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Effects of in-situ TiC reinforcements on the machining process characteristics of Al+12%Si matrix

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Abstract

The intent of the present study is to investigate the machining process characteristics of *in-situ* synthesized Al+12%Si/10wt%TiC composites. The experiment was conducted in the course of dry turning process with uncoated carbide tools using NH22 Lathe Machine having a spindle speed range of 20 to 2780 rpm and feed range of 0.04 to 2.24mm rev^{-1}. Cutting speed, feed rate and depth of cut are the process parameters and tool wear mechanism, cutting force (Fz), surface roughness (Ra) and physical appearance of chips are considered as the output measures. SEM, Tool Makers Microscope, Optical Profile Meter and Kistler Piezoelectric Dynamometer have been utilized to measure the outputs. The experimental results revealed that the tools mainly wear at the flank surface. Minimum cutting force (Fz) and better surface roughness have been observed at higher cutting speed and minimum feed rate. Dominantly short and curly chips were generated in the machining process.

Keywords

Aluminum, In-Situ, Titanium, Carbide, Reinforcement, Casting, Turning, Process

1. Introduction

The high strength, low weight, high modules, low ductility and high wear resistance properties of aluminium Metal Matrix Composites (MMCs) makes them attractive for wider range of applications. These unique properties of MMCs can be realized by selecting the right mixture of matrix and reinforcement [1]. Among the possible candidates of reinforcement particles SiC, TiC, B_4C, Al_2O_3, MgO, TiO_2, AlN, BN, Si_3N_4 and TiB_2 are preferred for reinforcing a range of engineered composite materials [2-4]. Recently, TiC particles reinforced aluminium based metal matrix composites (MMCs) have gained popularity in the areas of aerospace, automotive, defence, and structural applications owing to their superior mechanical and physical properties [5].

In the preparation of MMCs generally two processes are used to incorporate reinforcement particles in the metal matrix. These are the solid and liquid state processes. Porosity and contamination are the main drawbacks of the solid state process [6]. In the liquid state process, the reinforcement particles are synthesized through in-situ or ex-situ routes. In the ex-situ technique pre-prepared reinforcement particles are incorporated in the matrix melt. Uneven distribution, agglomeration and segregation of reinforcement particles are the most common shortcomings of the ex-situ techniques [7, 8]. Conversely, developing the reinforcement particles through direct chemical reaction which is called the in-situ process offers significant advantages like very small reinforcement size, homogeneous distribution, free of impurities, greater bond strength, enhanced fatigue resistance, good thermodynamic stability and better tailorability [3-4]. Although, the reinforcement particles provide a significant contribution to the enhancement of the properties of aluminium matrix, they also make the machinability of the composite very difficult. Consequently, the practical usage of this material is not widely expanded as expected [9].

Machining process, when used for MMCs, is characterized with unpredictably shorter tool life due to the ceramic nature of reinforcement particles [1]. It is well known that, one of the major indicators of the efficiency of a machining process is the durability of the cutting tools. The cost of cutting tools takes the major part of the total machining cost [10]. The presence of hard reinforcement particles during machining process introduces additional effects, such as tool–particle interactions, localized plastic deformation of matrix material, possible crack generation in the shear plane, etc. Moreover, the inclusions of reinforcement particles affect the cutting force, residual stress, machined surface profile generation, chip formation and tool wear mechanisms [9].

So far, considerable research work has been conducted on the machining characteristics of aluminum based ex-situ MMCs. Davim [11] investigated the evolution of cutting forces, tool wear and surface roughness during turning of A356/20/SiCp metal matrix composite at T6 condition using polycrystalline diamond (PCD) cutting tools. Palanikumar and Karthikeyan [12] examined the effect of machining variables on the surface quality of Al/SiCp composites in the course of dry turning process. Abdul [13] investigated the effect of reinforcement volume fraction and tool nose wear of tungsten carbide cutting tool inserts on the surface finish of the machined A359 Al/SiCp composites during turning operation. Uday et al. [14] studied the effects of size (15 μm and 65 μm) and volume fraction (20% and 30%) of reinforcements on the machining forces and machined surface roughness of Al/SiCp composites. Sahin et al. [15] assessed the tool wear and surface roughness of Al_2O_3 particle-reinforced 2024 Al alloy composite in the course of turning with TiN (K10) and TP30 coated carbide tools at various cutting speeds.

Sasimurugan and Palanikumar [16] examined the effect of feed rate, depth of cut and cutting speed on the surface roughness characteristics of Al6061-SiC-Al_2O_3 hybrid aluminium metal matrix composites. Rajesh et al. [17] investigated the influence of cutting speed, depth of cut, and feed rate on the surface roughness of 10 wt.% SiC particulate reinforced 7075 Al matrix composites. Muthukrishnan et al. [18] examined the machining property of A356/SiC/10p metal matrix composite in continuous turning process using medium grade polycrystalline diamond (PCD 1500) inserts. Anandakrishnan and Mahamani [19] analyzed the effects of cutting speed, feed rate, and depth of cut on flank wear, cutting force and surface roughness during turning operations of Al-6061–TiB_2 in-situ composites.

The aforementioned literature review showed that the machining process characteristics of *ex-situ* synthesized composites have been substantially addressed. However, there is limited number of research findings reported regarding the machining process characteristics of *in-situ* synthesised particulate reinforced composites. The purpose of the current study is to examine the influence of machining variables on the machining process characteristics of *in-situ* synthesized Al+12Si/10wt%TiC composites through dry turning operation with uncoated carbide tools. Cutting speeds, feed rates and depth of cuts were utilized as the control factors and cutting force, surface roughness, tool wear, BUE, and chip formation considered as the output measures.

2. Materials Development and Experimental Details

In the present investigation commercially pure titanium, activated charcoal and Al+12%Si alloy with additional alloying elements of 2.85wt%Mg, 0.78wt%Fe, 0.5%wtZn, 0.39wt%Mn and 0.24wt%Cu were used as the main input materials. Al+12%Si/10wt%TiC in-situ composites were produced through direct reaction synthesis (DRS). Initially Al+12%Si alloy was added in the graphite crucible and allowed to melt in the muffle furnace. About 700^0C the titanium is incorporated and the temperature rose to 1100^0C to diffuse the titanium in the aluminum melt. Then, the activated charcoal was added and the temperature increased to get sufficient exothermic reactions. The desired exothermic reaction was achieved at 1200 ^{0}C processing temperature and 30 min reaction time. To achieve the desired wt% of TiC, the amount of titanium and activated charcoal added and the process temperature and reaction time used in the process were determined based on the preliminary experimental results. The melting process was carried out under the cover of flux (50%NaF and 50%KF). Hexa Chloro Ethane (C_2Cl_6) was also used as degasser. The melt was then poured into a preheated 50mm x 450mm cylindrical mild steel mould.

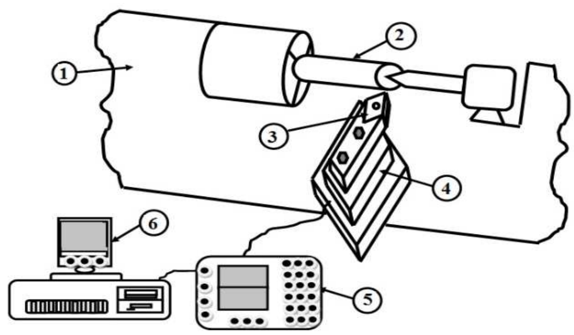

Figure 1. *Schematic of experimental set up: (1)-lathe machine, (2)-work piece, (3)-carbide insert, (4)- Kistler Piezoelectric Dynamometer, (5)-multichannel charge amplifier, (6)-computer interface.*

The machining process characteristics of Al+12%Si/10wt%TiC composites was investigated through single pass dry turning on NH22 Lathe Machine having a spindle speed range of 20 to 2780 rpm and feed range of 0.04 to 2.24mm rev^{-1}. Uncoated T-Max P, H13A Grade Carbide turning inserts of nomenclature 0^0 rack angle, 7^0 clearance angle, 80^0 cutting edge angle and 0.8 mm nose radius were utilized for the turning process. The tests were carried out at 50, 90 and 150 m min^{-1} cutting speeds, 0.06, 0.12 and 0.24 mm rev^{-1} feed rates and a 1.0 mm constant depth of cut. The size of the workpiece used in the experiment was 55mm diameter and 450mm length. The cutting speed was selected on account of the diameter of the workpiece after rough turning. After each test, the degree of the flank wear of the cutting tool was measured with CARLZEISS-JENA Tool Makers Microscope. The surface roughness (*Ra*) was measured by WYCO NT1100 Optical Profile Meter. The cutting forces (*Fz*) were measured using Kistler Piezoelectric Dynamometer of type 9257B with a load amplifier and interfaced data accusation system. The formation of BUEs and physical appearance of chips was investigated by taking digital photographs after each test. The schematic of the experimental setup is shown in Figure 1.

3. Results and Discussion

3.1. Microstructure Analysis

The SEM micrograph and XRD pattern of the as cast Al-12%Si/10wt%TiC composite are presented in Figure 1. The microanalysis result exhibited a uniform distribution of fine spherical (0.5 – 0.8μm) shaped TiC particles. Like most of aluminum composites, several interaction phases have been developed in the synthesization process of Al-12%Si/10wt%TiC composite. The XRD pattern revealed the presence of needle/flake shaped Al_3Ti intermetalic phases along with TiC particles.

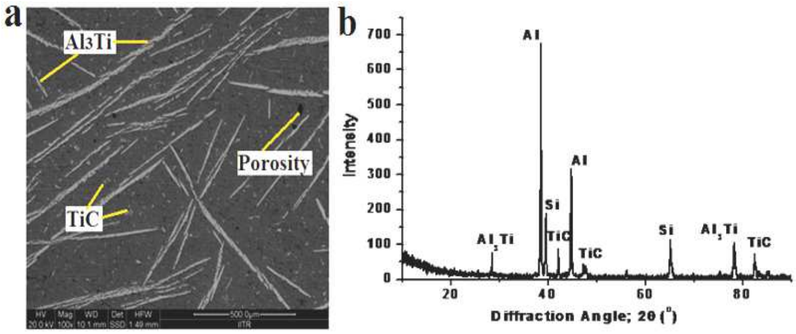

Figure 2. *(a) the SEM micrograph and (b) The XRD pattern of Al+12%Si/10wt%TiC composites.*

3.2. Analysis of Machining Process Characteristics

3.2.1. Effect of Cutting Speed

In the present study the flank wear was noticed as the main causes of the deterioration of the cutting tool inserts. Figure 3 illustrate the SEM and photomicrographs of the wear pattern of the cutting tools and formation of built up edge (BUE). Flank wear normally occurs due to the excessive friction between the machined surface and the flank face of the tool [13]. The amount of wear in the flank face normally evaluated by measuring the distance between the upper end of the cutting edge to the lower part of the flank face where the wear occurs. As per the 1993 international standard (ISO 3685), the cutting tool insert will finish its designed function when the width of the flank wear close to 0.76 mm for rough turning and 0.38 mm for finish turning [17].

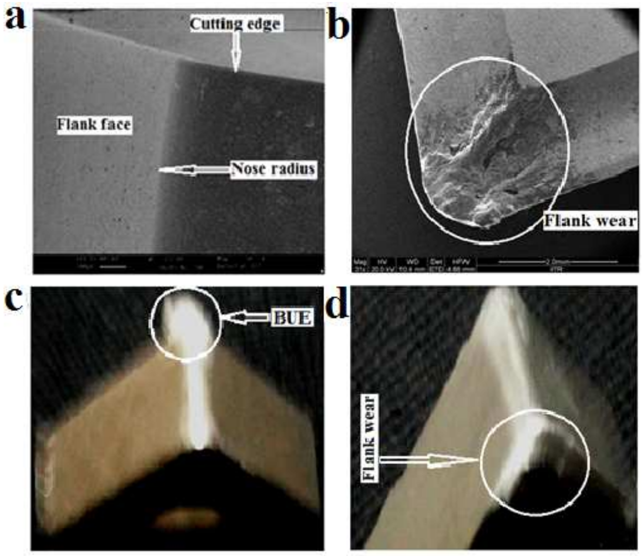

Figure 3. *(a) SEM micrograph of carbide insert before machining, (b) SEM micrograph of formation of flank wear, (c) Photographic view of formation of BUE and (d) Photographic view of formation of flank wear.*

Figure 4 (a) demonstrates the effect of cutting speeds on the flank wear of the carbide insert at 1.0 mm constant depth of cut. It has been observed that the flank wear increases with increasing the cutting speed. However, after 90 m/min the increasing trend became reduced. This indicates that the flank wear will significantly reduce when the cutting speed increased more. This may be associated with at high cutting speed a relative maximum temperature will developed in the interaction surface of the cutting edge of the tool and the machined surface and that causes to soften the material to be cut and as a result, removal of TiC particles from the matrix alloy being easier [20-22].

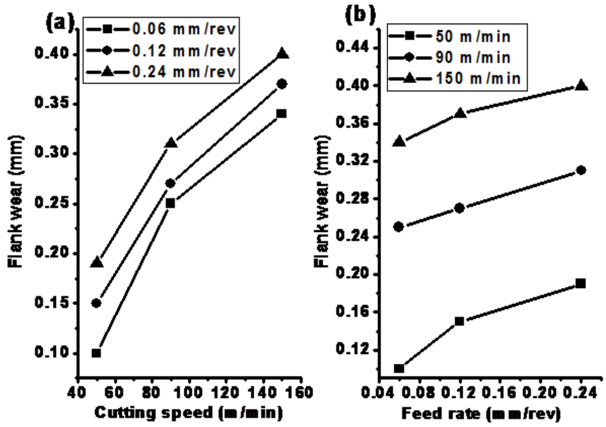

Figure 4. *Effect of cutting parameters on flank wear: (a) cutting speed and (b) feed rate.*

Figure 5 (a) shows the effect of cutting speeds on the cutting force (*Fz*) at a 1 mm constant depth of cut. As it has been observed in this Figure, the cutting force (*Fz*) uniformly reduced while the cutting speed increases. For example, when the cutting speed increases from 50 to 150 m min^{-1} the cutting force (*Fz*) decreases from 208.93 to 95.56 N, 341.38 to 118.92N and 432.58 to 341.74 N for 0.06, 0.12 and 0.24 mm rev^{-1} feed rates, respectively. This may be associated with the higher cutting speed aggravate the wear of the flank face and that causes to increase the contact area between the flank and the workpiece and that leads to increase the cutting force.

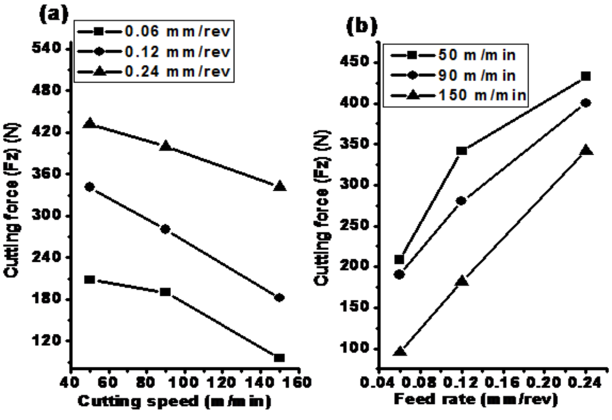

Figure 5. *Effect of cutting parameters on cutting force (Fz): (a) cutting speed and (b) feed rate.*

So as to improve the product quality and machining performance, higher emphasis should be given to the surface roughness improvement. A better machining surface granted for enhanced mechanical and physical properties [23]. The effect of cutting speed on the surface roughness during dry turning of Al+12Si/10wt%TiC composites is demonstrated in Figure 6 (a). This Figure revealed that at 1.0 mm constant depth of cut, the surface roughness decrease almost linearly with increasing the cutting speed. This may be associated with at higher cutting speed maximum temperature developed in tool material interface and that soften the cutting tool and that causes to the formation of BUE as a result the quality of the machined surface deteriorated [12].

The presence of hard reinforcements in MMCs alters the plastic deformation characteristics of the soft matrix material compared to those of a conventional alloy. Thus, the change in mechanical properties coupled with reinforcement, configuration and distribution in the matrix determines the mechanism of chip formation and hence the machinability of MMCs. Figure 7 demonstrate the type of chips formed during dry turning of Al+12Si/10wt%TiC composites with uncoated carbide tool at a constant depth of cut of 1.0 mm and various cutting speed and feed rates. As it has been observed in this Figure, the shape of chips generated at a cutting speed of 90 m min^{-1} was short and curly however when the feed rate increases the length of the chips increases and became curlier. On the other hand, during machining of the composites at a cutting speed of 150 m min^{-1} the shape of the generated chips was relatively longer and somewhat curly, however, when the feed rate increases the chips became more straight and lengthy.

3.2.2. Effect of Feed Rate

The effect of feed rates on the flank wear of the carbide insert at a constant depth of cut of 1.0 mm is demonstrated in Figure 4 (b). It has been observed that the flank wear increases uniformly with increasing of the feed rate. However, the influence of feed rates on the machining characteristics of Al+12Si/10wt%TiC composites is insignificant as compared to the cutting speeds. It has been also noticed that there is only a minor increment in the flank wear because of the increase in feed rates and similar trend was observed at all cutting speeds. For example, when the feed rate increased from 0.12 mm rev^{-1} to 0.24 mm rev^{-1} the flank wear increased by 0.09, 0.06 and 0.06 mm for 50, 90 and 150 m min^{-1}cutting speeds, respectively. This may be associated with high feed rates causes to soften the matrix material and that makes the removal of the hard TiC easier and consequently the tool wear minimized

The effect of feed rate on the cutting force (Fz) is presented in Figure 5 (b). It has been observed that the cutting forces (Fz) increase almost linearly with increasing the feed rate. However, the influence of the feed rate on the cutting force (Fz) is more significant in the higher cutting speed. For example, when the feed rate increases from 0.12

mm rev^{-1} to 0.24 mm rev^{-1} at 50 m min^{-1}cutting speed, the cutting force (Fz) increases from 208.3 N to 432.58 N. Whereas, at 150 m min^{-1}cutting speed, the cutting force (Fz) increases from 95.56 N to 341.74 N with the same feed range.

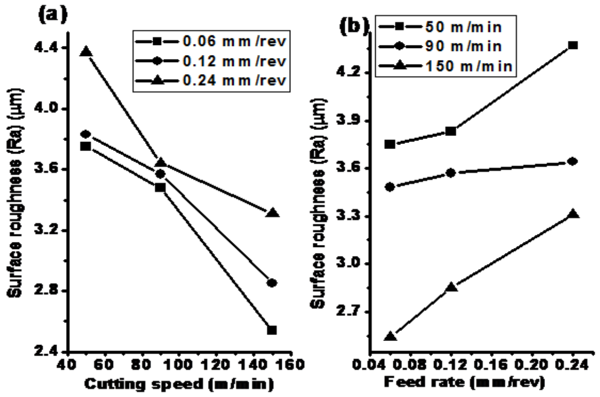

Figure 6. *Effect of cutting parameters on surface roughness (Ra): (a) cutting speed and (b) feed rate.*

Figure 6 (b) illustrates the effect of feed rate on the surface roughness (Ra). It has been observed that the larger feed rate develop a relatively rough machined surface. When the feed rate increased from 0.06 to 0.24 mm rev^{-1} the surface roughness increased by 0.62, 0.16 and 0.77µm, respectively. This may be attributed to higher feed rates causes to develop maximum temperature in the machined surface and that leads to decrease the bonding effect between the reinforcement and matrix and that causes to fracture and separation of particles. The fracture and separation of reinforcement particles causes to the formation of voids and cavities and that severely affect the surface roughness. The SEM micrograph of the typical machined surface of the Al+12Si/10wt%TiC composite (Figure 8) exhibited the formation of some surface damage in the form grooves and cavities.

As demonstrated in Figure 7, the physical appearance of chips produced at 0.06 mm rev-1feed rate and 50 m min^{-1} cutting speed was discontinuous and smaller in size, while the feed rate increases the appearance of chips became continuous and relatively longer. The shape of chips generated at 90 m min^{-1} cutting speed was short and curly, however when the feed rate increases the size of the chips also increases and it became curlier. On the other hand, at a cutting speed of 150 m min^{-1} the shape of the generated chips was relatively long and somewhat curly. Conversely, when the feed rate increases the chips became more straight and lengthy.

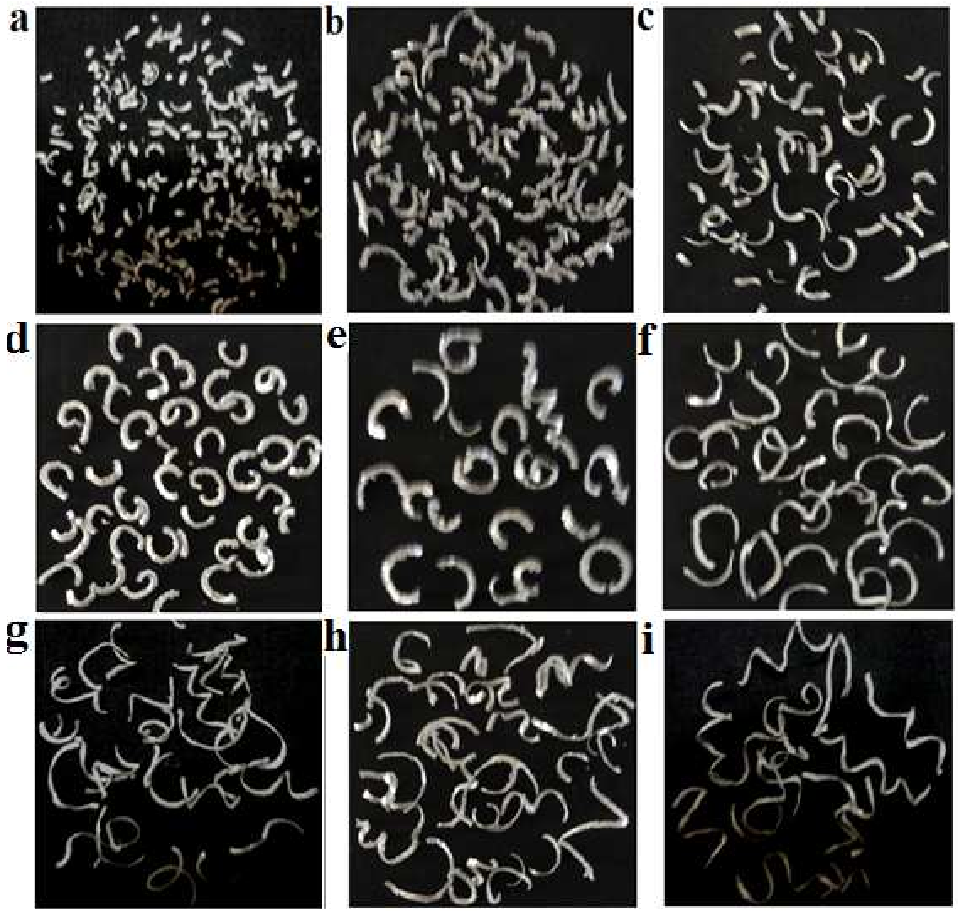

Figure 7. *The type of chips formed at a depth of cut of 1.0 mm and: (a) a cutting speed of 50 m/min and a feed rate of 0.06 mm/rev, (b) 0.12 mm/rev, (c) 0.24 mm/rev, (d) a cutting speed of 90 m/min and a feed rate of 0.06 mm/rev, (e) 0.12 mm/rev, (f) 0.24 mm/rev, (g) a cutting speed of 90 m/min and a feed rate of 0.06 mm/rev, (h) 0.12 mm/rev and (i) 0.24 mm/rev.*

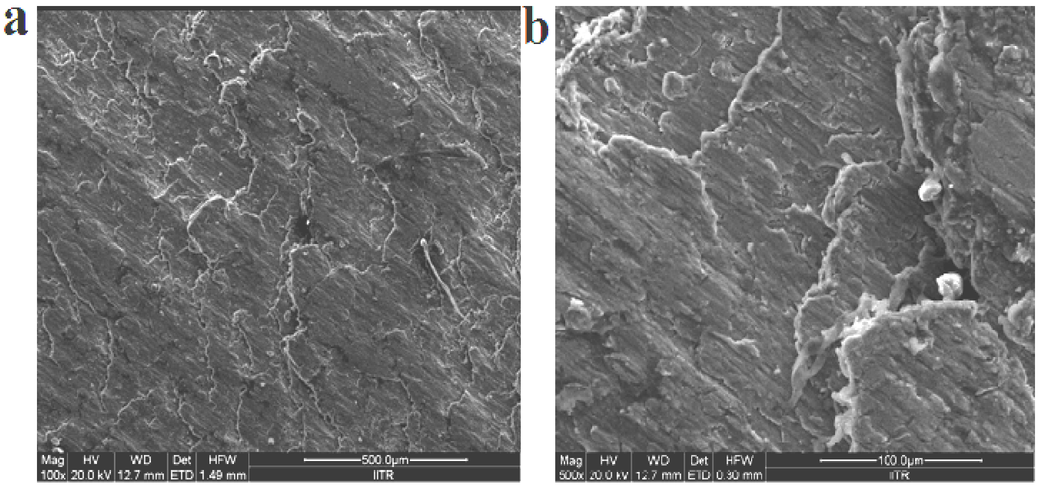

Figure 8. *SEM micrograph of Al+12Si/10wt%TiC composite showing: (a) typical machined surface and (b) cavity and crushed TiC particles.*

4. Conclusions

In the present investigation flank wear was identified as the major form of tool wear and its magnitude was relatively higher at lower cutting speed. Better surface roughness was achieved at higher cutting speed and minimum feed rate. The generated chips were dominantly short and curly. However, the size of chips relatively increased and their shapes become straight while the cutting speed and feed rates increased. In general, the findings of this study witnessed that effective machining of Al+12%Si/10wt%TiC composites with uncoated carbide insert tools is possible at relatively higher cutting speed about 150 m min^{-1} and minimum feed rates such as 0.06 mm rev-1. Emphasis should be given to the determination of the proper cutting speed, exceptionally high cutting speed may shorten the useful life of the cutting tool and makes economically unviable.

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