that the increase of TiC from 3wt% to 5wt% in Al6061 matrix composites, there will be a decrease in fracture toughness from 19.2 $\text{MPa}\sqrt{\text{m}}$ to 16.4 $\text{MPa}\sqrt{\text{m}}$ and further increase of TiC to 7wt% the



fracture toughness increases slightly to 17.6 MPa√m. Since, Al6061+wt5%TiC composite exhibits higher yield stress compare to other two compositions as discussed in our earlier work. The results show the variation of wt% TiC reinforcement particles with Al6061 matrix significantly affects the fracture toughness.

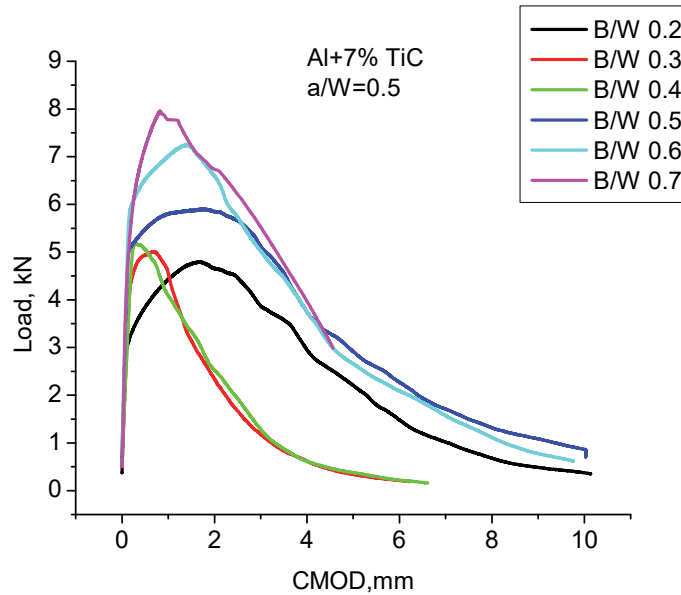


Figure 9: Load vs. crack mouth opening displacement curves for Al6061+wt7% TiC composite of various B/W ratios.

Finally, macroscopic and microscopic observation was made on the fractured surface of CT specimens for various Al6061-TiC composites and B/W ratios. Figs. 11 (a-c) show the fractograph of the fractured CT specimens surface with magnification of 1kX for various Al6061-TiC composites of $a/W=B/W=0.5$. From Fig.11 (a-c) the micromechanical failure mechanisms of composites show bimodal dimples and these dimples are characteristics of failure occurring by void nucleation, growth through the matrix and coalescence indicating ductile fracture. All the particles in the vicinity of crack tip are responsible for void nucleation by particle rupture and decohesion in the matrix. The crack initiation and fracture of the composites is mainly associated with voiding in the matrix around individual particles ahead of the main crack. Void initiation is more significant in the matrix near the interface. The micro-cracks grow from these micro-voids to absorb the energy. Crack propagates by linking these micro cracks locating the crack path preferentially in the matrix adjacent to the interface can be seen in Fig.12.

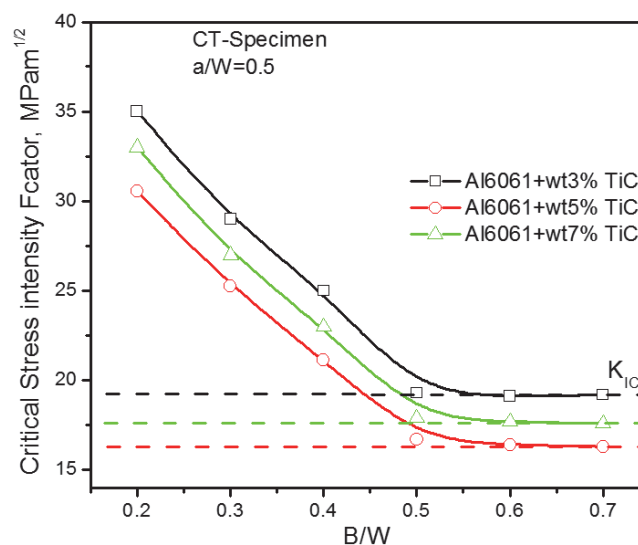


Figure 10: Variation of Critical stress intensity factor vs. B/W for various Al6061-TiC composites.

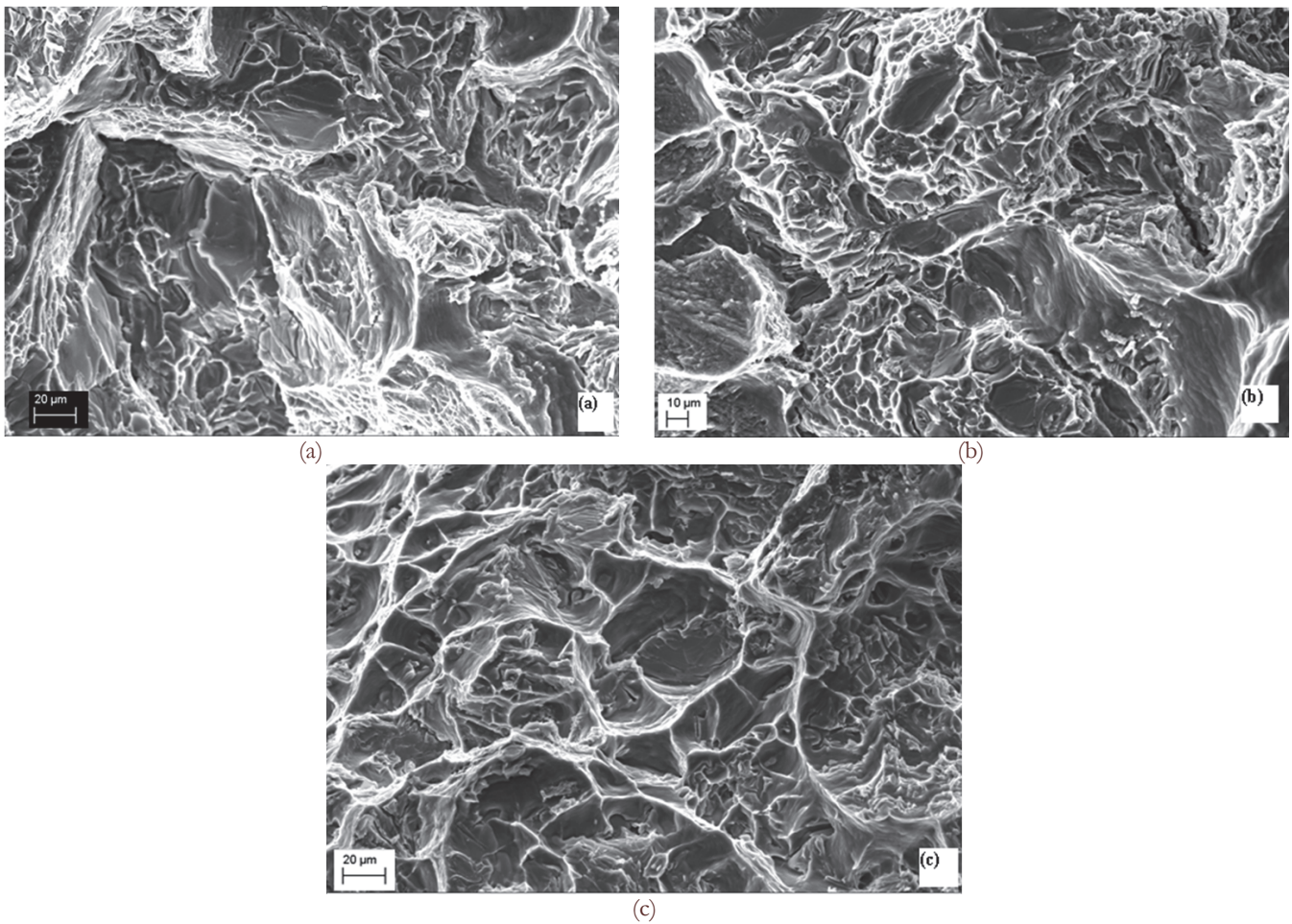


Figure 11: (a) SEM Fractographs of Al6061+3wt% TiC; (b) SEM Fractographs of Al6061+5wt % TiC; (c) SEM Fractographs of Al6061+7wt % TiC.

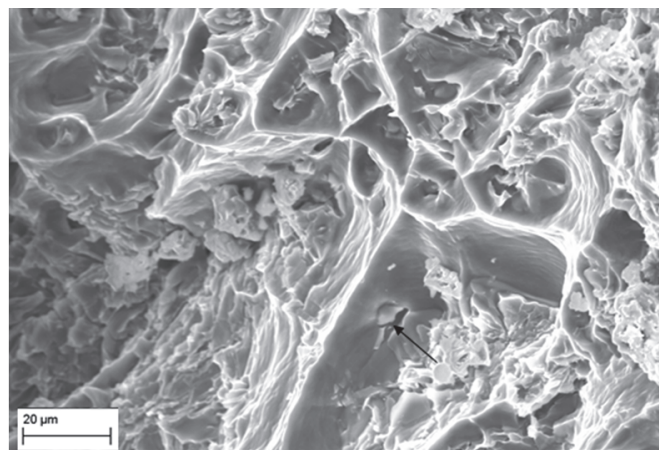


Figure 12: Matrix failure adjacent to Al/TiC interface for Al6061+5wt% TiC composite of $a/W=B/W=0.5$.

CONCLUSIONS

Following are the major conclusions:

- (a) The fatigue crack growth rate curve for Al6061-TiC (3wt %-7wt %) metal matrix composites fall over a narrower stress intensity range. Hence, the composites may be considered for aerospace sectors.



(b) Void initiation is more significant in the matrix near the interface. The micro-cracks grow from these micro-voids to absorb the energy shows ductile fracture. Also, crack propagates by linking these micro cracks locating the crack path preferentially in the matrix adjacent to the interface.

(c) The variation of TiC reinforcement particles with Al6061 alloy matrix will affect the fracture toughness of the material. The fracture toughness of Al6061-TiC (3 wt %-7 wt %) metal matrix composites varied between 16.4 - 19.2 MPa \sqrt{m} as compared to 25MPa \sqrt{m} for base alloy Al6061 [18]. The solution treatment and age hardening process can further increase the toughness of these composites. The work can be extended to higher wt% TiC reinforcement particles with Al6061 alloy matrix. This remains as a future work.

ACKNOWLEDGEMENTS

The authors thank the Research centre, Bapuji Institute of Engineering & Technology, Davangere-577004, BiSS and TUV Rheinland, Bengaluru for their support in extending the testing facilities and helpful discussions.

REFERENCES

- [1] McCartney, D.G., Grain refining of aluminium and its alloys using inoculants, *Int. Mater. Rev.*, 34 (1989) 247-260.
- [2] Mohanty, P.S., Gruzleski, J. E., Mechanism of grain refinement in aluminum, *Acta Metall. Mater.*, 43 (1995) 2001-2012.
- [3] Yang, Q., Senda, T., Ohmori, A., Effect of carbide grain size on microstructure and sliding wear behavior of HVOF-sprayed WC-12% Co coatings, *Wear*, 254 (2003) 23–34. DOI:10.1016/S0043-1648(02)00294-6.
- [4] Nukami, T., The growth of TiC particles in an Al matrix, *Materials Science Letters*, 17 (1998) 267-268.
- [5] Karantzalis, A.E., Lekatou, A., Georgatis, E., Poulas, V., Mavro, H., Microstructural Observations in a Cast Al-Si-Cu/TiC, *Composite Materials Engineering and Performance*, 10 (2009) 1-10.
- [6] Surappa, M.K., Rohatgi, P.K., Preparation and properties of aluminium alloy ceramic particle composites, *Journal of Material Science*, 16 (1981) 983–993.
- [7] Lloyd, D.J., Particle reinforced aluminum and magnesium matrix composites, *International Material Reviews*, 39 (1999) 1–23.
- [8] Fatchurrohman, N., Solidification characteristic of titanium carbide particulate reinforced aluminium alloy matrix composites, *Journal of Engineering Science and Technology*, 7 (2012) 248-256.
- [9] Raviraj, M.S., Sharanaprabhu, C.M., Mohankumar, G.C., Experimental Analysis on Processing and Properties of Al-TiC Metal Matrix Composites, *Procedia Materials Science*, 5 (2014) 2032 – 2038.
- [10] Yu Qiao, Fracture toughness of composite materials reinforced by debondable particulates, *Scripta Materialia*, 49 (2003) 491–496. DOI:10.1016/S1359-6462(03)00367-1.
- [11] Rabiei, A., Vendra, L., Kishi, T., Fracture behavior of particle reinforced metal matrix composites, *Composites: Part A*, 39 (2008) 294–300.
- [12] Alaneme, K.K., Aluko, A.O., Fracture toughness (K_{IC}) and tensile properties of as-cast and age-hardened aluminium (6063)–silicon carbide particulate composites, *Scientia Iranica, Transactions A: Civil Engineering* 19 (2012) 992–996.
- [13] Ajit Bhandakkar, Prasad, R.C., Sastry, M.L., Fracture Toughness of AA2024 Aluminum Fly Ash Metal Matrix Composites, *International Journal of Composite Materials*, 4(2) (2014) 108-124. DOI:10.5923/j.comaterials.20140402.10.
- [14] ASTM E399-83, Standard test method for plane strain fracture toughness, *Annual book of ASTM Standards*, PA (2005).
- [15] Wilson, C., Landas, J. D., Fracture toughness testing with notched round bars, *ASTM-STP1360, Fatigue and Fracture Mechanics*, 30 (2000) 69-82.
- [16] Harrison, J.D., Fatigue Analysis of welded joints, *Metal Construction and British Welding Journal*, Mar. (1970) 93.
- [17] Mohanty, J.R., Verma, B.B., Ray, P.K., Evaluation of overload-induced fatigue crack growth retardation parameters using an exponential model, *Engineering Fracture Mechanics*, 75 (2008) 3941–3951.
- [18] Davidson, D.L., Tensile deformation and fracture toughness of 2014+15 vol. pct SiC particulated composite. *Metall. Trans*, 22A (1991) 113-123.