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# EFFECT OF REINFORCEMENT CONTENT AND CUTTING PARAMETERS ON TOOL WEAR IN MACHINING OF ALUMINUM HYBRID COMPOSITES

The machinability of aluminum hybrid composites (AHCs) can be enhanced by utilization of optimum composition and cutting parameters. In this study, the machinability of AHCs containing micron-sized $TiB_2$ and $B_4C$ particles was investigated using the face milling operation with a double coated cemented carbide tool. The composites, fabricated via cold pressing and microwave sintering, were subjected to the face milling experiments using a CNC milling machine. The influence of hybrid reinforcement content, feed rate and cutting speed on tool wear and surface roughness was examined during the milling of these composites. After the machinability tests, the worn surface of inserts was examined by a scanning electron microscope to see the wear types. The reinforcement content and cutting speed were obtained to have a much greater effect on the machinability and surface roughness of the hybrid composites compared to the feed rate. Either increasing the feed rate or decreasing the cutting speed provided a larger amount of chip removal until the wear limit. Moreover, the feed rate was obtained to be more effective on the tool wear at lower cutting speeds and higher amounts of hybrid reinforcement.

*Keywords:* Aluminum hybrid composite; tool wear; machinability; milling

## 1. Introduction

Aluminum matrix composites (AMCs), including fiber, whisker, platelet or particle reinforcements, have been considered and used in different engineering applications owing to their distinctive features compared to aluminum and some other metallic alloys [1-3]. Hard ceramic particles in micron or nano scale are frequently incorporated into aluminum matrix to get improved mechanical properties, e.g. strength, wear resistance and hardness [4,5]. Size, distribution, fraction and properties of these ceramic particles as well as good interfacial bonding are very crucial in determining the final properties and performances of AMCs [1-5]. Recently, the utilization of at least two different particle types (hybrid reinforcement) in AMCs has become prominent since it can provide some certain advantages by combining the properties of different reinforcements in a single structure [6-8]. Use of various reinforcements in an aluminum matrix instead of a single reinforcing phase provides the mechanical and physical characteristics of composites to be adjusted extensively [6-8]. Hence, aluminum hybrid composites (AHCs) reinforced with different types of particles can get improved physical, mechanical and wear properties compared to those with only one kind of ceramic reinforcement [6-8].

Powder metallurgy, being one of common ways for producing AHCs at a moderate cost [6], maintains lower processing temperatures and so much lower defects and more homogeneous microstructures compared to liquid metallurgy route, such as stir casting [6,9]. In traditional powder metallurgy route, sintering operation should be carried out for consolidation of powders after shaping by cold pressing. Microwave sintering, being an innovative consolidation method, provides the manufacturing of materials using lower temperatures and time in comparison to the traditional one [10-13]. Moreover, it can also yield superior physical and mechanical properties of materials [10-13]. In microwave sintering, electromagnetic energy is absorbed volumetrically by powdered material and then it is transformed into heat. This kind of heating results in higher diffusion processes, fast heating rates and lower energy consumptions [10-13].

In order to attain close tolerances, good surface finish and desired geometry in AHCs after sintering, suitable machining operations should be applied with optimum cutting parameters by keeping lower tool wear and process time. Among these operations, milling, as a common machining process, has been applied to some AHCs to analyze the influence of cutting procedure and reinforcement amount on tool wear [14,15].

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Premnath [14] sought the impacts of important cutting parameters and graphite content on tool wear, cutting force and surface roughness during milling of $Al/Al_2O_3$ composites which were prepared by means of stir casting. The feed rate (FR) was obtained to be the most important variable on the tool wear and cutting force [14]. In addition, raising either the FR or the cutting speed (CS) increased the tool wear remarkably [14]. Furthermore, the lower flank wear levels were recorded for the polycrystalline diamond insert in comparison to the WC insert and the addition of the graphite particles diminished the flank wear for both tools [14]. In a recent study [15], it was recorded that increasing the TiC content expedited the flank wear on WC tool during the end milling of $Al6061/SiO_2/TiC$ hybrid composites which were produced via stir casting [15]. The works regarding the tool wear during milling of AHCs are very seldom in the literature [14,15]. And also, the alterations of tool wear with respect to key machining parameters and composition of materials need to be clarified.

In this paper, the effects of important machining variables as well as amount of hybrid reinforcement on the machinability of AHCs reinforced with $TiB_{2p}$ and $B_4C_p$ were investigated. The AHC samples were prepared via cold pressing and microwave sintering.

## 2. Experimental method

### 2.1. Production of AHCs

The AHCs reinforced with $TiB_{2p}$ and $B_4C_p$ were fabricated by the cold pressing and microwave sintering technique. As an initial step, the particle sizes of Al, $B_4C$ and $TiB_2$ were determined by a particle size analyzer (MALVERN MASTERSIZER 3000). Then, the particle images were taken by a scanning electron microscope (SEM), FEI Quanta 650. After the characterization of powders, the composite powders were prepared by mixing them in TURBULA T2F for 2 h. The AHC samples; C6, C12 and C18 were considered to be reinforced with 6, 12 and 18 vol.% $TiB_2 + B_4C$ particles, respectively. These ceramic particles were incorporated to the aluminum matrix in equal amounts. Then, the AHC powders were cold compacted at 400 MPa to get the square samples, 30x30x10 mm in size. After that, these compacted samples were subjected to the microwave sintering at 620°C for 45 min in an Ar atmosphere within a microwave furnace (ENERZI MicroHeat (MH2917)), having two magnetrons, 2.9 kW power and 2540 MHz working frequency. The densities of compacted and sintered composites were determined according to ASTM B962 – 17 [16].

### 2.2. Microstructure and hardness

The microstructure pictures and elemental maps of the AHCs by an SEM (ZEISS GeminiSEM 500) were taken after making the standard metallographic preparation to see the homogeneity of reinforcing phase distribution. On the other hand, the Brinell hardness of the AHCs was determined with the aid of a hardness tester (DIGIROCK-RBOV) by implementing a load of 62.5 kg with a steel ball (2.5 mm in diameter) [17].

### 2.3. Face Milling Tests

Face milling experiments of the AHCs were made using a CNC milling machine (SPINNER MVC1000). In these tests, three CSs (150, 200 and 250 m/min) at two FRs (0.10 and 0.18 mm/z) were used, whereas the depth of cut was selected to be 1.5 mm. For all cutting operations, the double coated (TiAlN-TiN) cemented carbide insert (Taegutec APKT 1604-REM TT7080) was used [18]. The chip volume detached from the AHCs as well as the flank wear on tool was recorded for every pass of the tool over the samples. Before taking the wear measurements, the tools were cleaned with a NaOH solution to remove the chip particles from the tool surfaces completely. The flank wear measurements were continued using a microscope (Dino-Lite Premier AM4113T) until the wear limit of 0.3 mm was reached. And also, the wear types of tools were investigated by means of SEM (FEI Quanta 650). Furthermore, the surface roughness levels of the AHCs were assessed at all cutting conditions individually after the first pass was completed just at the beginning of the milling operations. For these measurements, a surface roughness tester (DAILYAID DR100) was utilized.

## 3. Results and discussion

### 3.1. Properties of powders

The average size of Al, $TiB_2$ and $B_4C$ particles was obtained to be 19.1, 5.2 and 3.9 µm, successively. The size distribution of Al and $TiB_2$ was recorded to be relatively wide. The $D_{10}$ was found to be 6.5 and 1.5 µm while $D_{90}$ was measured as 98.5 and 48.6 µm for Al and $TiB_2$, respectively. Besides, the particle size distribution of $B_4C$ was determined to be much narrower. Fig. 1 denotes the SEM pictures of particles. The aluminum powders have a rounded and mostly rod-like shape. The $TiB_2$ particles are flake in shape while the $B_4C$ particles are irregular and polygonal.

### 3.2. Density, microstructure and hardness

TABLE 1 lists the density and porosity levels for the investigated hybrid composites. It is apparent that increasing the hybrid reinforcement amount increases the porosity level of the composites and reduces the densification. During the compaction, very hard $TiB_2$ and $B_4C$ particles restrict the packing of soft aluminum particles and show a resistance to densification of composites. The Brinell hardness was obtained to be 44.3, 50.7 and 56.0 for the C6, C12 and C18, respectively. Fig. 2 represents the microstructures of the hybrid composites. Furthermore, the elemental maps for the C6, C12 and C18 are shown in Figs. 3-5,

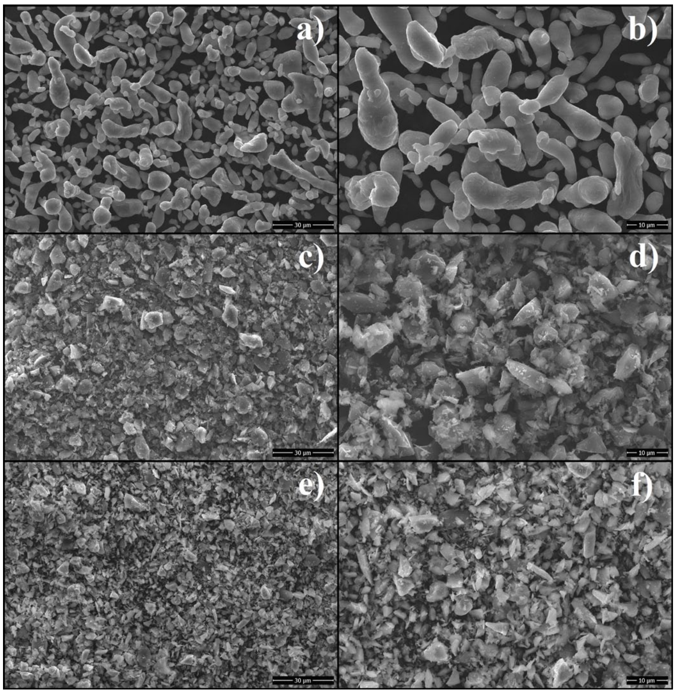


Fig. 1. The powders used in the hybrid composites: a) Al (2500×), b) Al (5000×), c) $B_4C$ (2500×), d) $B_4C$ (5000×), e) $TiB_2$ (2500×) and f) $TiB_2$ (5000×)

successively. The distribution of the hybrid ceramic particulates is observed to be quite homogeneous.

TABLE 1

Density and porosity of the investigated hybrid composites

| Sample | Theoretical density (g·cm$^{-3}$) | Green density (g·cm$^{-3}$) | Relative green density | Sintered density (g·cm$^{-3}$) | Porosity after sintering (%) |
|---|---|---|---|---|---|
| C6 | 2.749 | 2.511 | 0.913 | 2.560 | 6.88 |
| C12 | 2.798 | 2.546 | 0.910 | 2.597 | 7.18 |
| C18 | 2.848 | 2.574 | 0.904 | 2.628 | 7.72 |

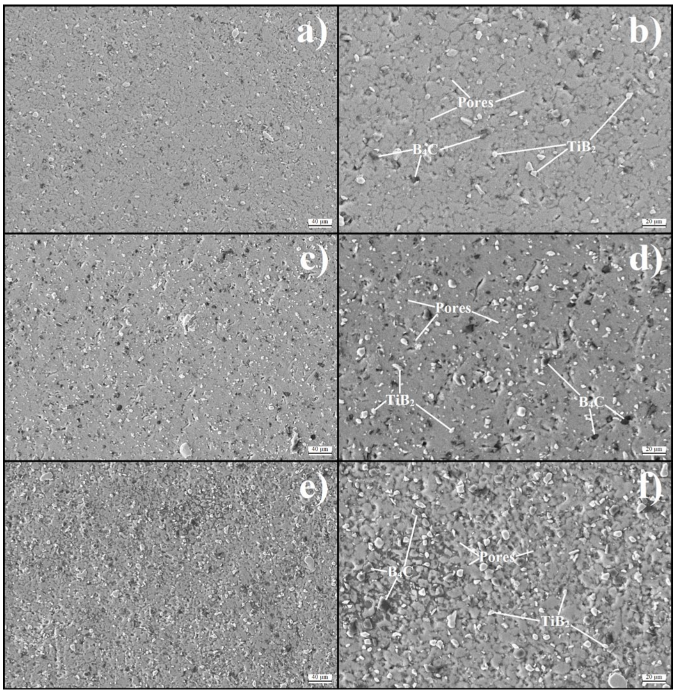


Fig. 2. Microstructure of the hybrid composites a) C6 (500×), b) C6 (1000×), c) C12 (500×), d) C12 (1000×), e) C18 (500×) and f) C18 (1000×)

### 3.3. Machinability of composites

The tool wear variation on the insert with the chip volume during the face milling of the AHCs at the FR of 0.10 mm/z is illustrated in Fig. 6. One can see clearly that an increment in the CS accelerates the flank wear of the tool and reduces the chip volume removed from all three composites significantly. Fig. 7 depicts the change of flank wear versus chip volume when the hybrid composites were face milled at 0.18 mm/z. The effects of CS on both flank wear and chip volume are again found to be in a similar manner at 0.18 mm/z. The similar tendency was

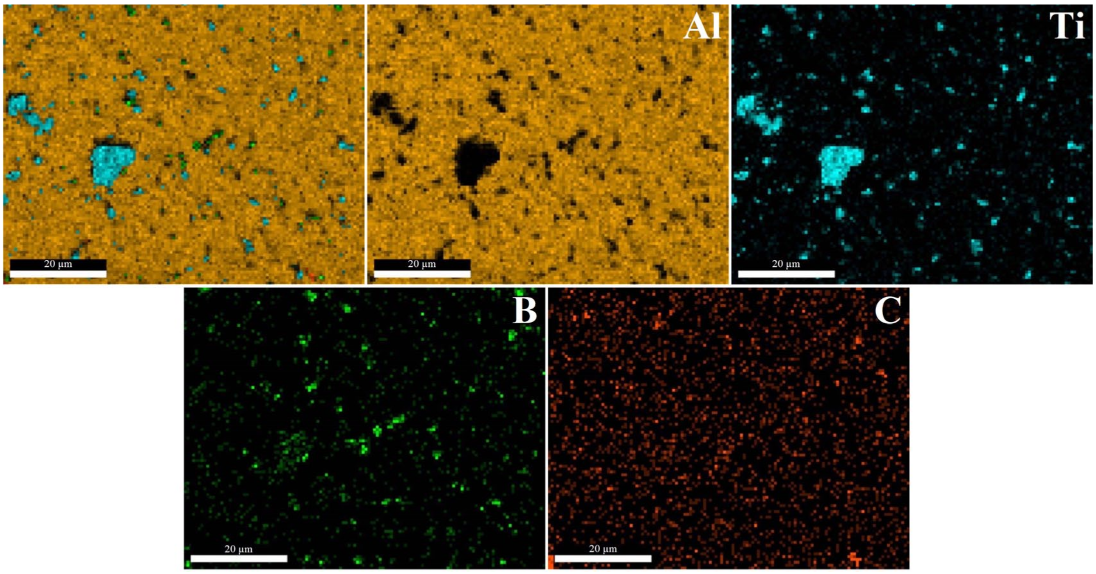


Fig. 3. Elemental distribution of the C6

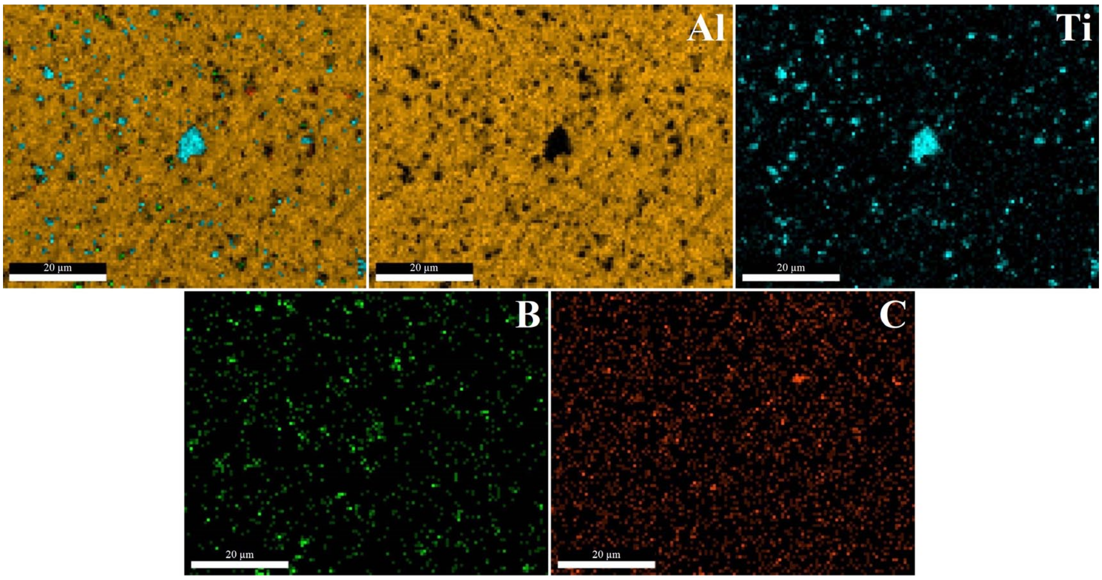


Fig. 4. Elemental mapping of the C12

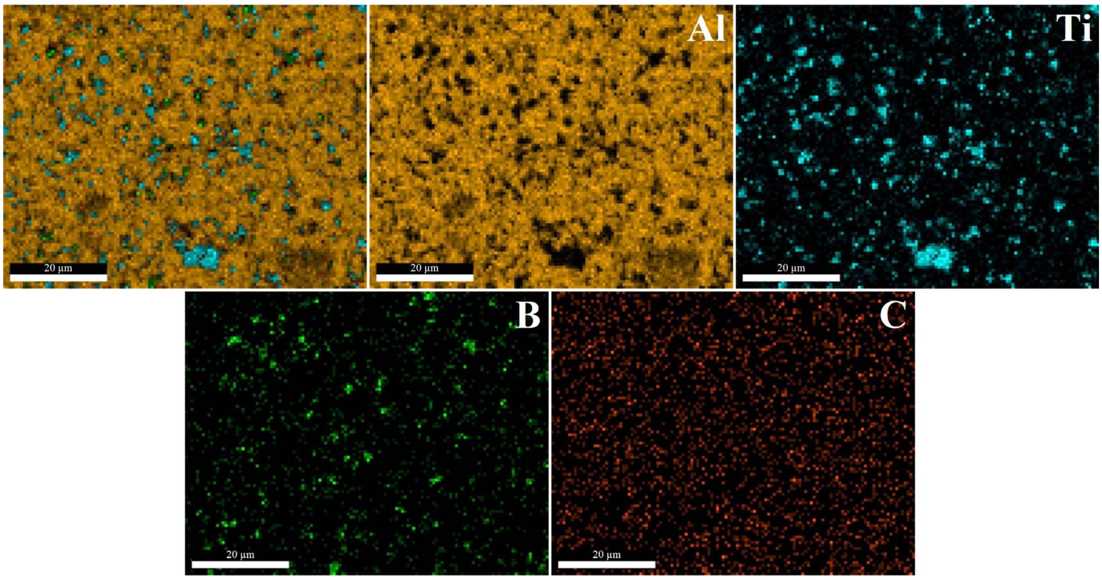
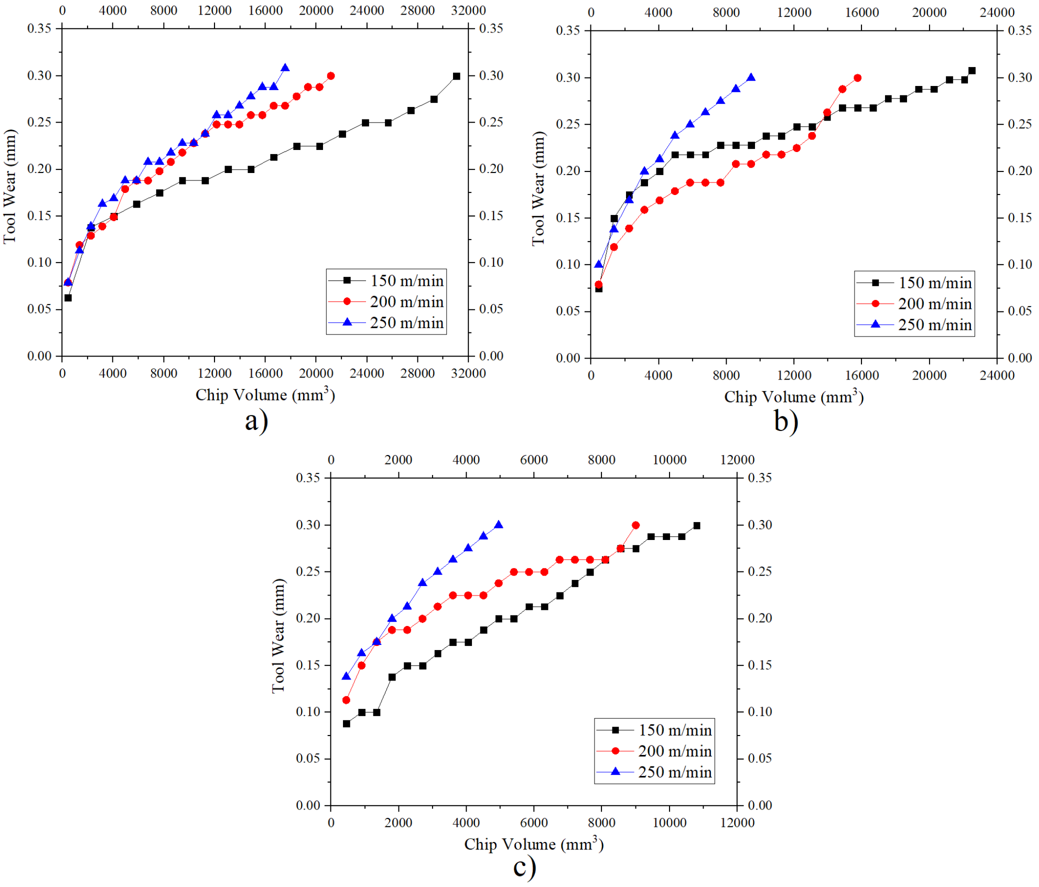


Fig. 5. Distribution of elements within the C18

also recorded in some previous studies related to the impact of CS on tool wear in the milling of particle reinforced AMCs [14,19-23]. The volume of chip taken away from the samples C6, C12 and C18 increases by ~77, 133 and 118% at 0.10 mm/z, and ~100, 192 and 150% at 0.18 mm/z, respectively while the CS is decreased by 40% (from 250 to 150 m/min).

When the FR is augmented from 0.10 to 0.18 mm/z, the tool flank wear decreases and the chip volume increases for all machined samples substantially. The preceding studies done on the milling of Al-4Cu/$B_4C_p$ [24] and Al/$SiC_p$ composites [25] also showed that increasing FR led to the lower flank wear of tools. The highest flank wear is observed for the C18 when the CS and FR are 250 m/min and 0.10 mm/z, successively. And also, the lowest one is obtained for the C6 at the CS of 150 m/min while the FR is 0.18 mm/z. As the FR is 0.10 mm in milling, the chip volumes of 31050 mm$^3$ and 17550 mm$^3$ are removed from the C6 at the CSs of 150 and 250 m/min, respectively until the flank wear limit. However, they increase by about 25 and 10%, successively while the FR is increased to 0.18 mm. The increment of the chip volume with increasing FR becomes more severe when the hybrid reinforcement content is augmented. The chip volume increases by ~46% for the C12 and C18 composites at the CS of 150 m/min while the FR is raised from 0.10 to 0.18 mm/z. It is apparently deduced that the effect of FR on the tool wear appears to be more operative at lower CSs and higher amounts of hybrid reinforcement (12 and 18%).

The incorporation of higher amount of hybrid $TiB_2$ and $B_4C$ particles into the aluminum aggravates the flank wear drastically and decreases the machinability of the composites as expected. The contact of these hard ceramic particles with the insert exacerbates the tool wear so that they are mainly responsible for worsening the machinability of composites by taking into ac-

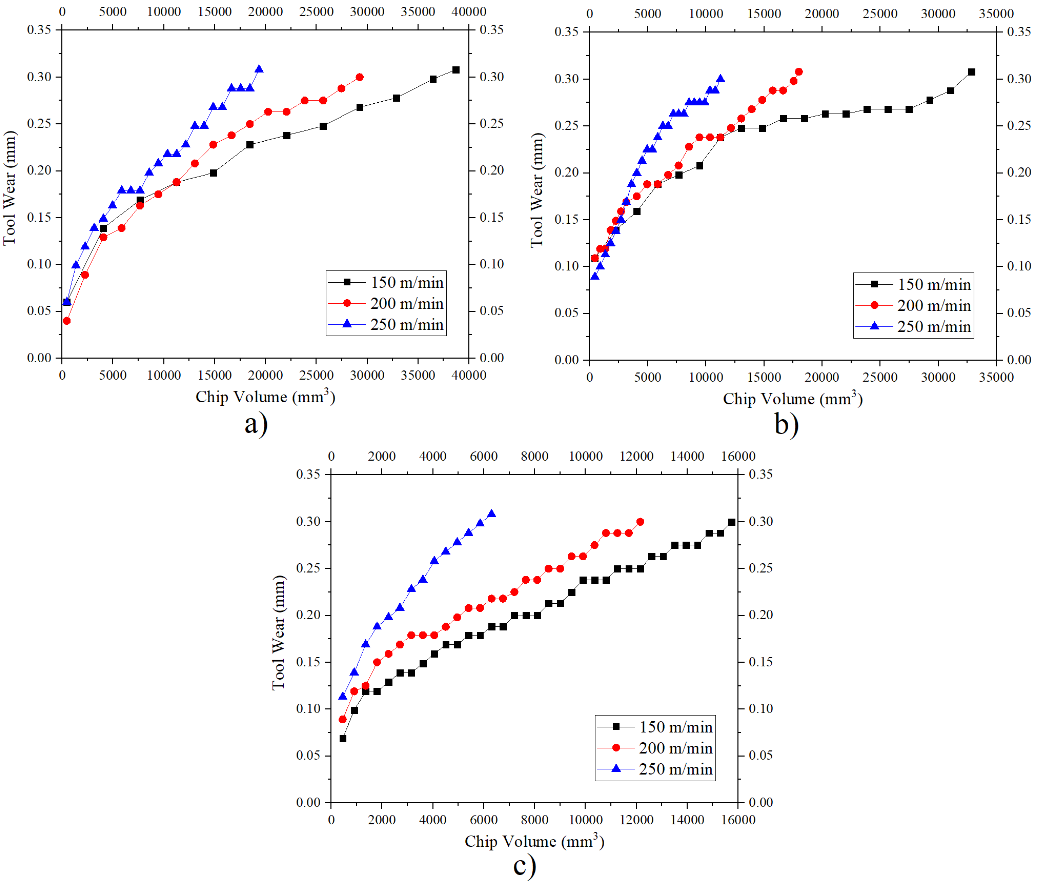


a)

b)

c)

Fig. 6. Tool wear vs chip volume during the machining of a) C6, b) C12 and c) C18 at the FR of 0.1 mm/z



a)

b)

c)

Fig. 7. The variation of tool wear with respect to chip volume in milling of hybrid composites a) C6, b) C12 and c) C18 at the FR of 0.18 mm/z

count of the composition alone. The amount of chip reduces by ~57 to 72% depending on the cutting conditions as the hybrid reinforcement ratio is increased from 6 to 18 vol.%.

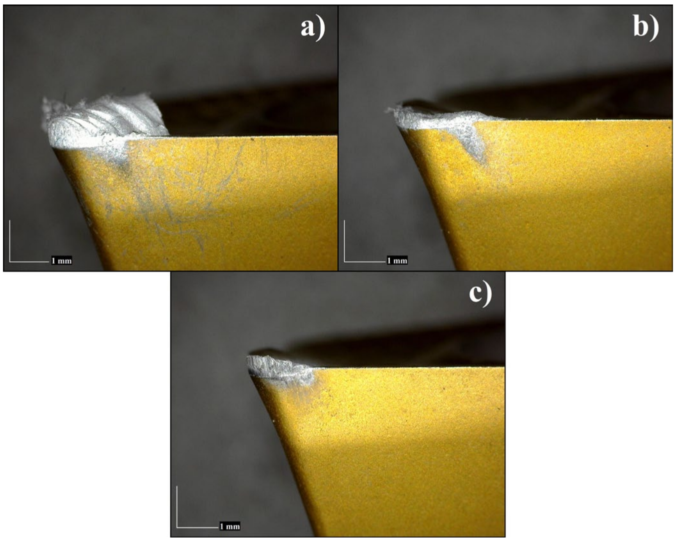


Fig. 8. The BUE formation on the tools when the hybrid composites a) C6, b) C12 and c) C18 were face milled at the FR of 0.18 mm/z and CS of 250 m/min

Increasing the CS, which raises the frictional heating between the insert and the composite causes higher temperatures at the cutting zone [19,20,23,26-30]. These high temperatures can also trigger the diffusion wear mechanisms on tool [23,28-30]. In addition to that, the existence of built-up-edge (BUE) between tool and workpiece also plays a key role. The BUE generates owing to the adherence of the removed chips onto the tool during the milling operation and it can be taken away from the cutting region more easily while the CS is high enough [19,20,22,23,26,27,29]. Fig. 8 displays the BUE constitution on the tool during the face milling of the investigated composites. It diminishes with an increase in the hybrid reinforcement content and the CS rapidly. The BUE that behaves like a protective layer between the tool and the composite, reduces the tool wear significantly [19,20,22,23,26,27,29].

The wear on the coated tool was also found to be very sensitive to the FR during the milling of AHCs. Increasing the FR led to a larger amount of chip removal per tool revolution. Therefore, the existence of BUEs at a larger extent with increasing FR can take place in the course of face milling. In addition, the incidence of contact between the insert and the hard ceramic particulates in the hybrid composites becomes lesser [24,31,32]. Moreover, Tomac et al. [31] previously mentioned that an increase in the FR can cause a higher heat transfer into the machined composite (AlSi7Mg/SiC) from the cutting region. This increases the softening of the composite and the hard ceramic particles are impelled to move into the soft matrix or chip more easily by the action of insert during the operation [31]. Although the dominant wear mechanism on the double coated tool during the milling was observed to be abrasive, adhesive wear was also recorded to some extent due to adhesion of the broken chips

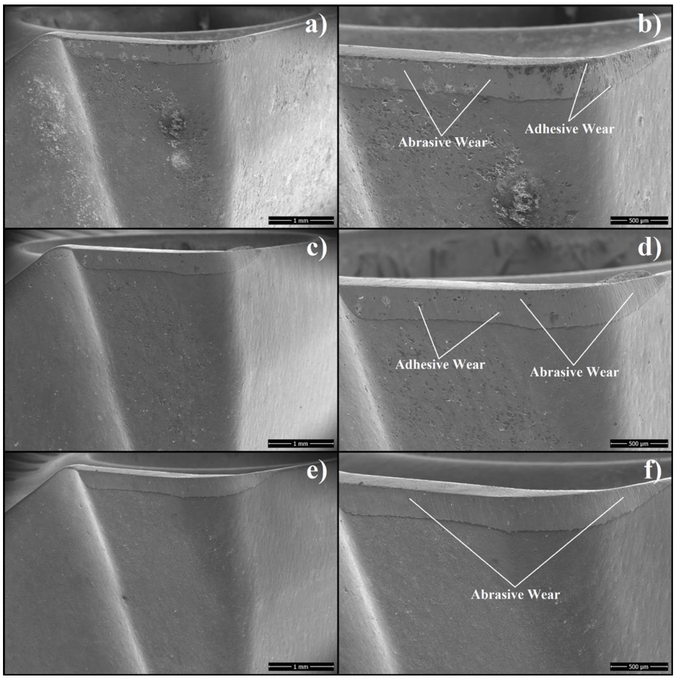


Fig. 9. SEM images of worn tool inserts after the milling of the composites a) C6 (80×), b) C6 (150×), c) C12 (80×), d) C12 (150×), e) C18 (80×) and f) C18 (150×) at the FR of 0.18 mm/z and CS of 250 m/min

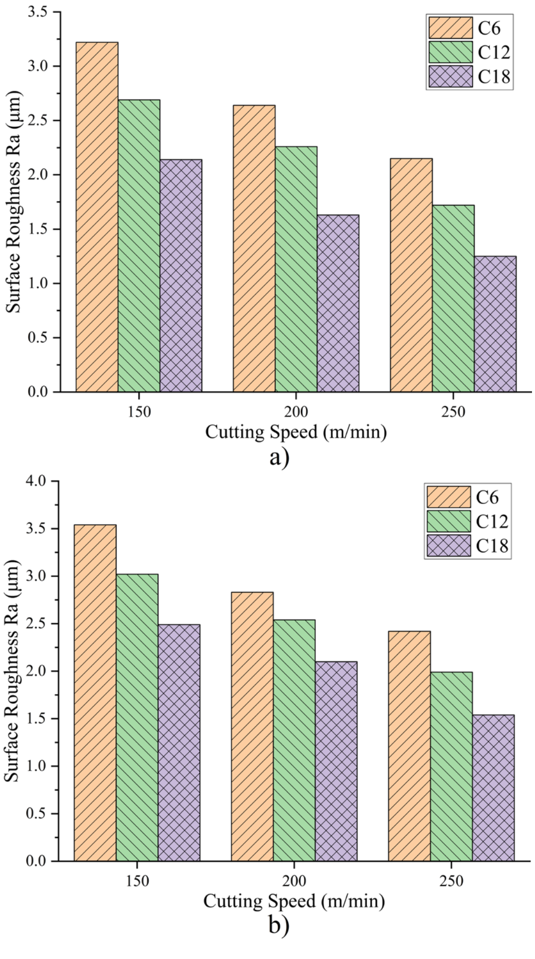


Fig. 10. Surface roughness of the hybrid composites after the milling at a) 0.1 mm/z and b) 0.18 mm/z

on the tool. The lines or grooves as a representative feature of abrasive wear in parallel to the cutting direction are clearly viewed (Fig. 9.).

The surface roughness of the AHCs varies between 1.25 and 3.54 µm depending on the cutting conditions and reinforcement ratio (Fig. 10.). Increasing the CS and decreasing the FR reduce the surface roughness of the hybrid composites remarkably. The results found in the current work show a parallelism with those found in some previous woks conducted on the milling of aluminum composites with micron-sized ceramic particles [33-35]. The variation in the surface roughness of AHCs is ascribed to the extent of BUE formation depending on the CS and FR [33-37]. The increment in the reinforcement content results in lower surface roughness levels. It is presumably owing to the easier removal of chips from the cutting zone by decreasing their adherence to the tool and so BUE formation [37].

## 4. Conclusions

The major outcomes concerning the results of the current study were epitomized as following.

- An increase in the hybrid ceramic particulate content reduced the tool life at all cutting conditions rapidly.
- The reinforcement content and CS were found to be more influential on the machinability and surface roughness of the hybrid composites compared to the FR.
- Increasing the CS or decreasing the FR in the face milling of the AHCs accelerated the tool wear significantly. Hence, using lower CSs and higher FRs seemed to be very crucial in order to prolong the tool life.
- The increments in the chip volume removed from the C6, C12 and C18 were by ~ 77, 133 and 118% at the FR of 0.10 mm/z and ~100, 192 and 150% at the FR of 0.18 mm/z, successively while the CS is lowered by 40% (from 250 to 150 m/min).
- The effect of FR on the tool wear increased at lower CSs and higher hybrid reinforcement contents.
- Higher hybrid reinforcement ratio and CS together with the lower FR resulted in the lower surface roughness of the composites.

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