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Dry and Semi-Dry Turning of Titanium Metal Matrix Composites (Ti-MMCs)

Seyed Ali Niknam*[a], Jules Kouam[b], Victor Songmene[b], Marek Balazinski[c]*

[a]*School of Mechanical Engineering, Iran University of Science and Technology, Iran*
[b]*Deaprtment of Mechanical Engineering Ecole de technologie Superieure (ETS), Canada*
[c]*Deaprtment of Mechanical Engineering, Polytechnique Montreal, Canada*

* Corresponding author. Tel.: +98-21-7724-0203 ; fax: +98-21-7724-0203. *E-mail address:* saniknam@iust.ac.ir

Abstract

Metal matrix composites (MMCs) are composed of non-metallic reinforcements (i.e., ceramic) in metal matrices which feature high toughness, wear and fatigue resistant and relatively light-weight. One of the metallic composites with remarkable mechanical properties is titanium metal matrix composite (Ti-MMC) that is considered as an alternative to nickel-based alloys. Despite excellent mechanical and physical features of Ti-MMC, due to high price and presence of hard and abrasive ceramic particles in metal matrices, machining, and machinability of Ti-MMCs is a complex subject. Knowing that very limited studies are available on machining Ti-MMCs under various flow rates and lubrication modes, adequate knowledge about the effects of cutting parameters and lubrication modes on machining attributes is a critical issue. Therefore, this study intends to present the turning of Ti-MMC under dry and semi-dry modes at various levels of flow rates. Effects of cutting parameters on several machining attributes including cutting forces, surface roughness, and particle emission will be presented in the course of this study.

Keywords: "Turning; Ti-MMC; Lubrication;Cutting force;Surface quality"

Introduction

One of the most respected hard to cut materials with superior features is Ti-MMC, which can be however considered as an alternative to superalloys. Despite numerous recent works on machining and machinability of titanium alloys [1], only limited studies are reported on machining Ti-MMCs with traditional and non-traditional approaches [2-6]. Among machining and machinability attributes, the tool wear, directional cutting forces, surface quality (e.g., surface roughness), particle emission and dust generation [7, 8] are of prime importance. In fact, severe tool wear, low quality machined surface, and also short tool life are known as the main difficulties and problems hindering the machining and machinability of Ti-MMCs. Within the most of reported works in the literature, no clear knowledge is available on the effects of lubrication modes on cutting forces and surface quality attributes when turning Ti-MMC. Furthermore, dust generation when machining Ti-MMC is a unique topic which has received very low consideration. Furthermore, except limited works [2-4, 9], low amount of works are available about turning Ti-MMC when using carbide insert. Therefore, the effects of cutting parameters and lubrication modes (dry and semi-dry) on aforementioned machining attributes will be presented in the course of this study when commercial uncoated carbide inserts were used.

Experimental plan

The cylindrical blocks of Ti-6Al-4V with 10-12% volume fraction of TiC particles with uneven shapes and 10-20µm size with 53.62mm in diameter and 210mm in length were used. The cutting tests were conducted on Mazak Nexus 100-II M under various lubrication modes and experimental parameters, such as constant depth of cut 1 mm and feed rate 0.15 mm/rev.

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Furthermore, five levels of cutting speed (20,30,40,50,60 m/min) and constant length of cut 65mm were used. The SECO uncoated carbide insert was used in the tests (Fig.1). The bio-lubricant MecGreen was used in the semi-dry tests which included the flow rates of 100-300 ml/min. To better elaborate the effect of cutting parameters and tool wear mode on the surface quality, the surface roughness measurement was conducted within the entrance and exit sides of the work part using the profilometer Mitutoyo SJ 400 (Fig.2). The measurement length of each section was 5.6 mm. The particle emission was measured using Scanning Mobility Particle Sizer (SMPS) for ultrafine particle (UFP) and Aerosol Particle Sizer (APS) for fine particle (FP).

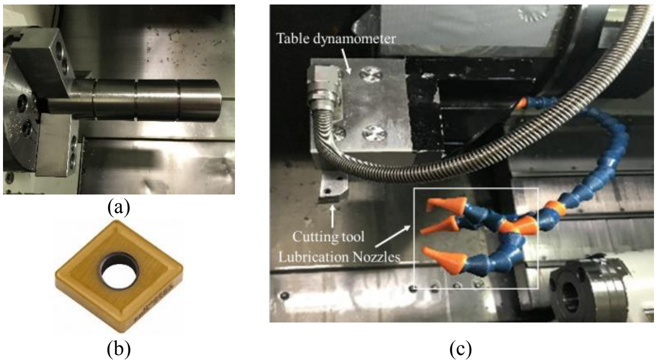


Fig. 1. (a) The Ti-MMC work part; (b) The uncoated carbide insert; (c) system set-up

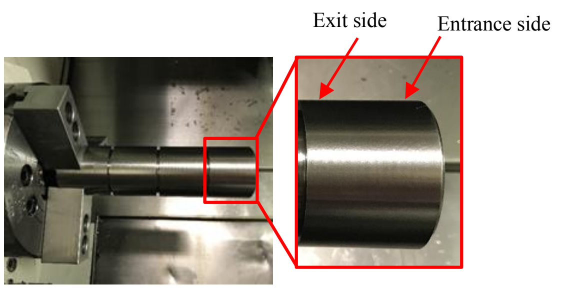


Fig. 2. Overview of surface roughness measurement approach

1. Results

Cutting forces

The directional cutting forces were analyzed using a sampling frequency of 12 KHz. A typical cutting force signal during turning operation consisted of cutting forces in radial force (FR), feed force (FF) and cutting force (FC) as presented in Fig.3. Knowing that in turning of hard to cut materials (i.e., Ti-MMC) the FF is sometimes even higher than FC, the resultant force (F_{Res}) in each test was also calculated using Eq.(1), incorporating the effects of FF. According to Fig.4, the rapid increase in the cutting forces is the evidence insert's wear. When dry turning Ti-MMC at high cutting speed is in progress, very high local temperature is generated within the tiny area around the cutting edge. This phenomenon could be attributed to the low thermal conductivity of Ti-MMCs. Consequently, severe problems including rapid tool wear may occur [10]. Moreover, as a result of oxidation and chemical wear mechanisms, tool life reduction is expected. The tendency of migration of the tool materials to Ti-MMC's matrix as well as elevated temperature resulted from tool-work part engagement leads to the chemical reaction, material diffusion and adhesion in the cutting tool [11]. Consequently, even within the specific cases related to high material removal rate, the substantial thermal loads generated in the cutting zone cannot be evacuated using the generated chips [12]. Moreover, the tool slides than cutting the work part at a low shear angle; therefore, as similar as friction, higher resulting values of pressure and temperature in the cutting zone is expected [13]. It may lead to adhesion of the scraped particles to the tooltip [14]. Consequently increased cutting forces are observed. On the basis of Fig.4 and despite the flow rate used, higher F_{Res} was observed at higher levels of cutting speed. Although it is believed that easier plastic deformation may occur at higher cutting speed, however, since Ti-MMC is classified as a hard to cut material, elevated temperature at higher speed is expected. This phenomenon may lead to increased FC and wear rate under higher cutting time. Other major affecting elements are built-up edge formation (BUE) and built up layer formation (BUL). Based on Fig.5, adhesion is thought to be the main wear mode at lower to moderate levels of cutting speed. As a result of initial wear on the flank side of the insert, a sudden increase in the cutting force is observed (Figs.4 and 5). The presence of adhesion would generate a thin and smooth layer on the cutting tool surface, so-called brace shield (Fig.5) which not only acts as a barrier of the cutting tool, but it also tends to decelerate the wear rate.

$$F_{Res} = \sqrt{FF^2 + FR^2 + FC^2} \qquad \text{Eq.(1)}$$

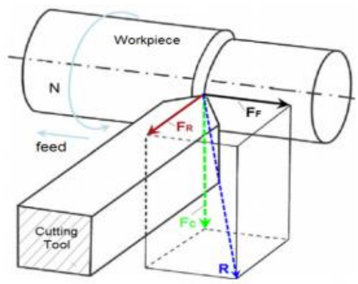


Fig. 3. Overview of turning cutting forces [15]

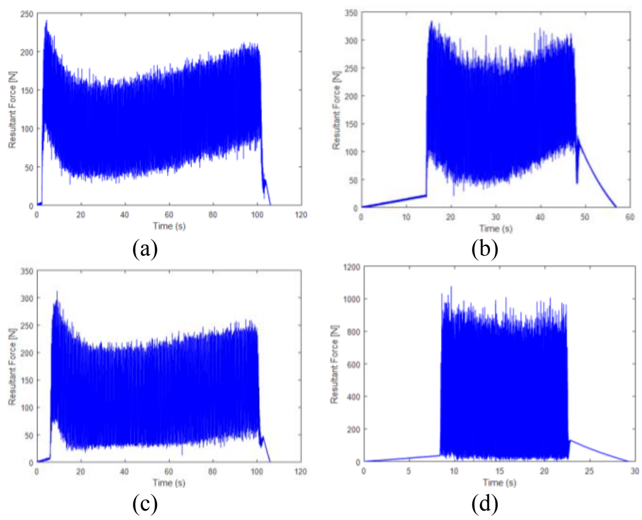
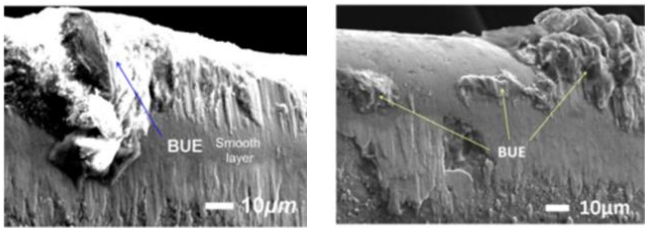


Fig.4. The F_{Res} at dry condition when using (a) V_c=20 m/min (b) V_c =60 m/min and flow rate 300 ml/min when (c) V_c=20 m/min and (d) V_c=60 m/min

The mean values of cutting forces under different flow rates are presented in Fig.6. It can be exhibited that higher cutting forces (FC, FF, and F_{res}) were resulted in semi-dry conditions. In fact, under lubricated modes, although lower temperature and tool wear is expected, generation of a thin film of lubricant prevents the smooth progress of the cutting tool within the work part. Consequently, higher cutting forces and surface roughness are resulted. The negligible difference between cutting forces at semi-dry conditions with various flow rate is related to several noise factors including configuration and position of the lubrication nozzles, which are of prime importance. Furthermore, adequate knowledge of flow rates, as well as the type of commercial machining lubricants are demanded in prospective studies.



(a) (b)

Fig.5. The BUE occurs within initial period when using cutting speeds (a) V_c= 50 m/min and (b) V_c= 60 m/min

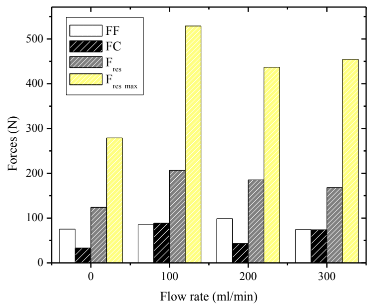


Fig.6. The mean values of cutting forces under various flow rates

Surface roughness

The average and root mean square (RMS) values of the surface roughness profile denoted as R_a and R_q were used as the surface roughness variables. The effects of cutting parameters and lubrication modes on both variables are presented within the entrance, and exit sections of the cutting tools in each test (Fig.2).

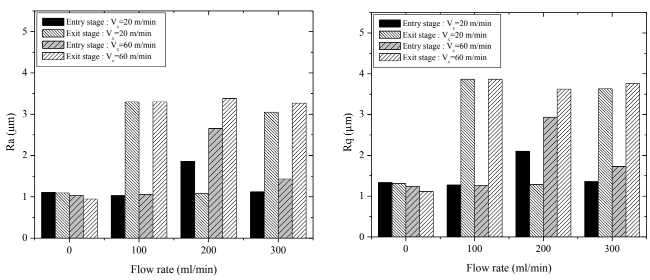


Fig.7. The R_a and R_q at various flow rates

Referring to the cutting tool progress within the cutting tool under semi-dry tests, higher resulting values of R_a and R_q were observed under higher levels of cutting speed. In particular, expect few cases, higher values of R_a and R_q were observed on the exit side, while contrary under dry cutting conditions and despite the cutting speed used, more deteriorated surface quality was observed on the entrance side of the work part (Fig.7). This phenomenon could be directly related to the rapid tool wear on the initial moments of the cutting process under dry mode. However, due to the presence of brace shield, better surface roughness was observed when the cutting tool progresses in the work part. The different trend was observed under semi-dry mode, and in general, higher values of R_a and R_q were observed at higher speed.

Particle Emission

During the machining operation, dust generation is an evitable phenomenon which leads to health and environmental concerns. It is expected that the lubricated machining may reduce the dust. However, the outcomes are widely related to the flow rate as well as machining parameters (i.e., feed rate, coating) used. As shown in Fig.10, despite cutting speed used, lower particle number concentration of ultrafine particle rate was observed where higher flow rate was used. Similarly, lower particle number concentration at the dry condition as compared to flow rate 100 and 200 ml/min up to the 40 nm diameter. As shown in Fig.9, lower resulting values of particle number concentration of ultrafine particle can be seen under dry condition, followed by semi-dry at a higher level of flow rate. Since uncoated insert was used in this work, this observation indicates that there is an interaction effect between lubrication mode, cutting speed and tool coating. Therefore, further studies on the effects of coated tools on particle size are demanded.

2. Conclusion

The primary intention of this work as aforementioned is to compare the effects of lubrication modes on critical machinability attributes, although the experimental results are limited to only one type of insert and specific cutting parameters. According to experimental results, the following conclusions are drawn:

- Surprisingly, larger resulting values of cutting forces were observed under semi-dry modes. Although lower temperature and tool wear are expected under semi-dry modes, however, generation of a thin film of lubricant prevents the smooth progress of the cutting tool within the work part.
- Under dry mode at cutting speed 50 m/min, the F_{Res} tends to increase when cutting time increases. This phenomenon is the evidence of rapid tool wear, which can be highly affected by vibration, tool wear modes (e.g., BUE, BUL, adhesion) as a result of elevated temperature in the cutting zone. However, more considerable resultant force (F_{Res}) was observed when higher lubrication flow rate was used. Further studies concerning adequate levels of flow rate, type of lubricant and the configuration and position of the lubrication nozzles are demanded.
- Referring to the cutting tool progress within the cutting tool under semi-dry tests, higher resulting values of R_a and R_q were observed under higher cutting speed. In particular, expect few cases, higher values of R_a and R_q were observed on the exit side of the work part, while contrary under dry cutting conditions and despite the cutting speed used, more deteriorated surface quality was observed on the entrance side.

This phenomenon could be directly related to the rapid tool wear on the initial moments of the cutting process under dry mode.

- Despite cutting speed used, lower particle number concentration of ultrafine particle rate was observed where higher flow rate was used. Similarly, lower particle number concentration was observed under the dry condition as compared to that observed under other conditions. It is exhibited that the effects of coating on particle number concentration of ultrafine and fine particles are of prime importance for adequate selection of cutting parameters.

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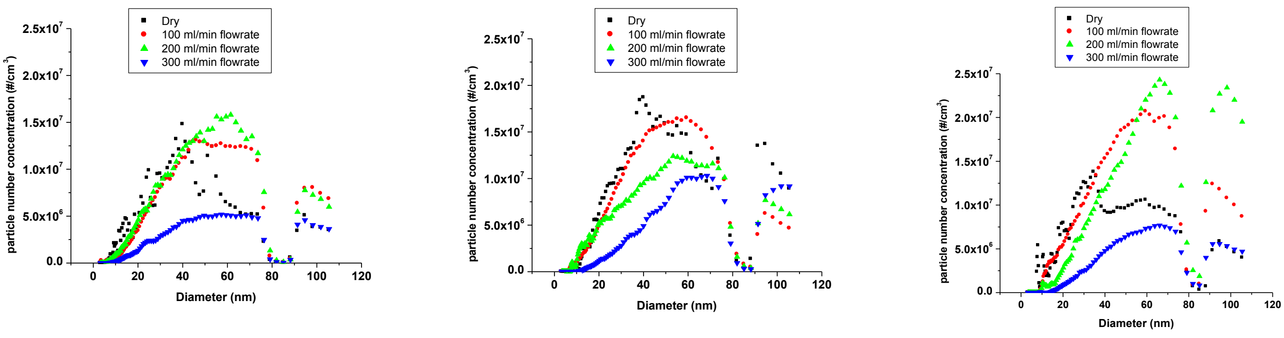

V_c= 20 m/min V_c= 40 m/min V_c= 50 m/min

Fig 8. Particle number concentration of ultrafine particle (UFP) under different cutting speeds and flow rates

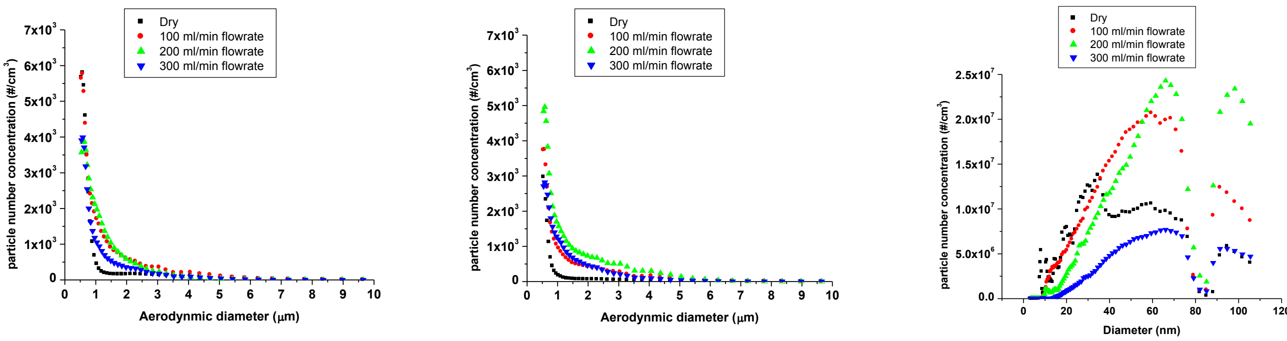

Fig 9. The particle number concentration of fine particle (FP) under different cutting speeds and flow rates

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