



Titre: Tool wear Characterization, Morphology and the effects of the initial cutting Conditions when Machining TI-MMCS
Title:

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Author:

Date: 2023

Type: Mémoire ou thèse / Dissertation or Thesis

Référence: Kamalizadeh, S. (2023). Tool wear Characterization, Morphology and the effects of the initial cutting Conditions when Machining TI-MMCS [Thèse de doctorat, Polytechnique Montréal]. PolyPublie. <https://publications.polymtl.ca/55224/>
Citation:

 **Document en libre accès dans PolyPublie**
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URL de PolyPublie: <https://publications.polymtl.ca/55224/>
PolyPublie URL:

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Programme: Génie mécanique
Program:

POLYTECHNIQUE MONTRÉAL

affiliée à l'Université de Montréal

**TOOL WEAR CHARACTERIZATION, MORPHOLOGY AND THE
EFFECTS OF THE INITIAL CUTTING CONDITIONS WHEN
MACHINING TI-MMCS**

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Thèse présentée en vue de l'obtention du diplôme de *Philosophiæ Doctor*

Génie mécanique

Juin 2023

POLYTECHNIQUE MONTRÉAL

affiliée à l'Université de Montréal

Cette thèse intitulée :

**TOOL WEAR CHARACTERIZATION, MORPHOLOGY AND THE
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MACHINING Ti-MMCS**

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en vue de l'obtention du diplôme de *Philosophiæ Doctor*

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DEDICATION

To my son, Evan, my family, and colleagues

ACKNOWLEDGEMENTS

I sincerely thank my advisor, Professor Marek Balazinski, for his outstanding support, open door, help, suggestions, great encouragement, and guidance. He has always inspired me with his wisdom, kindness, and trust in my life. I would also like to thank my co-supervisors, Prof. Sylvain Turenne and Dr. Seyed Ali Niknam, for their invaluable support and guidance. This work would not succeed without their precious advice.

I should thank the Natural Sciences and Engineering Research Council of Canada (NSERC) and the NSERC Canadian Network for their financial support for research and innovation in manufacturing technology (NSERC-CANRIMT).

Thank you to all my PhD defence jury members for guiding me through completing my doctorate. Finally, thank the school administration teams for their valuable comments, which significantly improved this thesis.

RÉSUMÉ

Les composites à matrices métalliques de titane (Ti-MMCs) sont des nouvelles générations de matériaux et sont utilisés dans les domaines industriels de l'aérospatiale et de l'automobile. Les particules de renfort TiC sont très dures et abrasives et améliorent les propriétés mécaniques et physiques du titane. Toutefois, cela entraîne plusieurs problèmes tels que l'usure sévère des outils ainsi que leur vie utile très brève lors de l'usinage de ces matériaux. La littérature indique très peu d'études concernant usinabilité des Ti-MMC, en particulier pour l'estimation de la durée de vie utile et de l'amélioration de la rugosité de surface.

Une partie de cette thèse décrit la caractérisation de l'usure d'outil dans le fraisage à grande vitesse des Ti-MMC. Les enquêtes statistiques sur les tests de fraisage utilisant des plaquettes de carbure X500 et PCD ont conclu que la vitesse de coupe et la profondeur de coupe sont les principaux paramètres de coupe affectant le taux d'usure de l'outil, tandis que la rugosité de surface n'était pas affectée par les paramètres de coupe utilisés lors de l'utilisation de plaquettes PCD et n'était pas sensible à la variation de l'avance lors de l'utilisation de la plaquette carbure X500. Les mécanismes d'usure des outils et l'évaluation de la qualité de surface lors du tournage de Ti-MMC avec des carbures et des outils CBN ont été enquêtés. Les principaux modes d'usure observés sur le "flanc" des outils testés sont l'adhésion, l'abrasion et l'oxydation. Selon les résultats expérimentaux, la rugosité de surface et le taux d'usure de "flanc" lors de l'utilisation d'outils en carbure et CBN peuvent être contrôlés par les paramètres de coupe utilisés, en principe la vitesse de coupe. La vitesse de coupe et l'avance sont les paramètres de coupe déterminants pour le taux d'usure de "flanc" lors du tournage des Ti-MMC avec l'outils en carbure.

Plusieurs études ont rapporté que les mécanismes d'usure initiaux jouent un rôle clé dans la durée de vie de l'outil et la rugosité de surface lors de l'usinage des Ti-MMC. Donc, le contrôle du comportement d'usure initiale peut permettre d'améliorer la durée de vie de l'outil ainsi que la rugosité de surface. Afin d'éclairer des effets de conditions de coupe initiaux, une solution innovante a été proposée pour l'usinage interrompu avec deux vitesses de coupe différentes. Les méthodes TOPSIS et Taguchi ont été utilisées pour classer et optimiser des taux d'usure de l'outil et la rugosité de surface. Le premier niveau de vitesse de coupe a été utilisé pour 1 seconde et le deuxième niveau a été utilisé pour le reste du processus. Les résultats expérimentaux indiquent que la vitesse initiale et l'avance peuvent affecter notablement la durée de vie de l'outil. En outre,

l'utilisation de la stratégie proposée avec différents niveaux de vitesse de coupe pendant le processus d'usinage permet d'améliorer la durée de vie de l'outil et la rugosité de surface en même temps, comparé à l'usinage conventionnel avec une vitesse de coupe constante pendant le processus. La stratégie de coupe avec deux vitesses différentes, les vitesses de coupe initiale et secondaire, a amélioré le taux d'usure de 51.3 % et la rugosité de surface de 58.9 % comparé à ceux de l'usinage conventionnel avec une vitesse de coupe constante. Les résultats de ce travail s'alignent avec des études précédentes sur la formation d'une couche protectrice aux tout premiers instants de l'usinage.

ABSTRACT

Titanium metal matrix composites (Ti-MMCs) are a new generations of materials used in the aerospace and automotive industries. The tough and abrasive TiC ceramic particles improve titanium's physical and mechanical properties. However, it causes several issues, such as severe tool wear and short tool life when machining these materials. There are still a few studies regarding the machinability of Ti-MMCs, especially in tool life estimation and surface roughness improvement. One part of this thesis describes the tool wear characterization in the high-speed milling of Ti-MMCs. The statistical investigations on the milling tests using Carbide X500 and PCD tools concluded that cutting speed and depth of cut are the major cutting parameters affecting tool wear rate. In contrast, surface roughness was not affected by the cutting parameters used when using the PCD tool and was only sensitive to feed rate variation when using the Carbide tool X500. Tool wear mechanisms and surface quality evaluation were investigated when turning Ti-MMCs with carbides and CBN tools. The main wear modes observed on the flank side of the tested tools were adhesion, abrasion, and oxidation. According to experimental results, the surface roughness and the flank wear rate when using carbide and CBN tools can be controlled by the cutting parameters used, in principle, cutting speed. Cutting speed and feed rate are the governing cutting parameters on the flank wear rate during turning Ti-MMCs with carbide tools.

Several studies reported that the initial wear mechanism plays a vital role in the tool life and surface roughness during the machining of Ti-MMCs. Hence, controlling the initial wear behaviours can improve the tool's life and surface roughness. An innovative solution was proposed for interrupted machining with two different cutting speeds to shed some light on the effect of the initial cutting conditions. TOPSIS and Taguchi methods were used to rank and optimize tool wear rate and surface roughness. The first level cutting speed was used for 1 second, and the second level was used for the rest of the process. The experimental results indicate that the initial speed followed by the feed rate can significantly affect tool life. In addition, using the proposed strategy with different levels of cutting speed during the machining process led to improved tool life and surface roughness compared to conventional machining with uniform cutting speed throughout the entire process. The strategy of cutting with two different speeds, mainly the initial and the secondary cutting speed, improved wear rate by 51.3% and surface roughness by 58.9% compared to readings made in conventional machining with a constant cutting speed. The results of this work align with

previous studies on forming a brace shield at the very first moments of machining, acting as a protection layer.

TABLE OF CONTENTS

DEDICATION	III
ACKNOWLEDGEMENTS	IV
RÉSUMÉ.....	V
ABSTRACT	VII
LIST OF TABLES	XIII
LIST OF FIGURES.....	XV
LIST OF SYMBOLS AND ABBREVIATIONS.....	XVIII
LIST OF APPENDICES	XX
CHAPTER 1 INTRODUCTION.....	1
1.1 Problematic of research.....	1
1.2 Hypothesis statement.....	1
1.3 Research objectives	2
1.4 Structure of thesis.....	3
CHAPTER 2 LITERATURE REVIEW.....	5
2.1 Different aspects of machining of Ti-MMCs.....	5
2.1.1 Tribology	5
2.1.2 Metal composites.....	5
2.2 Cutting tools	11
2.2.1 Poly crystalline diamond (PCD)	11
2.2.2 Cubic boron nitride (CBN).....	11
2.2.3 Carbides.....	11
2.3 Tool wear.....	12

2.3.1	Tool wear in end milling	13
2.3.2	Tool wear progress	14
2.4	Cutting temperature	15
2.5	Tool wear mechanisms	16
2.5.1	Adhesion	17
2.5.2	Abrasion	17
2.5.3	Diffusion	17
2.5.4	Dissolution	18
2.6	Chemical reaction	18
2.7	Optimization	18
2.8	Conclusion of literature review and refining of objectives	19
CHAPTER 3 ARTICLE 1: TOOL WEAR CHARACTERIZATION IN HIGH-SPEED MILLING OF TITANIUM METAL MATRIX COMPOSITES		21
3.1	Introduction	22
3.2	Materials and methods	25
3.3	Results and discussions	27
3.3.1	Face milling Ti-MMC with carbide tools	27
3.3.2	Face milling Ti-MMC with PCD tools	31
3.4	Conclusion	35
CHAPTER 4 ARTICLE 2: TURNING TITANIUM METAL MATRIX COMPOSITES (Ti-MMCS) WITH CARBIDE AND CBN INSERTS		42
4.1	Introduction	43
4.2	Experimental plan	45
4.3	Results and discussions	48
4.3.1	Turning tests with carbide tools	48

4.3.2	Turning tests with CBN tools.....	51
4.4	Conclusions	54
CHAPTER 5 ARTICLE 3: THE USE OF TOPSIS METHOD FOR MULTI-OBJECTIVE OPTIMIZATION IN MILLING TI-MMCS		59
5.1	Introduction	60
5.1.1	Background	60
5.1.2	Contribution of this Work	64
5.2	Materials and Methods	65
5.3	Results	71
5.3.1	Cutting conditions and experimental results	71
5.3.2	Conversion of multi responses into a single response using the TOPSIS method.....	73
5.3.3	Determination of optimum cutting parameters using Taguchi approach	78
5.4	Discussion	79
5.5	Conclusions	83
5.6	References	84
CHAPTER 6 GENERAL DISCUSSION.....		88
6.1	Guiding principles	88
6.2	An unsuccessful approach.....	89
6.3	Confocal microscopy.....	91
6.4	Main discussion.....	92
6.4.1	Face milling tests with carbide tools	92
6.4.2	Face milling tests with PCD tools	93
6.4.3	Turning tests with carbide tools	95
6.4.4	Turning tests with CBN tools.....	96
6.5	Novelty	100

CHAPTER 7	CONCLUSION	102
CHAPTER 8	REFERENCES	105
APPENDICES		109

LIST OF TABLES

Table 2-1: Mechanical properties of a Ti-MMC, (Ti-6Al-4V, 10-12% TiC by volume)	6
Table 3-1: Characteristics of PCD tools used in milling (BECKER)	25
Table 3-2: Carbide tools X400 and X500 specifications	27
Table 3-3: Elemental composition of Ti-MMC	27
Table 3-4: Experimental conditions and responses when using carbide tool X400.....	28
Table 3-5: Experimental conditions and responses when using carbide tool X500.....	29
Table 3-6: ANOVA table of the surface roughness and tool wear rate when using carbide tool X500	30
Table 3-7: Surface roughness and wear rate when using PCD tools on the basis of orthogonal array L9	32
Table 3-8: ANOVA of the tool wear and the surface roughness of the work parts machined with PCD tools	32
Table 3-9: Milling results with PCD tool.....	33
Table 4-1: Characteristics of the carbide and CBN tools used in turning tests (Becker).....	46
Table 4-2: Elemental composition of Ti-MMC	46
Table 4-3: Cutting conditions and two types of tools used	48
Table 4-4: ANOVA table of turning tests when using carbide tools	49
Table 4-5: Turning tests with CBN tools	51
Table 4-6: ANOVA table of results recorded in turning by carbide and CBN tools.....	51
Table 5-1: Elemental composition of Ti-MMC [32].....	66
Table 5-2: CoroMill 245 -12T3 carbide tool.....	67
Table 5-3: Considered input cutting parameters	71
Table 5-4: Input cutting parameters and their responses.....	72

Table 5-5: Normalized, weighted values of the responses.....	74
Table 5-6: Separation measures, closeness coefficient, and signal-to-noise ratios.....	76
Table 5-7: Responses for signal-to-noise ratios (larger is better)	78
Table 6-1: ANOVA table of turning tests when using carbide tools	95
Table 6-2: ANOVA table of results recorded in turning by carbide and CBN tools	96

LIST OF FIGURES

Figure 1-1: Summary of the research.	4
Figure 2-1: Applications of Ti-MMC in a) different parts of a sport car b) Turbofan blades [9]....	6
Figure 2-2: a) SEM image of the tool flank face after dry machining b) oxygen map, c) magnesium map [13].	9
Figure 2-3: (a) Hardnesses of tool materials (GPa); (b) Average flank wear (mm) (KC 850, a carbide tool) [31].	12
Figure 2-4: Two types of tool wear for the turning process, according to the ISO standard [32].	13
Figure 2-5 : End-mil cutter wear [33]	14
Figure 2-6: (a) Typical tool wear stages; (b) three tool wear curves related to three machining speeds [32].....	15
Figure 2-7 : Three zones where heat is generated in a typical orthogonal cutting [36].	16
Figure 3-1: a) Trajectory of milling tool b) Ti-MMC machining using carbide X500.	26
Figure 3-2: a) Optical microscope b) Profilometer Mitutoyo SV- C4000.	26
Figure 3-3: Milling Ti-MMC with carbide tool X400 a) $V_c = 100$ m/min; $f_r = 0.35$ mm/rev; $a_p = 2$ mm b) $V_c = 75$ m/min; $f_r = 0.35$ mm/rev; $a_p = 1.5$ mm.	28
Figure 3-4: a) X500 carbide tool wear in milling of Ti-MMC with $V_c = 95$ m/min; $f_r = 0.1$ mm/rev; $a_p = 1.6$ mm. b) SEM micrograph of flank face, and deposited layer observed on flank face near the nose with the appearance of spread butter. (c) EDS Elemental mapping analysis of SEM micrograph.	30
Figure 3-5: Edge chipping of the PCD tool at low speed ($v_c = 200$ m/min, $f_r = 0.17$ mm/rev and $a_p = 1$ mm) after 2 minutes of machining.	34
Figure 3-6: (a) Edge peeling and (b) notch wear on the flank face of the PCD tool at high speed ($v_c = 250$ m/min, $f_r = 0.3$ mm/rev and $a_p = 1$ mm) after 10 seconds of machining.	34
Figure 3-7: (a) Adherent material on the flank face. (b) Line scan of adhered material.....	35
Figure 4-1: (a) Inserts used; (b) The CNC turning center MAZAK Nexus 200	47

Figure 4-2: (a) Optical microscope (b) Profilometer Mitutoyo SV-C4000	47
Figure 4-3: The flank wear on the carbide tool when a) $v_c = 80$ m/min; $f_r = 0.35$ mm/rev; $a_p = 0.5$ mm; b) $v_c = 60$ m/min; $f_r = 0.25$ mm/rev; $a_p = 1$ mm.....	49
Figure 4-4: (a) SEM micrograph of flank face, rake face and deposited layer observed on the flank face near the nose (b) highly magnified flank face shows scratches and grooves caused by TiC particles	50
Figure 4-5: An EDS spectrum of the deposition layer on the flank surface of the carbide tool (Zone 1 in Figure 4-4b) along with the element content table showing the existence of vanadium	50
Figure 4-6: Flank wear of CBN tools under cutting tests (a) $V_c = 150$ m/min; $f_r = 0.3$ mm/rev; $a_p = 0.5$ mm (b) $v_c = 200$ m/min; $f_r = 0.45$ mm/rev; $a_p = 0.75$ mm and (c) SEM image of a serrated chip	52
Figure 4-7: (a) SEM image of tool flank face after dry machining with $v_c = 150$ m/min, $f_r = 0.3$ mm/rev, and $a_p = 0.5$ mm, machining time 30 s; (b) magnified image of the zone 2 in image a, no trace of holes or grooves.....	53
Figure 4-8: Elemental maps of the entire zone 2 (a) titanium, (b) aluminum, (c) vanadium (d) magnesium (e) oxygen and (f) nitrogen.	54
Figure 5-1: (a) Milling experimental setup and (b) the insert.	66
Figure 5-2: (a) Optical microscope (b) Profilometer Mitutoyo SV- C4000	68
Figure 5-3: Mean roughness value R_a	68
Figure 5-4: A typical tool wear, $V_{B \max}$ and different wear zones [26]	69
Figure 5-5: Tool wear after different moments of machining, b) corresponding captured cutting forces	70
Figure 5-6: (a) Three distinctive tool wear periods; (b) chaos theory: a small change in the initial period can result in a big change in the entire process [21].	79
Figure 5-7: Main effects plot for signal-to-noise ratio (S/N) for closeness coefficients.....	80
Figure 5-8: Probability plot of S/N, data points (blue dots) are relatively close to fitted normal distribution lines.....	81

Figure 5-9: Tool wear curves for different cutting conditions	82
Figure 5-10: The recorded values of surface roughness under different cutting conditions.....	82
Figure 6-1: Three distinctive tool wear periods [11].....	89
Figure 6-2: (a) Tool wear region and wear profile characterization using CT scan (b) another view of the wear region.....	90
Figure 6-3: (a) An image of the worn-out zone using CLSM (b) a colored 3D profile of cutting edge and worn-out region.....	91
Figure 6-4: a) X500 Carbide tool wear in milling of Ti-MMC with $V_c = 95$ m/min; $f_r = 0.1$ mm/rev; $a_p = 1.6$ mm b) SEM micrograph of flank face, and deposited layer observed on flank face near the nose with the appearance of spread butter (c) EDS elemental mapping analysis of SEM micrograph	93
Figure 6-5: Chip formation at (a) 400 ms and (b) 500 ms of machining	98
Figure 6-6: Two distinct zones in a chip, deformation line, and the flow direction	99

LIST OF SYMBOLS AND ABBREVIATIONS

Ti-MMC	Titanium metal matrix composite
a_p	Depth of cut
BUE	Built-Up-Edge
CBN	Cubic boron nitride
CNC	Computer-aided manufacturing
EDS	Energy dispersives
F_r	Feed rate
HRC	Rockwell C hardness
HSS	High-speed steel
MMCs	Metal matrix composites
PCBN	Poly-crystalline cubic boron nitride
PCD	Polycrystalline diamond
PVD	Physical vapour deposition
SEM	Scanning electron microscope
TiC	Titanium carbide
WC	Tungsten carbide
V	Cutting speed (m/min)
F	Feed (mm/rev)
T	Tool life
t	Time
VB_B	Average flank wear land width (mm)

VB_{Bmax}	The maximum amount of VB_B
VB_C	The width of the flank wear land
VB_{BC}	Tool wear in different speeds
VB_1	Uniform flank wear
VB_2	Non-uniform flank wear
VB_3	Localized flank wear
V_C	Cutting speed
W	Width of cut (mm)

LIST OF APPENDICES

APPENDIX 1 ARTICLE 4: FIRST MOMENTS OF THE CHIP FORMATION WHEN TURNING OF TITANIUM METAL MATRIX COMPOSITES.....	109
APPENDIX 2 ARTICLE 5: DEFINITION OF TRANSITION TIME IN MACHINING TITANIUM METAL MATRIX COMPOSITES (TI-MMCS).....	117

CHAPTER 1 INTRODUCTION

This chapter presents general information on the subject, followed by a statement about the research questions and motivation for the research project. The research approach, objectives, and hypothesis statements are then discussed to bring out the problem statements.

1.1 Problematic of research

Ti-MMC is a new material generation with considerable potential for widespread applications in the aerospace and automotive industries. However, limited information, experiments, and references about their machining could be found in the literature. Indeed, reinforcing ceramic particles (TiC) added to the matrix to improve their wear resistance performance cause high abrasive wear on the cutting tool. This increases the costs of the machining process and limits the application of Ti-MMCs. The other problems are the workpiece's unpredictable and poor surface quality and the possibility of fire during machining due to the high-temperature rises [1]. Furthermore, due to the low thermal conductivity of Ti-6Al-4V (6.7 W/m.K) as the matrix, high local temperatures concentrated in a tiny cutting zone area, and the high affinity of titanium to oxygen, different wear mechanisms have been reported [2-4].

On the other hand, a few research studies have been done on the milling of Ti-MMCs, and to the author's knowledge, no study has been reported earlier. Therefore, this study might help insight into this part of machining knowledge and improve the understanding of Ti-MMCs milling.

1.2 Hypothesis statement

The following hypotheses were considered to discover the effects of cutting parameters on machinability attributes when machining Ti-MMCs. A particular interest will be paid to surface integrity attributes, tool wears morphologies and tool life.

- Tool life and tool wear are affected by the cutting conditions.
- All the inserts/cutting tools should be used from the same production batch with similar geometry and microstructure to respect repeatability.
- Average flank wear length (VB_B) is an accepted criterion to quantify tool wear (ISO 3685, 1993).

- The tool rejection criteria for rough machining are used, and the tool life testing results are assessed according to ISO Standard 3685. In addition, maximum flank wear > 0.7 mm, maximum crater wear > 0.14 mm, and notch wear > 1.0 mm were quantified from [5].

1.3 Research objectives

A lack of information is still observed in the machinability evaluation of titanium alloys, mainly when longer tool life is demanded. Furthermore, as noted before, no adequate and reliable knowledge exists on the effects of initial cutting conditions on the ultimate tool life when machining Ti-MMCs. Therefore, the primary goal of this work is to propose innovative strategies to increase tool life when machining Ti-MMCs.

Specific objectives

O1. Study the mechanism and morphologies of initial tool wear when machining Ti-MMCs

It is believed that the duration of initial tool wear and various wear morphologies in the initial moments when machining Ti-MMCs have intense effects on the ultimate tool life. Therefore, those factors governing initial tool wear must be analyzed, then determining the transient time when the initial tool wear ends and the steady-state wear region starts. Next, the transition time needs to be evaluated, followed by microstructural evaluations of the cutting tools and the chips, which help better understand the tool wear modes at each interval. Finally, the effects of cutting speed on the tool wear mode under a similar feed rate and cutting time must be discussed.

O2. Define the effects of the initial cutting conditions on ultimate tool life

As noted earlier, it is expected that a good selection of the cutting parameters to improve the initial tool wear may tend to optimize the useful tool life. Therefore, theories and algorithms are needed to correlate the initial tool wear and the cutting forces to the ultimate tool life. However, according to the literature review, no work was found on predicting the ultimate tool life based on initial tool wear recorded within the primary moments of the cuts.

O3. Tool life optimization using a multi-objective optimization model

An optimization method was employed based on the influences of the initial moments of machining on the whole process as one of the outputs.

1.4 Structure of thesis

This thesis consists of 8 chapters and is organized as follows:

Chapter 1 covers the introduction of the research work. It also shows the main research objectives and specific research objectives.

Chapter 2 presents a comprehensive literature review based on the research problematic. In the preliminary versions of this thesis, there was a methodology chapter but the author decided to remove it to avoid repetitions since the methodology is presented in detail in each paper.

Chapter 3 presents a published journal article about tool wear characterization in high-speed milling of Ti-MMCs.

Chapter 4 presents a published article about tool wear mechanisms and surface quality characterization when turning Ti-MMCs with carbide and CBN tools.

Chapter 5 presents a journal article about using the TOPSIS method for multi-objective optimization in milling Ti-MMC.

Chapter 6 provides a general discussion and a substantial thesis summary, highlighting the most critical findings from each research phase. It allows for linking the outcomes of this work and the previous studies. In addition, it helps clarify certain aspects and shortcomings. The discussion also shows the achievements of this research work on improving certain aspects of science related to tool life improvement when machining Ti-MMCs. An unsuccessful approach with tomography also is presented in this chapter.

Chapter 7 concluding remarks and recommendations are presented in this chapter.

Chapter 8 finally, this chapter presents the references of this research.

In addition to the main chapters, this thesis has two appendices:

Appendix 1 presents the first conference article about the first moments of chip formation when turning of Ti-MMCs.

Appendix 2 presents the second conference article about the definition of transition time in the machining Ti-MMCs.

To have a better understanding and to visualize the different phases of this study and also to show the variables and methodologies involved in each phase, a summary of this research is presented in Figure 1-1:

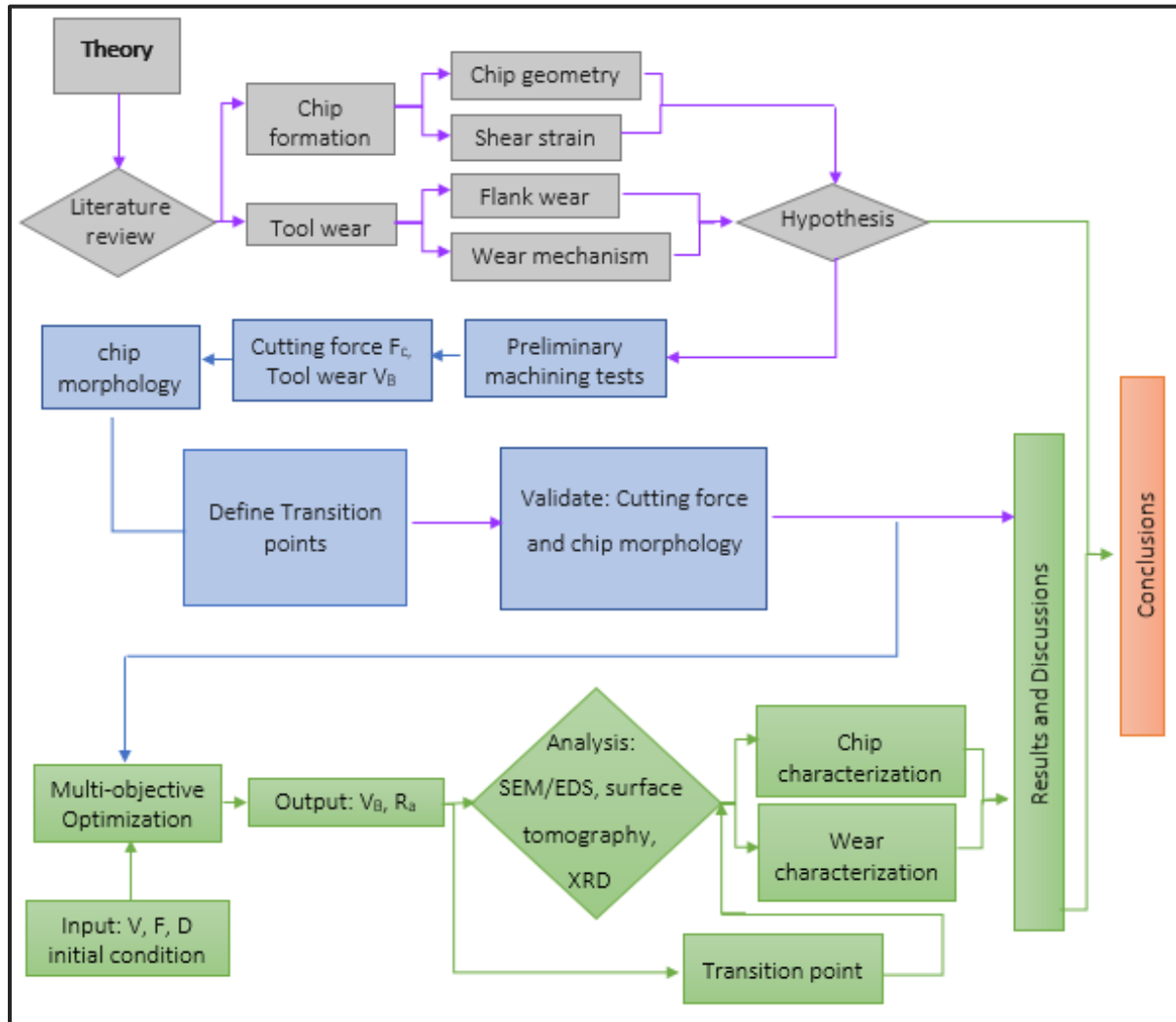


Figure 1-1: Summary of the research.

CHAPTER 2 LITERATURE REVIEW

2.1 Different aspects of machining of Ti-MMCs

The machining of hard-to-cut materials such as titanium alloys is still not completely understood due to the non-linear nature of the process and the complex coupling between deformation and temperature fields.

2.1.1 Tribology

In the literature [6], the word “Tribology” has been defined as “the science and technology of interacting surfaces in relative motion and of related subjects and practices”. Friction, wear, and lubrication are the three principal phenomena of tribology. The insertion of forces, converting mechanical energies, and changing surface topography may lead to the complexity of the contact between tribological surfaces. Understanding the root cause of the complexity that typically leads to some technical issues is necessary for designing the machining process [7].

2.1.2 Metal composites

World-leading manufacturing sectors, particularly aerospace and automotive, aspire to more light materials with significant physical, mechanical, and chemical properties than prevalent hard-to-cut materials. Therefore, there was considerable attention to alternative materials such as metal matrix composites (MMCs). MMCs are non-metallic reinforcements (i.e., ceramic) in metal matrices with high toughness, wear, fatigue resistance, superior corrosion and erosion resistance in many environments, and relatively low density. Although they are expensive due to their desirable properties, titanium alloys, especially Ti-6Al-4V, are widely used as the matrix in MMCs. Their densities usually are between aluminum and iron and give a suitable strength-to-weight ratio, allowing lighter and more robust structures. The specific features, such as high-temperature capabilities and high toughness, expand their applications in numerous engineering components such as gears, turbine engine components (Figure 2-1), and artificial biomedical parts [8]. Furthermore, the mechanical properties of MMC, such as strength, ductility, creep resistance, fracture toughness, and crack propagation resistance, can justify their costs in specific applications. Combining a robust metallic matrix with a hard-ceramic reinforcement material offers good potential, especially in aerospace industries, due to their superior mechanical properties.

One of the metallic composites with remarkable mechanical properties is titanium metal matrix composite (Ti-MMC), an alternative to nickel-based alloys. As a result, Ti-MMC has been successfully incorporated into many products within various industrial sectors. However, despite excellent mechanical and physical features, due to hard and abrasive ceramic particles (TiC) in the metal matrix (Ti-6Al-4V), various issues have emerged in the machining and machinability evaluation Ti-MMCs. Among significant machinability attributes, high tool wear, and poor surface quality, surface roughness are the principal concerns when machining Ti-MMCs. These, therefore, prevent their widespread in engineering applications.

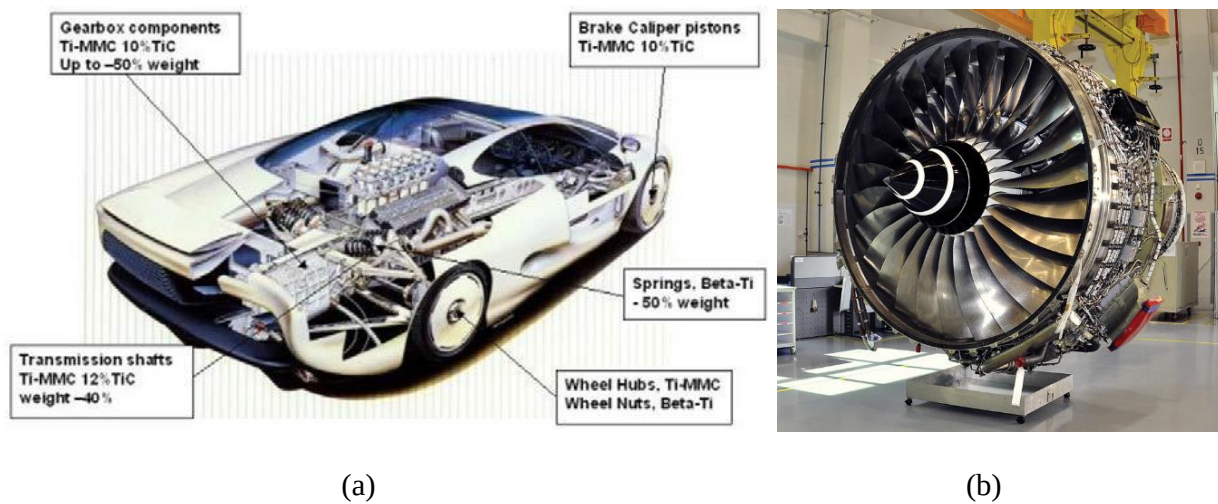


Figure 2-1: Applications of Ti-MMC in a) different parts of a sport car b) Turbofan blades [9].

Mechanical properties of Ti-MMC with 10-12% of TiC are presented in Table 2-1, according to data provided by the manufacturer (RTI International Metals).

Table 2-1: Mechanical properties of a Ti-MMC, (Ti-6Al-4V, 10-12% TiC by volume)

Density (kg/m ³)	Yield strength (MPa)	Tensile strength (MPa)	Elastic modulus (GPa)	Shear modulus (MPa)	Melting temperature (K/°C)	Thermal conductivity (W•m /K)	Specific heat (J/kg.K)
4500	1014	1082	135	51.7	1738/1465	5.8	610

Ti-MMCs remain relatively new materials for researchers, and many uncertainties exist about their production, forming, and machining of this family of materials. Therefore, an overview of the machinability attributes of MMCs is introduced in the following sections.

High tool wear rate, short tool life, and poor surface quality are the main concerns in machining Ti-MMCs. Due to the very low thermal conductivity of Ti-MMCs, very high local temperatures are generated in a tiny area around the cutting-edge resulting in a high tool wear rate [10]. Indeed, because of hard and abrasive particles in Ti-MMCs, flank wear is the major issue in their machining. The successful and high production of components made of Ti-MMCs, such as engine parts of airplanes or cars, sometimes having a good surface finish is more critical than machining costs.

Usually, the tool life is identified based on a typical tool wear curve evolution versus cutting time. This curve shows three regions: the primary or initial, the steady-state, and the accelerated wear period. Most researchers have focused on the steady-state zone, which makes sense for traditional materials. However, in machining difficult-to-cut materials due to the short tool lifetime, the initial moments of machining become more critical. In other words, the effects of the first moment of machining on the tool life and initial tool wear mechanism have not been determined clearly, and this field is open to more investigations. X. D. Troung [11] performed several experimental studies about the initial tool wear in the machining of Ti-MMCs and investigated the effect of the initial tool wear and initial cutting conditions on tool wear progression and tool life. He found a protective layer forming in the first stage of tool wear, which could influence the tool life. He suggested a theory about the formation mechanisms of wear-protective tribofilms. However, the formation mechanisms of the protective tribofilms are not yet fully understood due to the complex chemo-mechanical interactions at the contact region and the limited three-dimensional resolution of many characterization methods typically used. Also, he presented a new theory to relate the initial moments of machining to the rest of the process. Still, some of his test results, such as the initial wear mechanism, are dissimilar to observations made by R. Bejjani [12] and M. Aramesh [13].

Troung reported a diffusion wear mechanism at the first transition wear period. However, Bejjani and Aramesh reported an abrasion wear mechanism. Aramesh also conducted several XRD examinations and observed no phase transformation during the first transition wear period. Furthermore, Troung proposed two new mathematical models; first, to quantify chaotic tool wear during machining based on the Lyapunov exponent and fractal dimension and second, to characterize the variation in wear curves under different initial parameters.

Kamalizadeh [14] focused on initial tool wear in turning Ti-MMCs using carbide tools. It was observed that the first transition time within the tool wear curve occurs in the first second of machining. Furthermore, a good correlation was found between the transition time in tool wear progression charts and the cutting force diagrams. As noted in [39], the primary wear mechanism during the initial moments of machining Ti-MMC is abrasion, and the dominant wear mechanism is adhesion.

Theoretically, two factors can play the more critical roles in surface roughness: feed rate and tool geometry [15]. However, the high affinity of almost all tool materials to Ti-MMC's matrix, especially at elevated temperatures in the tool-workpiece engagement, leads to the chemical reaction, material diffusion, and adhesion in the cutting tool [16]. Consequently, even at high material removal rate, the chips cannot evacuate the massive thermal loads [17]. Moreover, the tool mostly slides than cuts the workpiece at a low shear angle; therefore, the cutting zone temperature and pressure arise similar to friction. Then, the scraped materials melt and adhere to the tool tip. The hot-adhered particles in the vicinity of oxygen turn into fragments, including titanium oxide (TiO_2) and vanadium (III) oxide (V_2O_3) [18].

Characteristically of academic debate, polycrystalline diamond (PCD) tools are generally the first choice for machining Ti-MMCs [19]. Cubic boron nitride (CBN) and carbide PVD-coated tools are the other options for machining Ti-MMCs. Indeed, unlike carbides generally used in the rough machining of MMCs, PCD tools are mainly employed for finishing. This is because of the carbide tools' effects on the finished workpiece's properties [20].

According to the literature review, contact conditions, the interface between the tool and workpiece, and cutting temperatures are the most influential factors in the wear mechanisms [12]. R. Bejjani [12], with a speed of 90 m/min, feed rate 0.2 mm/rev, and depth of cut 0.15 mm, machining has the optimal conditions, meaning less tool wear and better surface roughness. In contrast, X. D. Troung [21] found that at lower speeds, i.e. 50 m/min, tool wear is less than that at higher speeds. In this regard, Aramesh et al. [10] observed a unique wear morphology of cubic boron nitride (CBN) tools during turning Ti-MMCs. They noted that the adhered material consists of the Ti, Al, and V elements and a black zone. The zone separates the contact area's inside and outside (Figure 2-2). It is surrounded by a white zone containing Mg and O. They implied that the

Mg coming from tool or workpiece material might be oxidized during machining and perform this white zone.

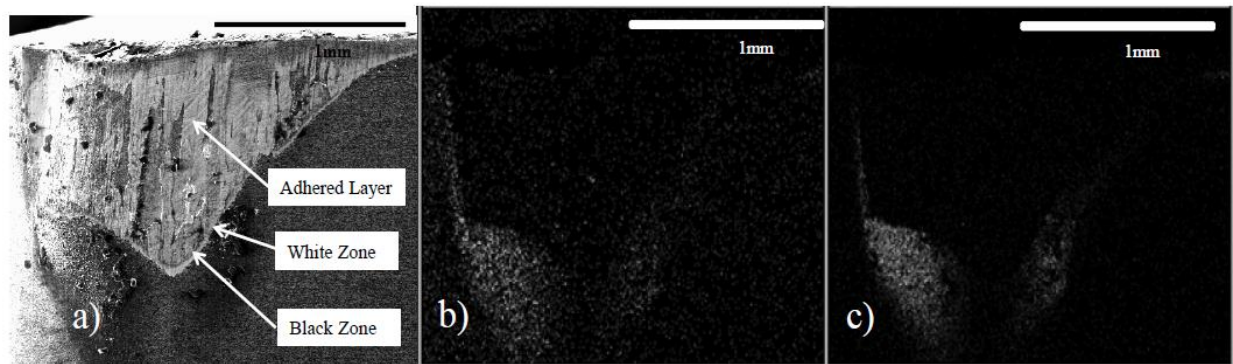


Figure 2-2: a) SEM image of the tool flank face after dry machining b) oxygen map, c) magnesium map [13].

A new analytical tool wear model, considering the influence of both abrasive and diffusive tool wear mechanisms, was presented by Attanasio et al. [22]. They simulated tool wear of uncoated carbide tools in turning operations to forecast tool wear progression and calibrate and validate the FEM model along with some experimental tests. Using a FE model, R. Bejjani [23] also simulated the chip segmentation, cutting forces, temperatures, stresses, and strain rates in laser-assisted machining (LAM) of Ti-MMCs. His simulations explained possible reasons for the prolonged tool life because of the LAM application. Using the simulation temperature profiles, he pointed out that the possibility of phase transformation inside the adiabatic shear band (ASB) results in higher tool life. The significant effects of the tool wear on the workpiece surface quality and the cutting force led the researcher to monitor the forces for tool life estimations. However, other options are cutting temperature, vibration, acoustic emission, etc. The chip formation morphology is one of the primary phenomena affecting the surface quality and the tool wear mode. Bejjani et al. [12] studied the chip formation and microstructure evolution in adiabatic shear band machining (Ti-MMCs). They declared that no phase transformation appeared inside the ASB, and the microstructure overview of the ASB was composed of elongated nano-size grains. Moreover, they also implied that the chips' segmentation mechanism starts from a crack in the material on a free region on the tool's surface, not at the tooltip. Aramesh et al [10] investigated the phase transformation and probability of martensite transformation and formation of metastable phases on the chips produced during turning titanium metal matrix composites. To assess the phase transformation of the chip

during the cutting process, they performed some X-ray diffraction analysis (XRD). They didn't see any phase transformation from α to β during the machining Ti-MMC in the heating process. Doung et al, [24] proposed an innovative method: electroless plating of a sacrificial coating nickel-boron (Ni/B) onto the cutting tool to adjust the chemical wear behavior at the first moment of cutting process. Their goal was to change the initial wear mechanisms and it was for the first time that an electroless nickel deposition was applied to the titanium nitride-coated carbide tools in a machining process. Their proposed sacrificial coating on the cutting tool resulted in changing the chemical wear behavior and wear mechanism at the first wear period. However, this method didn't improve tool life since the wear shield was not formed at the first transition wear period when turning Ti-MMCs using their sacrificial coating. Moreover, their study showed a change from adhesion to abrasion wear mechanism in the first cutting period.

Abdelali, Beste, and colleagues [25, 26] demonstrated in two studies that when machining starts, in an extremely brief length of time, the cutting forces increase drastically, as does the friction between two new surfaces where the relative sliding speeds are near zero. As a result, high stress is generated in a small area at the tool-workpiece interface. This rapid increase in cutting forces, which causes an immediate increase in cutting temperature, occurs within one second and is followed by a slow but constant rate of increase during the second wear period [14].

The friction between tool and workpiece in the rake and flank faces is a source of cutting forces. In truth, as stated in several studies [15], cutting parameters directly influence the cutting force. The abrasive particles and high resistance to plastic deformation of Ti-MMC also force a high energy load on the tool-workpiece interaction zone. Rimpault et al. [27] studied fractal analysis of cutting force and acoustic emission signals during carbon fibre-reinforced plastics (CFRPs) machining. They stated that fractal parameters efficiently describe the tool wear evolution and the surface roughness quality. Moreover, their study suggested that fractal analysis can be used for other composite types, such as metal matrix composites. Feng et al. [28] applied fractal dimension to gear damage evaluation and focused on the signal components in a certain range of frequencies band of vibration signals without any preprocessing to reveal the real condition of a machine. Based on their study, the more severe the gear damage, the more complicated the dynamic system and the larger the fractal dimension. The literature review states that few studies have been performed previously on the machining of Ti-MMCs, but research candidate couldn't not find in-depth studies regarding milling of Ti-MMCs.

2.2 Cutting tools

2.2.1 Poly crystalline diamond (PCD)

One of the most rigid materials for machining titanium alloys is polycrystalline diamonds (PCD). PCD tools usually consist of a thin layer (0.5-1.5 mm) of fine diamond particles sintered together and brazed onto a cemented carbide substrate. These materials are hard, strong, stable and tough and offer the best heat conductivity among common tool materials (550 W.m /K at 300°C[29]). As a result, fine, smooth cuts, geometrically excellent threading, and high-precision grinding and milling applications can be achieved using PCDs. The downsides of PCD tools include their elevated price and reactivity at high temperatures with titanium to form titanium carbides (TiC).

2.2.2 Cubic boron nitride (CBN)

Cubic boron nitride tools are second to diamond in hardness. CBN tools are also two times harder and four times more abrasion-resistant than carbides. In addition, CBN tools exhibit high thermal conductivity and excellent surface integrity. CBNs are manufactured from hexagonal boron nitride under high temperatures and high pressures. CBN tools possess desirable characteristics, including high hardness, strength, abrasion resistance, thermal and chemical resistance, and the ability to maintain sharp cutting edges. However, CBN tools wear relatively fast when water-based fluid is used as a coolant because of Chemical-Thermal degradation.

2.2.3 Carbides

The cemented carbide family is one of the most common and affordable tool materials classes for machining titanium alloys. These materials offer good tool wear performance [29] at an affordable price. Generally, a carbide tool is manufactured through the sintering process in which carbide particles (WC) with chosen sizes are bounded in a cobalt matrix. It is well known that the ductility of the tool is linked to the cobalt phase and that the hardness depends more on the WC phase. Therefore, the amount of cobalt is chosen to function the desired toughness and hardness, often from three to twenty percent of the tool composition [30].

Selecting the suitable grade of carbides is essential in developing a machining process. Figure 2-3 (a) compares tool materials based on hardness. As can be seen, polycrystalline diamond (PCD)

tools appear to be the best choice for machining Ti-MMCs. However, due to their high cost, CBN and carbide tools are the alternatives.

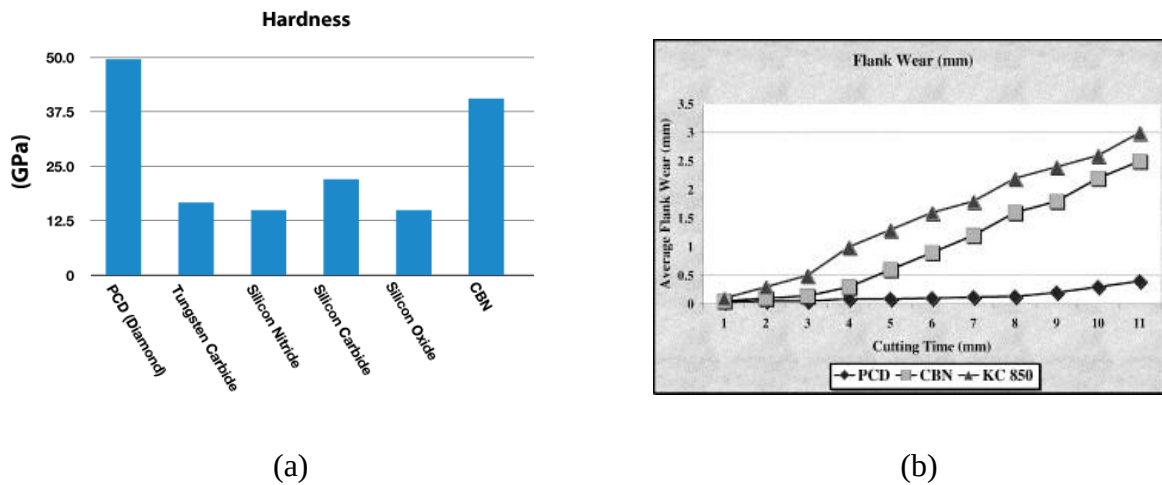


Figure 2-3: (a) Hardnesses of tool materials (GPa); (b) Average flank wear (mm) (KC 850, a carbide tool) [31].

2.3 Tool wear

Tool wear is central to machining and affects the surface quality of the workpiece. In addition, dimensional accuracy, chip flow, and the tool structural integrity depend on the tool wear. It is, therefore, essential to characterize the tool wear. According to ISO 3685:1993 [32], tool wear is: “The change of the tool from its original shape, during cutting, resulting from the gradual loss of tool material.” Tool wear is caused by the contact of two bodies in the contact zone. Contact results in stress and temperature gradients near the surface of the tool. Tool wear may be divided into two major types: flank and crater.

To specify flank wear, four distinct regions are defined [32] as shown in Figure 2-4; region N is outside of the contact area of the tool and workpiece, for approximately $\frac{1}{4}$ of the worn-out length b . Region C is from the tool's corner, where the curve starts at the endpoint. The area between regions N and C is region B. VB_B is commonly used as a tool wear index and is measured inside region B, measured from the unworn position of the cutting edge to the end of the effective, worn-out region. In Figure 2-4, the cross-section AA of the worn-out zone presents the rake or crater wear. The crater depth KT is the maximum distance between the crater bottom and the original

face in region B. The maximum amount of VB_B is called VB_{Bmax} . The width of the flank wear land is VB_C [30].

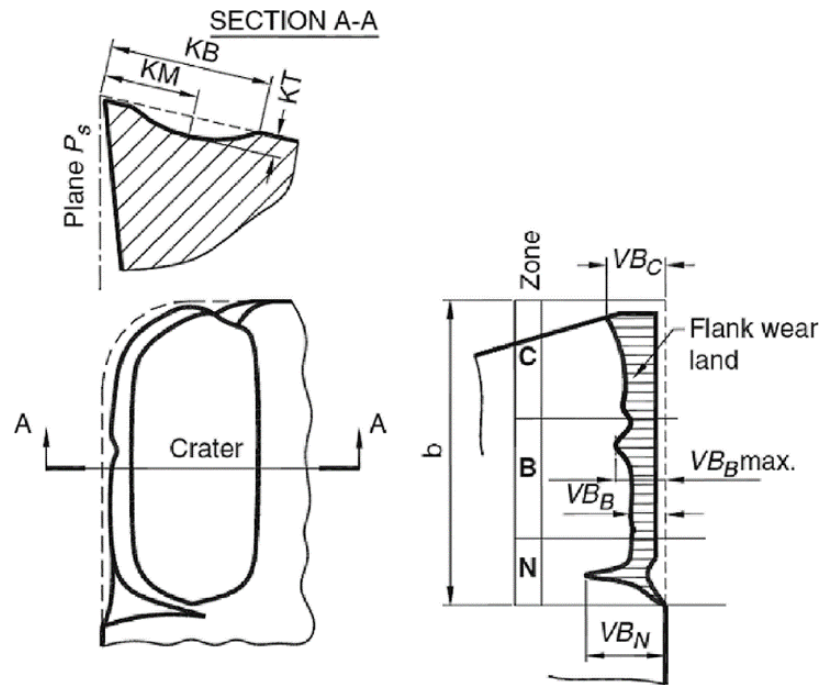


Figure 2-4: Two types of tool wear for the turning process, according to the ISO standard [32].

2.3.1 Tool wear in end milling

The wear on the end mill tool, adapted from ISO 8688-2 1989 [33], is shown in Figure 2-5. Wear is quantified similarly to flank wear on turning tools. VB_1 is uniform flank wear, VB_2 is non-uniform flank wear, VB_3 localized flank wear, and a_a is the flank wear width.

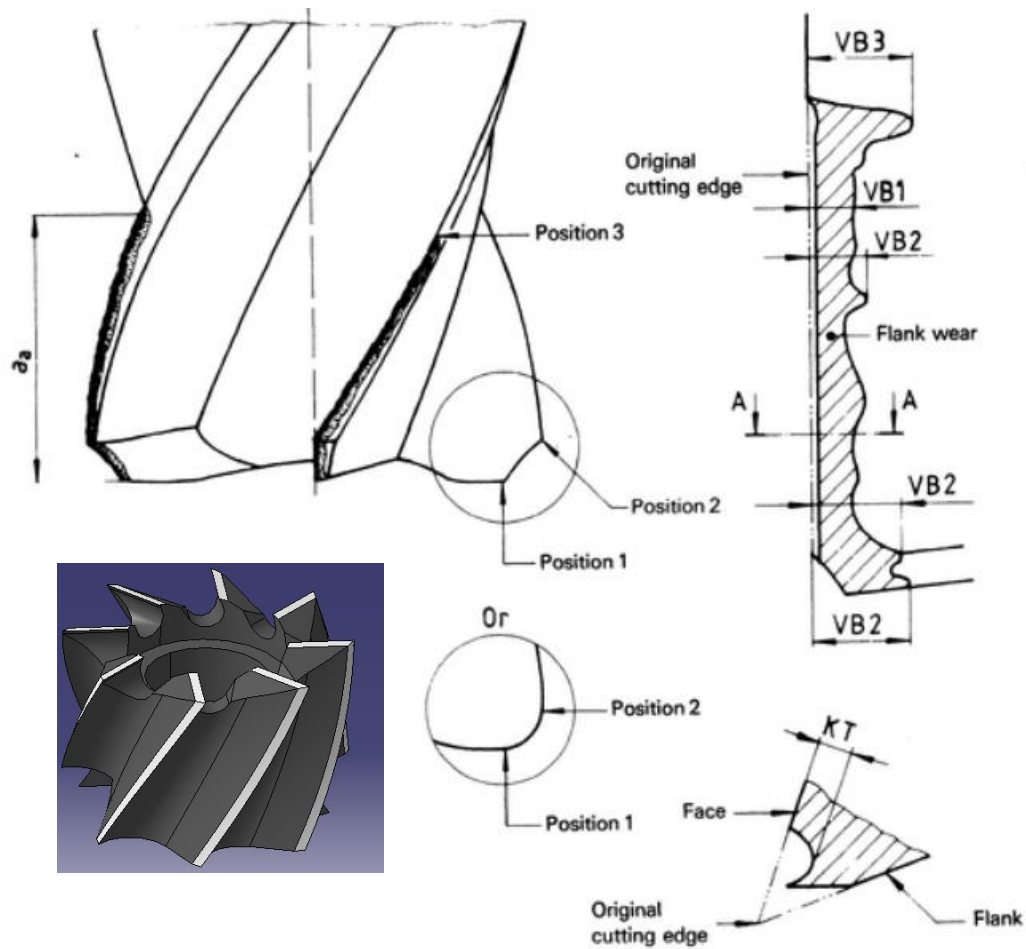


Figure 2-5 : End-mil cutter wear [33]

2.3.2 Tool wear progress

A higher wear rate can be observed in machining titanium alloys than in aluminum alloys [34]. The greater wear rate could be due to the low thermal conductivity of titanium alloys and the elevated normal stress concentrated on a tiny area of the tool-workpiece contact region, resulting in high temperatures [34]. Tool wear curves usually illustrate the flank wear VB_B versus the cutting time or the cut length. Figure 2-6 (a) shows that three distinct curve regions are initial (also called primary wear or break-in wear), steady-state wear, and accelerated wear.

The tool wear rate in the first region (region I) is high due to the breakage of the sharp tooltip. As a result, the tip is subjected to concentrated, elevated cutting stress. Tools generally wear out quickly in this stage. Region II is usually the regular operating regime of the tool and is called the steady-state wear region. The tool wear rate in this region is steady or lesser than in the first region.

Eventually, after a time that depends on the machining parameters, including tool geometry, the tool wear rate increases quickly, and the machining quality degrades. This stage is called the tertiary or accelerated wear region (III).

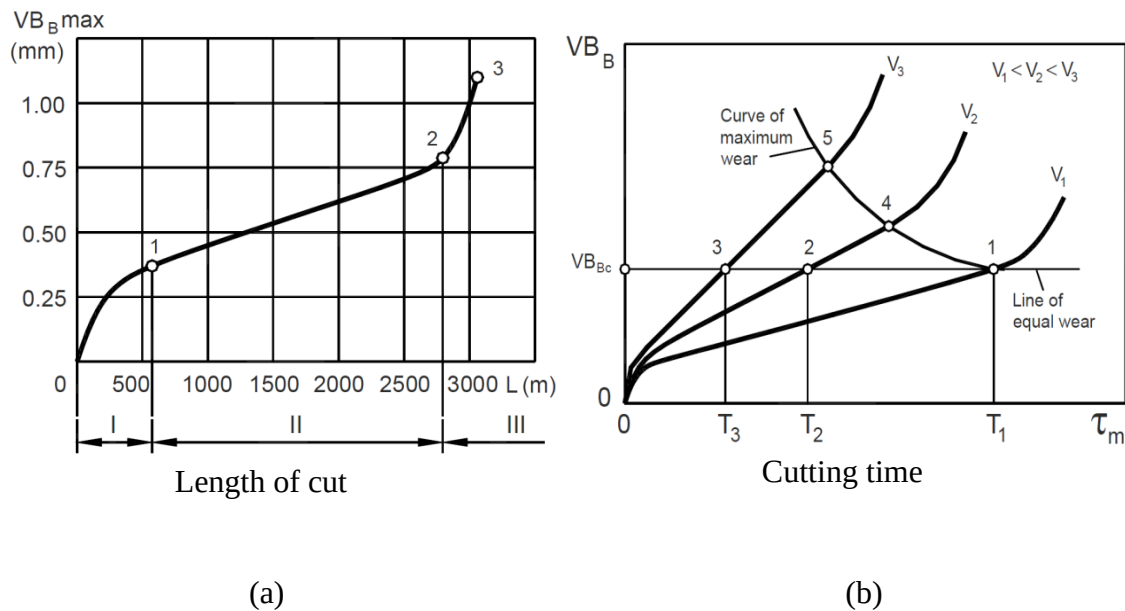


Figure 2-6: (a) Typical tool wear stages; (b) three tool wear curves related to three machining speeds [32].

Three tool wear rates associated with different cutting speeds ($V_3 > V_2 > V_1$) are shown in Figure 2-6 (b). It can be seen that useful tool life is inversely related to cutting speed, as determined by some wear criterion VB_{Bc} . The tool, therefore, wears out sooner at greater speeds.

Based on the desired machining purposes and goals, the curve of maximum wear is employed to reach the most appropriate speed. For instance, instead of speed V_1 , cutting time T_1 , and tool wear VB_{Bc} (point 1), speed V_3 and cutting time T_5 (point 5) could be replaced. The curve of maximum wear presents the possible speed choices in a machining process based on achievable surface integrity. Also, based on an ASME standard [35], the tool's useful life ends when VB_B reaches 500 μm .

2.4 Cutting temperature

The cutting process thermal aspects extensively affect the machining process accuracy, tool life, and chip formation mechanism and play an essential role [36]. During machining operations, the

generated temperature in the workpiece increases. Thus, it softens the surface layers, changes the friction coefficient between the tool and workpiece, and affects the cutting force. Three zones of heat generation in a regular orthogonal cutting are shown in Figure 2-7.

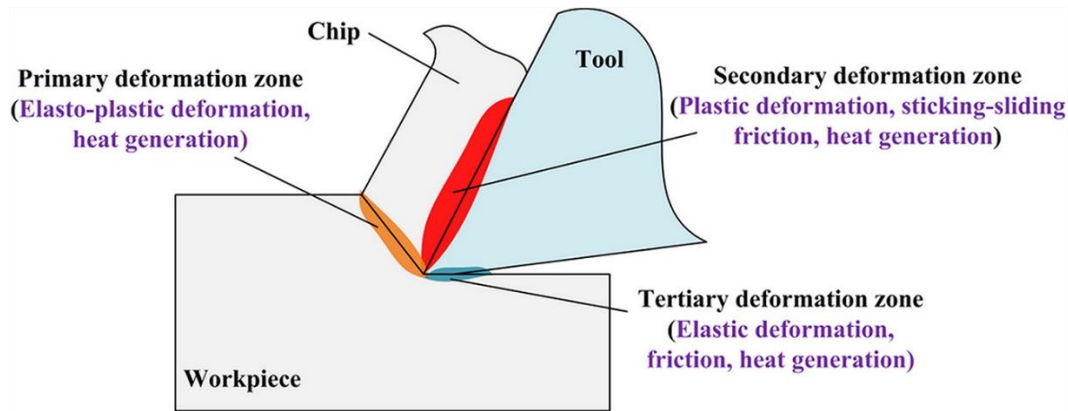


Figure 2-7 : Three zones where heat is generated in a typical orthogonal cutting [36].

The primary deformation zone is the first place where heat is generated due to the plastic deformation at the shear zone. This heat results in the softening of the local material and deformation. The hard contact of the chip/tool surface at the secondary deformation zone results in sliding friction. The highest cutting temperatures are typically observed in this zone. The contact between the tool flank face and the workpiece increases friction and leads to performing the third deformation zone. As is well-known, cutting conditions such as speed, feed rate, and depth of cut affect the heat generation and cutting temperatures in the primary and secondary deformation zones. However, flank wear is the primary reason and highly affects the heat generation in the tertiary deformation zone. Besides, there are other phenomena, such as the physical and chemical properties of the workpiece and tool materials. Also, tool geometry may be critical in heat generation during machining.

2.5 Tool wear mechanisms

Studying the tool wear mechanisms and determining the governing parameters on the tool wear are demanded. Therefore, it is crucial to understand interaction and tool wear mechanisms in the machining process to avoid or reduce tool damage and poor surface quality. Adhesion, abrasion,

diffusion, dissolution, chemical reaction, and oxidation are typical tool wear mechanisms [37]. It is noted that two or more mechanisms normally interact and complicate the process. An overview of the tool wear mechanisms is presented as follows.

2.5.1 Adhesion

When two bodies interact, some elements, often from the softer body, may adhere to the more rigid material. This process is called adhesion. Adhesion occurs under high temperatures and pressure. At the scale of the atoms, there is an adhesive force between atoms, and when they get close to each other under elevated temperatures, the force increases [38]. In practice, adhesion creates a layer on the flank or rake face by bonding the workpiece or chip with the tool.

Rabinowicz et al. [39] found that the workpiece material's load, sliding distance, and hardness affect adhesion. They suggested that due to material softening at high temperatures and less tendency at low temperatures, commonly, adhesion occurs at medium temperatures. Soft materials such as aluminum and high-speed steel (HSS) tools are prone to adhesion, and adhesion often becomes the dominant wear mechanism in such cases [40].

2.5.2 Abrasion

Material loss caused by scratching hard particles on a softer surface is called abrasion [38]. When machining, the hard particles of the workpiece slide onto the tool's surface, causing abrasion. Low-stress abrasion occurs when the abrasive particles have slight contact with the tool surface and are insufficient to scratch it deeply. Meanwhile, the sublayers do not show any plastic flow. High-stress abrasion occurs when the hard particles crush the surface, leading to coarse grooving and gouges.

2.5.3 Diffusion

When the temperature generated in the cutting region is too high for the tool material, it diffuses into the workpiece or the chip. In particular, the chemical properties and affinity of the tool material to the workpiece material determine the development of the diffusion wear mechanism. However, the metallurgical relationship between the tool-workpiece materials controls the amount of wear. High cutting speeds, feeds, or intense friction cause diffusion wear mechanisms [37]. Furthermore, diffusion mainly occurs at the rake face and is linked to crater wear.

2.5.4 Dissolution

Depending on the chemical affinity of the tool elements with the workpiece material, a solid layer is transferred to the chip from the tool material. This phenomenon is called dissolution, typically occurring at the rake face at high temperatures. Dissolution generally occurs when machining materials such as steel with carbide or ceramic tools [\[41\]](#).

2.6 Chemical reaction

Although the chemical reaction is not considered a wear mechanism, it might affect the tool's productivity. For instance, some elements like titanium react with the workpiece elements or atmosphere oxygen at high temperatures. Oxidation or corrosive wear typically results in surface discolouration, and a layer of oxide covers the tool surface [\[29\]](#).

2.7 Optimization

Numerous studies and publications have been reported on optimizing cutting parameters and proposing a model for the relationship between cutting parameters and responses. Furthermore, cutting criteria such as cutting forces, power consumption, surface roughness, and tool life have all been optimized by several researchers. On the other hand, finding the optimal cutting parameters for specific objectives or responses necessitates machining knowledge and a thorough understanding of the relationship between the input parameters and responses. Garg et al. [\[42\]](#) proposed an empirical model to optimize machining parameters to reduce power consumption. They also investigated the effect of machining parameters on energy consumption and their model reduced machine tool power consumption. Kant and Sangwan [\[43, 44\]](#) developed a predictive and optimization model to predict the optimal machining parameter value while minimizing surface roughness. Their model could calculate the best machining parameters. Pusavec et al. [\[45\]](#) also investigated the effects of the cutting process on cutting forces, surface roughness, and tool wear as inputs.

Although single-objective optimization is widely used, it has a significant limitation when used in machining. It displays the optimal cutting parameters for a specific response while ignoring the other objectives. In contrast to a single objective, the multi-objective optimization method concurrently targets all important objectives by determining the optimum value of the input factors.

Bilga et al. [46] published a single-objective optimization of energy consumption for turning EN 353 alloy steel using the Taguchi method with Analysis of Variance in 2016. (ANOVA). They optimized the cutting parameters for each response individually. In each case, the results show different optimum values. Kumar et al. [47] repeated the Bilga's work but for multi-response optimization, optimizing six responses using TOPSIS (Technique for Order Preference by Similarity to Ideal Solution). Hwang and Yoon [48] proposed this method in 1981 to find the best alternatives with the shortest separation from the positive ideal solution and the greatest distance from the perfect negative solution.

Mandal et al. [49] used MOPSO TOPSIS with four controlling components to conduct several experiments to optimize electro-discharge machining. The experiments used a Taguchi L9 orthogonal array and TOPSIS to determine the optimal solution for the Pareto set. The Taguchi method is a popular and effective approach for analyzing machining parameters and determining the best process control factors. One of the main advantages of this method over others is that it produces more quantitative results with fewer experiments, which reduces the amount of experimentation and, as a result, the experimental costs. Taguchi's method is also simple and easy to apply to machining. However, it is a single-response optimization method and is not suitable for optimizing multiple responses at the same time. Another disadvantage of this method is that it does not test all variable combinations and is highly dependent on and relative to the number of input parameters. Despite these drawbacks, Taguchi's method is beneficial for experimental design.

2.8 Conclusion of literature review and refining of objectives

In light of the literature survey, although many research studies were reported on the steady-state wear period, initial tool wear and its significant influences on tool life have not been studied at an acceptable rate. The initial wear period of a cutting tool arises very fast at a high wear rate and has an essential role in system productivity. Moreover, the complexity makes this more important for the machining process of difficult-to-cut materials such as Ti-MMCs. Thus, the general objective of the proposed research is to characterize tool wear, investigate the morphology and, precisely, the effect of the initial cutting conditions when machining Ti-MMCs.

This was done by performing machining tests and conducting different tool surface analyzes (EDS, XRD, etc.). The results may help to gain insight into the milling process of Ti-MMCs.

- Tool wear characterization and morphology during the milling of Ti-MMCs were not studied earlier, but there are some studies regarding the turning of Ti-MMCs.
- Tool wear mechanisms and process optimizations of CBN tools as the second alternative for machining this material were not studied before.
- Tool wear rate and surface roughness optimization using initial cutting conditions as an input has not been done before.
- TOPSIS model has not previously been used in multi-objective optimization of Ti-MMCs machining.

CHAPTER 3 ARTICLE 1: TOOL WEAR CHARACTERIZATION IN HIGH-SPEED MILLING OF TITANIUM METAL MATRIX COMPOSITES

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The International Journal of Advanced Manufacturing Technology (2019) 100:2901–2913
<https://doi.org/10.1007/s00170-018-2651-0>

Received: 25 October 2017 /Accepted: 27 August 2018 /Published online: 22 October 2018
 # Springer-Verlag London Ltd., part of Springer Nature 2018, (cited by 11 as of 4/29/2023)

Abstract

World leading manufacturing sectors, in particular, aerospace and automotive industries aspire more light materials with significant physical, mechanical and chemical properties than the prevalent hard to cut materials. This, therefore, has brought considerable attentions to alternative materials such as metal matrix composite (MMCs). In fact, 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. Ti-MMC has been successfully incorporated into a vast number of products within various industrial sectors. Despite excellent mechanical and physical features, due to the presence of hard and abrasive ceramic particles in metal matrices of Ti-MMCs, various issues have emerged in the area of machining and machinability evaluation of Ti-MMCs. Among important machinability attributes, tool/insert wear and surface quality, in principle surface roughness are the principal critical attributes. According to the review of literature, limited information is available on milling Ti-MMCs. The lack of knowledge determined will be remedied in this work by studying

the various wear modes that appeared on PCD and carbide tools during face milling of Ti-MMCs. The main wear modes observed were adhesion, abrasion, and diffusion. Adhesion is the main wear component appearing on the flank side of the tool. Oxidation that seems to appear due to the high temperature at the cutting zone was also observed. Regardless of the cutting tool used, edge chipping was also observed in milling tests under various levels of cutting. The statistical investigations on the milling tests using carbide X500 and PCD insets led us to conclude that cutting speed and depth of cut are the major cutting parameters affecting tool wear rate, whereas surface roughness was not affected by the cutting parameters used when using PCD tool and only was sensitive to variation of feed rate when using carbide X500 tool.

Keywords

Tool wear, Ti-MMC, tool, PCD, carbide, milling, hard to cut materials.

3.1 Introduction

The performance of the individual family of the tool materials (i.e. PCD, Carbide, and CBN) may vary under different machining operations and cutting parameters. High cutting energy and temperature cause several complications in the cutting process, including reduced strength, hardness and wear resistance of the cutting tool; degraded the dimensional accuracy of the work part as well as thermal damage to the machined surface [1]. This, therefore, recalls further investigations regarding the effects of cutting parameters on machining attributes when machining hard to cut materials. One of the most respected hard to cut materials with superior features is titanium metal matrix composite (Ti-MMC), which can be however considered as an alternative to superalloys such as Inconel and other titanium alloys.

Based on the review of the literature, despite numerous works on machinability of titanium alloys [2-21], a few studies are reported on machining Ti-MMCs with traditional and non-traditional approaches [22-28], in which most of them characterize the tool wear when turning Ti-MMC using carbide tools [24-27]. This reveals that a small number of studies are available on milling Ti-MMC, which could be related to the partial database on the cutting information, tooling as well as the extremely high cost of Ti-MMC work parts, which led to incomplete knowledge on machinability of Ti-MMCs. However, among machinability attributes, the tool wear and surface roughness are the major machinability attributes which are of prime importance in scientific research works. High and rapid tool wear is considered as one of the main concerns in machining Ti-MMCs which tends

to lead to short tool life and poor surface finish (quality). Due to the very low thermal conductivity of Ti-MMCs, very high local temperatures are generated in a very small area around the cutting edge that results in high tool wear rate [24]. Moreover, oxidation and chemical wear mechanisms are involved, and tool life reduction is expected. High affinity of almost all tool materials to Ti-MMC's matrix and elevated temperature in the tool-work part engagement leads to chemical reaction, material diffusion and adhesion in the cutting tool [29]. Consequently, even at high material removal rate, the chips cannot evacuate the massive thermal loads [30]. Moreover, at low shear angle (e.g. initial cutting cycles), the tool slides instead of cutting the work piece, therefore, as similar as friction, the cutting zone temperature, and pressure arise [31]. Then, the scraped materials melt and adhere to the tool tip. The hot adhered particles in the vicinity of oxygen turn into fragments including TiO_2 and V_2O_3 [32]. Therefore, the abrasive particles and high resistance to plastic deformation in Ti-MMC compel high energy load to the tool-work part engagement. Unlike carbides which are normally used in rough machining of MMCs, PCD tools are mostly employed for finishing. This is because of the effects of the carbide tools on the properties of the finished workpiece [1]. Several studies [36,38-40] have been performed to investigate the wear mechanism of the PCD tools in machining of MMCs. Joshi and his co-workers [36] found out that the main wear mechanism in turning of MMCs using PCD tools is abrasion due to the scratches of hard reinforcements on the contact zone. They also observed that the PCD tools have a lower tendency to adhesion than the PCBN tools.

In terms of power consumption, higher cutting speeds result in less power consumption. This is due to the fact that at higher cutting speeds removal of hard particles from the matrix becomes easier [51]. Some studies [41,42] show that finding the optimal cutting speed is more effective on the tool life than simply increasing or decreasing it. They also suggested that cutting speed has the most significant impact on the surface roughness and the tool wear. Pramanik et al. [37] noted that at low federate machining of MMCs, fracture of the hard particles controls the surface roughness quality. However, at higher feeds, it is less effective. Moreover, other studies [43, 44] suggest that the effect of cutting speed on tool wear is more important than feed rate. Another cutting parameter which can affect the tool life and the surface quality (less than speed and feed [45]) is depth of cut. It is suggested that if surface roughness is the first priority in machining, the depth of cut should be minimized. Otherwise, if the tool wear is important, depth of cut should be set higher [46]. It is believed that at certain cutting speeds formation of a built-up edge (BUE) protects the tool surface

from abrasive particles and improves the tool life [47]. Other factors like coolant pressure could affect the tool life. A. Silva et al. [48] investigated the tool life in high-speed machining of Ti-6Al-4V alloy using PCD tools under several coolant pressures. They found that with the coolant pressure at 20.3 MPa and the cutting speed of 175 m/min the tool life is maximum. Boswell et al. [50] studied the effects of the machining parameters on the surface finish of a boron carbide particle-reinforced aluminum alloy under dry cutting conditions. Their results showed that the surface finish of the workpiece improved with increasing the feed rate to a certain point. Although this improvement in surface quality, in every specimen they examined there were some micro cracks on the surface, as well.

Performance evaluation of two types of PCD tools on turning of Al-SiC-metal matrix composite was investigated by Kaarmuhilan et al. [40]. It was observed that to decrease the power consumption and to improve the tool life, it is necessary to machine the workpiece at a lower depth of cut and low feed rate. One of the major components affecting the surface quality and the tool wear mode is the chip formation morphology. Bejjani et al. [26] studied the chip formation and microstructure evolution in the adiabatic shear band in machining of titanium metal matrix composites (Ti-MMCs). It was declared that no phase transformation appears inside the adiabatic shear band (ASB), and the microstructure overview of the ASB was found to be composed of elongated nano-size grains. Moreover, it was observed that segmentation mechanism of chips is initiated from a crack on the material free surface ahead of the tool, not at the tooltip. As noted earlier, except a few works available on turning Ti-MMCs [23, 25, 26, 28,49], less work [24] was found on a comprehensive comparison between the various tool materials used in milling Ti-MMCs. Furthermore, the main tool wear modes when milling Ti-MMCs with commercial cutting tools and tools are not yet reported in the open literature. According to state of the art in this domain, it can be stated that contact conditions, the interface between the tool and workpiece and cutting temperatures are as the most effective factors on the wear mechanisms [34].

In this regard, Aramesh et al. [23] observed a unique wear morphology of CBN tools during turning Ti-MMCs. They noted that the entire adhered material consists of the Ti, Al, and V elements and a black zone. The zone separated the inside and the outside of the contact area and surrounded by a white zone containing Mg and O. They found out that the Mg coming from tool or workpiece material might be oxidized during machining and perform this white zone. Kamalizadeh [25] focused on initial tool wear in turning of Ti-MMCs using carbide tools. It was observed that the

first transition time within tool wear curve occurs in the first second of machining. A good correlation was found between the transition time in tool wear progression charts and the cutting force diagrams. As noted in [25], the preliminary wear mechanism during the initial moments of machining Ti-MMC is abrasion, and the dominant wear mechanism is adhesion.

The main objective of this work is to present the tool wear modes in face milling Ti-MMC when using carbide, CBN, and PCD tools. Furthermore, the controllability of the flank wear and the surface roughness on the basis of cutting parameters used will be investigated in this work. The effects of cutting parameters and different tools on the recorded values of average surface roughness (R_a) and tool wear rate will be studied on the basis of statistical evaluation.

3.2 Materials and methods

As can be seen in the following section, three sets of face milling tests with two replications were completed with PCD tools (#BFPL280508, Table 3-1), as well as carbide tools of grades X400 and X500 (Table 3-2). The trajectory of tool path as shown in Figure 3-1(a) was executed to decrease the tool impact on the work quality. The carbide X500 has multi-layers coatings of TiN-TiC-TiN which are laminated by CVD technique. Carbide X400 is coated with a single layer of PVD. In X400, the substrate binder contains 13 wt% of Ru and 4 microns of TiAlN coating. A precisely measured elemental composition of the workpiece material (Ti-MMC) is presented in Table 3-3. Ti-MMC is made of Ti-6Al-4V as metal matrix and titanium carbide (TiC) as particles.

Table 3-1: Characteristics of PCD tools used in milling (BECKER)

Item Description	Grade	l (mm)	l_1 (mm)	r (mm)	
BFPL280508	PDC-CU-S	22.6	3.5	0.8	100% diamond, Without carbide reinforcement, coarse grains, solid polycrystalline

A four-axis CNC Mitsui Seiki machine was employed for the experimental tests. The orthogonal array L9(3^4) design of experiment was used to build up those cutting tests using carbide tool X400, and PCD tool, while orthogonal array L18 was used on those tests using carbide tool X500. Due to lack of information on milling Ti-MMCs as aforementioned, the cutting conditions were selected based on recommendations by the tool manufacturer. The work part surface roughness and tool

flank wear were measured after each test using the optical microscope (Figure 3-2a) and surface profilometer Mitutoyo SV-C4000 (Figure 3-2b). The statistical approaches using analysis of variance (ANOVA) was used to define the factors governing flank wear. To that end, the statistical parameters including R^2 , R^2_{adj} , P-value, and F-ratio were employed for result analysis. To study the tool wear mechanisms, a Jeol JSM 7800F FEG-SEM equipped with an Oxford X-ray detection system (Aztec EDS) for elemental analysis and quantitative mapping was employed.

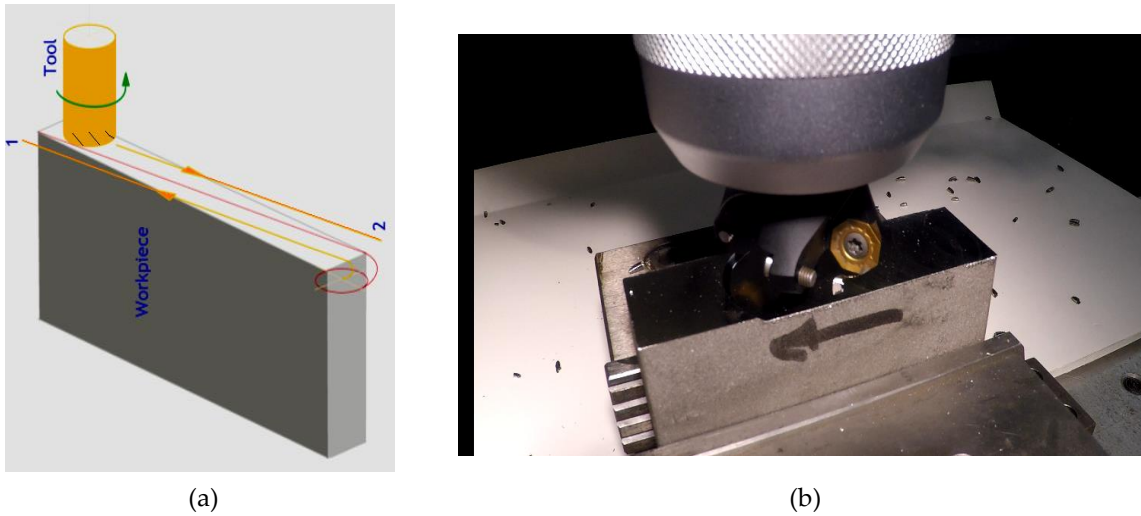


Figure 3-1: a) Trajectory of milling tool b) Ti-MMC machining using carbide X500.

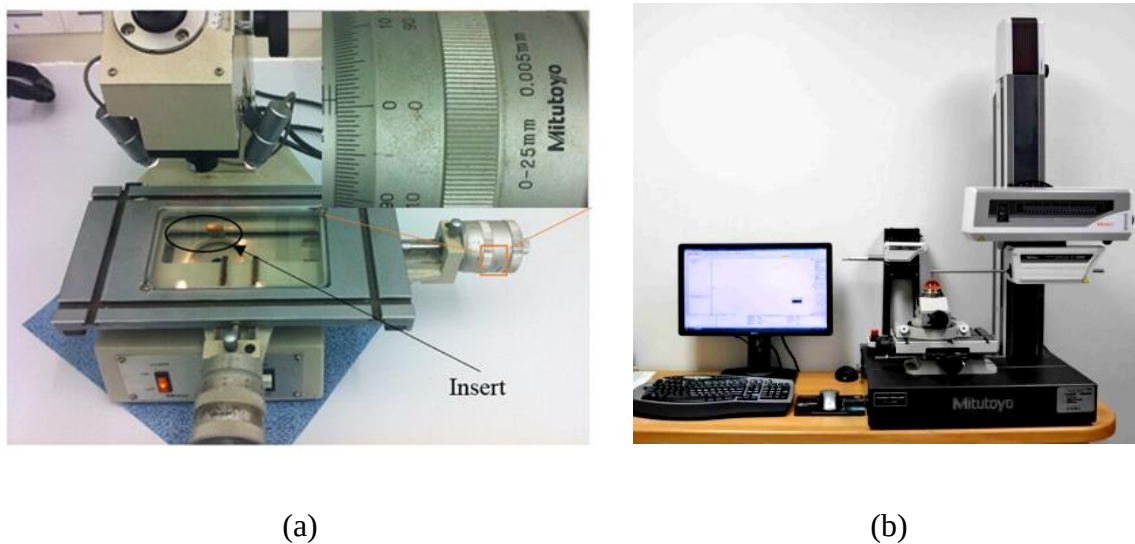


Figure 3-2: a) Optical microscope b) Profilometer Mitutoyo SV- C4000.

3.3 Results and discussions

3.3.1 Face milling Ti-MMC with carbide tools

The cutting conditions used in the face milling tests with carbide tools are presented in Table 3-4 and Table 3-5. Based on cutting conditions used in Table 3-4, severe tool vibration was observed in several tests, especially in those with higher levels of feed rate and cutting speed. In fact, tool X400 has a plunging approach angle that induces sensible vibration. However, despite monitored vibration, high wear rate was only observed in two individual tests. Nevertheless, except minor cases, acceptable tool wear was observed in all cutting tests. Contrary, based on cutting conditions presented in Table 3-5, no particular failure, in principle, tool breakage, and chatter vibration were observed when carbide tool X500 was in operation.

Table 3-2: Carbide tools X400 and X500 specifications

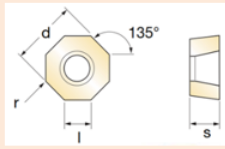
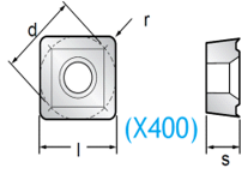
Part Number	Grade	d (mm)	I	S	r	Number of edges	Schematic
ODMT040408EN-41	X500	12.7	4.00	0.187	Facet	8	
SCCT-12M5-ACTR	X400	12.7	12.7	5.00	Facet	4	

Table 3-3: Elemental composition of Ti-MMC

Chemical Analysis of Ti- MMC	Aluminium (Al)	Vanadium (V)	Carbon (C)	Oxygen (O)	Iron (Fe)	Nitrogen (N)	Hydrogen (H)	Titanium (Ti)
Mass %	5.55	3.84	0.97	0.26	0.004	0.21	< 0.003	Remainder (89.163)

Due to several interrupted cutting tests, as shown in Table 3-4, no statistical analysis was conducted to assess the sensitivity of machining responses to the variation of cutting parameters when using carbide tool X400. Machining duration was 2 minutes for each test.

Table 3-4: Experimental conditions and responses when using carbide tool X400

Test No.	Experimental parameters			VB_{max} (μm)
	v_c (m/ min)	f_r (mm/ rev)	a_p (mm)	
1	70	0.2	1	40
2	70	0.35	1.5	34
3	70	0.5	2	57
4	100	0.2	1.5	36
5	100	0.35	2	53
6	100	0.5	1	Stopped
7	130	0.2	2	
8	130	0.35	1	
9	130	0.5	1.5	

Despite of chatter vibration observed in milling tests with tool X400, the tool cutting edge exhibited acceptable performance and stability (Figure 3-3b). The structural dynamics and the vibrations evaluations are not however within the scope of this study.

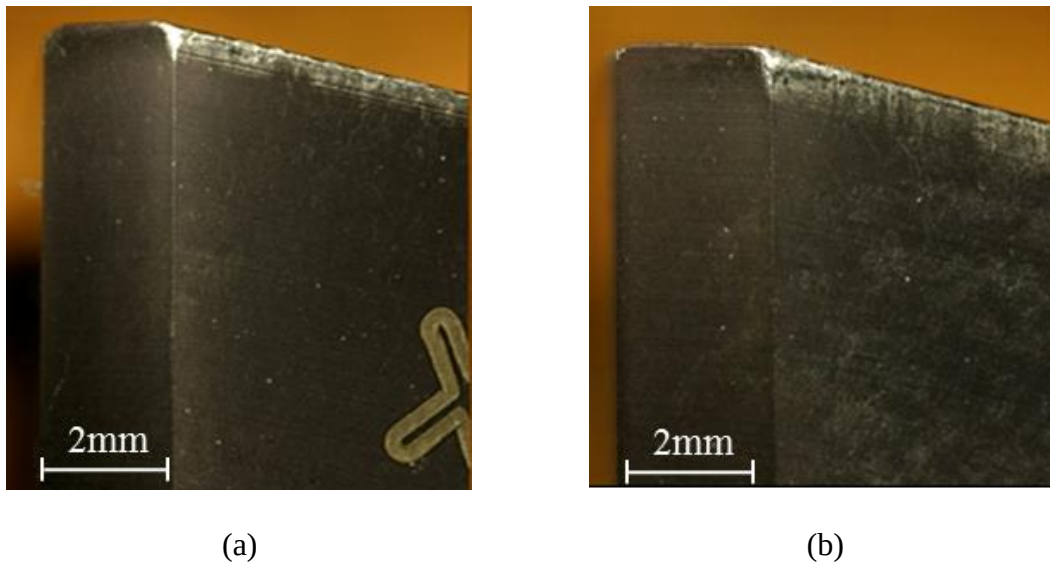


Figure 3-3: Milling Ti-MMC with carbide tool X400 a) $V_c=100$ m/min; $f_r=0.35$ mm/rev; $a_p=2$ mm b) $V_c=75$ m/min; $f_r=0.35$ mm/rev; $a_p=1.5$ mm.

Table 3-5 reveals that promising tool wear rates were recorded under low levels of cutting speed and high levels of feed rate when using carbide tool X500. Moreover, at a certain level of cutting speed and feed rate, the best conditions were obtained with acceptable productivity and cutting volume.

Table 3-5: Experimental conditions and responses when using carbide tool X500

No.	Experimental parameters			Responses	
	a_p (mm)	v_c (m/min)	f_r (mm/rev)	Surface roughness (μm)	VB_{max} (μm)
1	1.1	45	0.1	0.75	120.2
2	1.1	45	0.2	1.66	132.2
3	1.1	45	0.3	1.65	124.2
4	1.1	70	0.1	0.87	199.0
5	1.1	70	0.2	2.20	209.7
6	1.1	70	0.3	1.68	199.0
7	1.1	95	0.1	1.15	168.3
8	1.1	95	0.2	1.37	179.0
9	1.1	95	0.3	2.61	196.3
10	1.6	45	0.1	0.69	128.6
11	1.6	45	0.2	1.74	83.6
12	1.6	45	0.3	1.36	114.5
13	1.6	70	0.1	1.15	123.5
14	1.6	70	0.2	1.85	153.0
15	1.6	70	0.3	2.39	204.5
16	1.6	95	0.1	0.90	162.0
17	1.6	95	0.2	0.24	151.7
18	1.6	95	0.3	3.17	199.3

As shown in Table 3-6, cutting speed and depth of cut have the most significant influences on the tool wear rate, while feed rate has no statistically significant effects on the tool wear rate. This could be attributed to severe effects of cutting speed on generated temperature within the cutting zone that directly increases the tool wear rate. Machining duration was 2 minutes for each test.

Table 3-6: ANOVA table of the surface roughness and tool wear rate when using carbide tool X500

Experimental Parameters	Machining responses			
	Tool wear rate		Surface roughness	
	F	P	F	P
(1) v_c	17.80	0.0002	0.62	0.5507
(2) f_r	2.28	0.1447	6.15	0.0145
(3) a_p	5.56	0.0361	0.03	0.8599
	$R^2 = 0.79$		$R^2 = 0.531$	

Wear mechanism

In order to have a better insight of the morphology and composition of different elements around the workpiece/tool interaction area, SEM image of zone 1 is shown in Figure 3-4.

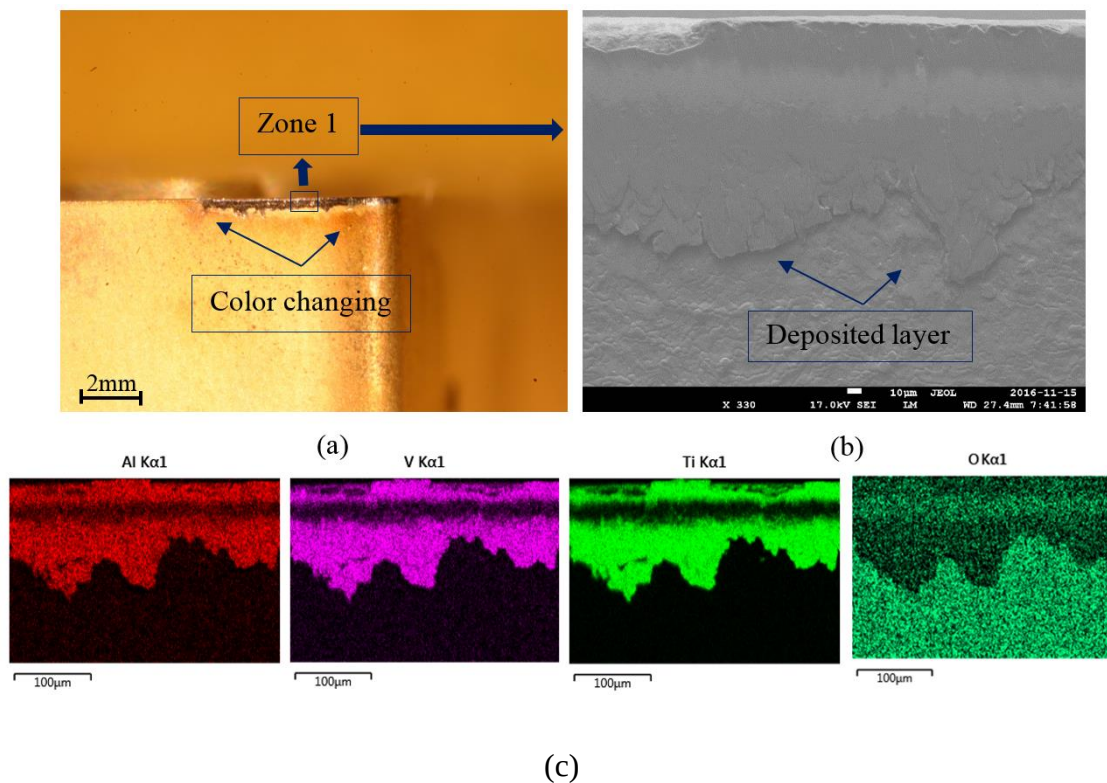


Figure 3-4: a) X500 carbide tool wear in milling of Ti-MMC with $V_c = 95$ m/min; $f_r = 0.1$ mm/rev; $a_p = 1.6$ mm. b) SEM micrograph of flank face, and deposited layer observed on flank face near the nose with the appearance of spread butter. (c) EDS Elemental mapping analysis of SEM micrograph.

The SEM micrograph clearly shows that the deposited materials smear on the flank face and the thin deposited layer has the appearance of spread butter. The corresponding chemical compositions of the worn flank face detected by EDS are presented in Figure 3-4c. The existence of vanadium (V) in the elements deposited on the zone 1 (Figure 3-4a) is suggested to belong the Ti-6Al-4V transferred from the work-piece material showing adhesion mechanism. It is believed that a major color changing around the tool-workpiece interaction area (Figure 3-4a) is due to the resistance to thermal loads with a high strain-hardening coefficient of Ti-MMCs. The elevated temperature generated during machining operation constantly results in the oxidation of titanium outside the tool/chip contact region, where exposed to oxygen (Figure 3-4c). Thus, it is suggested that the oxidation is a degradation mechanism during the machining.

3.3.2 Face milling Ti-MMC with PCD tools

The last set of face milling tests was conducted using PCD tools as aforementioned. The experimental conditions, as well as machining responses, are presented in Table 3-7 and Table 3-8. Unfortunately, there is no systematic database about allowable levels of cutting parameters for milling Ti-MMC with PCD tools/tools. As depicted in Figure 3-5, milling tests with PCD tools at high levels of cutting speed (350-600 m/min) led to tool failure. The milling results on PCD tools which led to tool failure are presented in the following section. Therefore, lower levels of cutting speed were then used in other tests and satisfactory results were observed. Furthermore, under low levels of depth of cut and speed and high level of feed rate, acceptable tool wear rate can be observed. In principle, at a low level of cutting speed, the matrix behavior and hydrostatic pressure of the cutting edge provide sufficient hardness which prevents abrasion and resists against the deflection forces. The surface roughness and the tool wear results when milling Ti-MMC with PCD tool are shown in Table 3-7. The corresponding statistical analysis of the responses based on ANOVA is shown in Table 3-8.

Despite the high value of R^2 (Table 3-8), none of cutting parameters are statistically significant on the variation of surface roughness. It denotes that the variation of surface roughness in milling with PCD tools are highly controlled by the interaction effects between cutting parameters.

Table 3-7: Surface roughness and wear rate when using PCD tools on the basis of orthogonal array L9

Test No	Ra(μm)	VB _{max} (μm)
1	0.19	399
2	0.17	475
3	0.23	1131
4	0.25	194
5	0.25	474
6	0.24	394
7	0.34	1622
8	0.30	934
9	0.32	151
Mean	0.25	793

Table 3-8: ANOVA of the tool wear and the surface roughness of the work parts machined with PCD tools

Parameter	Tool wear rate		Surface roughness	
	F	P	F	P
(1) v_c	94.428	0.0104	5.7552	0.1480
(2) f_r	13.857	0.0673	3.2327	0.2362
(3) a_p	25.000	0.0384	1.9165	0.3428
	$R^2 = 0.992$		$R^2 = 0.916$	

This is, however, a non-desirable phenomenon in process control and optimization studies. Moreover, unlike the surface roughness results, it is exhibited that the cutting speed has the highest effect on the tool wear rate, followed by the depth of cut. Moreover, the high values of R^2 and R^2_{adj} indicate that the tool wear rate is highly controlled by variation of process parameters, mainly cutting speed. As discussed earlier, this could be attributed to intense effects of high-speed machining that in fact increases the temperature in the cutting zone and the tool and the work part interface which in fact tends to decrease the tool life. Further studies on modelling cutting temperature in the shear zone and chip-tool contact zone when machining Ti-MMCs are demanded.

The effects of abrasive particles on temperature generation and variation need to be understood. However, these topics are not within the current scope of this study. As shown in Table 3-8, both tool wear rate and surface roughness are affected by different cutting parameters. This means that optimum selection of cutting parameters by means of simultaneous multiple response optimization techniques is a delicate subject which needs further investigations.

Table 3-9 presents the cutting parameters (relatively high levels) used as well as milling responses when using PCD tools. As noted earlier, there is no systematic database about allowable levels of cutting parameters for milling Ti-MMC with PCD tools. As depicted in Table 3-9, milling tests with PCD tools at high levels of cutting speed (350-600 m/min) led to tool breakage. Therefore, lower levels of cutting speed were then used in the rest of cutting tests. Table 3-9 reveals that at very low level of depth of cut and high level of feed rate, acceptable tool wear rate (according to manufacturer) can be observed. Moreover, at a certain level of cutting speed under the steady level of depth of cut (0.05 mm), the optimum values of cutting volume and productivity were achieved. Moreover, promising tool wear rate was recorded under low levels of cutting speed and high levels of cutting feed. Despite the chatter vibration occurred in cutting tests (Table 3-9), high wear rate was only observed in two tests.

Table 3-9: Milling results with PCD tool

Test No.	V_c (m/min)	f_r (mm/ rev)	a_p (mm)	Cutting Time (Seconds)	n (rev/min)	Tool status
1	600	0.1	1	9.2	6018	Failed
2	450	0.3	1	8.2	4514	Failed
3	350	0.2	1	10.5	3511	Failed
4	350	0.3	0.7	209.7	3511	Failed
5	300	0.5	0.7	146.9	3009	Functional ($V_b = 0.28$ mm)
6	250	0.6	0.7	146.9	2508	Functional ($V_b = 0.225$ mm)
7	250	0.9	0.7	4.9	2508	Failed
8	250	0.85	0.5	145.1	2508	Functional ($V_b = 0.16$ mm)
9	250	0.7	0.5	220.1	2508	Functional ($V_b = 0.105$ mm)
10	150	0.4	0.5	275.4	1505	Failed

Wear mechanism

After machining for two minutes, edge chipping was observed (Figure 3-5). This could be due to the hard TiC particles of workpiece material and the high hardness of PCD tools.

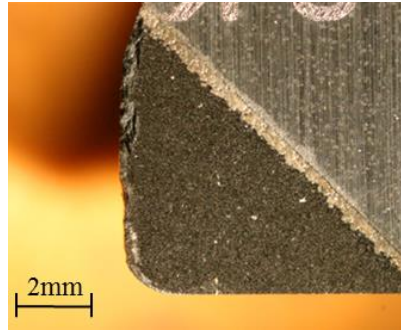


Figure 3-5: Edge chipping of the PCD tool at low speed ($v_c = 200$ m/min, $f_r = 0.17$ mm/rev and $a_p = 1$ mm) after 2 minutes of machining.

A massive tool material (Figure 3-6(a)) was peeled out during the machining showing the low fracture toughness of polycrystalline diamonds which limits the tool life. Notch wear was another issue observed after 10 seconds of machining (Figure 3-6(b)).

Material sticking and slight adhesion were also observed on the flank face of the PCD tool as shown in Figure 3-7(a). To reveal what elements are present on the surface a line scan was performed and the results presented in Figure 3-7(b). As can be seen, line scan analysis shows the proof of the presence of the Ti, N, Al, V, and Co elements. Ti, Al, and V are suggested to be the workpiece elements showing the adhesion mechanism. Although a slight material adhesion was observed, edge chipping, peeling, and abrasive wear are the main mechanisms on the PCD tools.

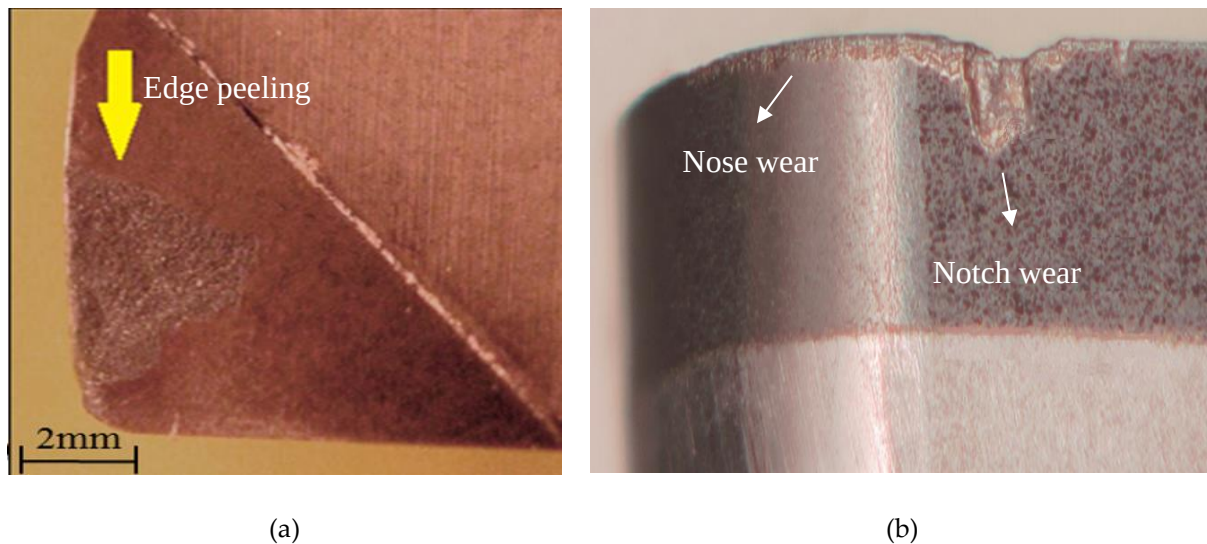


Figure 3-6: (a) Edge peeling and (b) notch wear on the flank face of the PCD tool at high speed ($v_c = 250$ m/min, $f_r = 0.3$ mm/rev and $a_p = 1$ mm) after 10 seconds of machining.

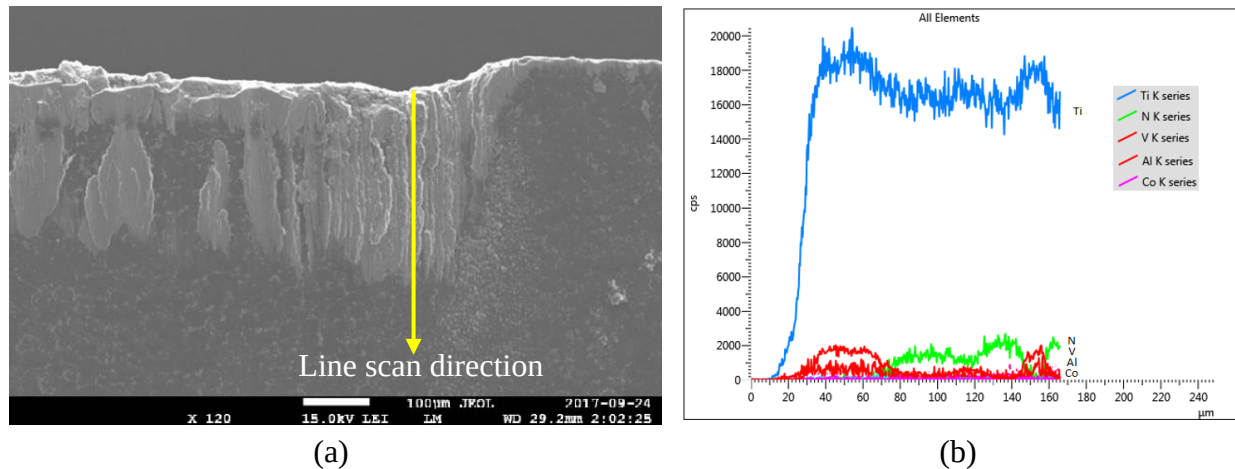


Figure 3-7: (a) Adherent material on the flank face. (b) Line scan of adhered material.

3.4 Conclusion

During high-speed machining of hard to cut materials, including Ti-MMC, hard abrasive TiC particles are the typical problem; this cutting tool should resist the high abrasion and thermal loads. Based on the experimental observations during milling Ti-MMC with carbide and PCD tools, the following conclusions are drawn:

- In carbide tools, adhesion is the main wear component appearing on the flank side of the tool. Another main wear mode is oxidation that seems to appear due to the high temperature at the cutting zone.
- Despite the sensible vibration occurred when using carbide tools, acceptable tool wear rate was observed.
- In PCD tools, although a slight material adhesion was observed, edge chipping, peeling, and abrasion wear are the dominant mechanisms.
- The PCD tools failed at cutting speed range 350-600 m/min, while optimum tool wear and productivity were observed under low levels of feed rate and cutting speed. This could be attributed to the intense effects of matrix behavior and hydrostatic pressure of the cutting edge at low levels of cutting speed which provide sufficient hardness to prevent abrasion and resists against the deflecting forces.
- The statistical investigations on the milling tests using carbide X500 and PCD inserts led us to conclude that cutting speed and depth of cut are the major cutting parameters affecting tool

wear rate, whereas surface roughness was not affected by the cutting parameters used when using PCD tool and only was sensitive to variation of feed rate when using carbide tool X500.

- Although the experimental results are limited to the cutting parameters used, based on the manufacturer recommendations, the highest possible range of cutting parameters applicable in real industrial applications were used. The experimental results denote that the milling responses studied in this work, in principle tool wear rate and average surface roughness are affected by different cutting parameters. This means that optimum selection of cutting parameters by means of simultaneous multiple response optimization techniques is a delicate subject which needs further investigations.

Acknowledgments

Authors would like to acknowledge the financial supports received by the Fonds Québécois de la Recherche sur la Nature et les Technologies (FQRNT) and NSERC Canadian Network for Research and Innovation in Machining Technology Network (CANRIMT).

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CHAPTER 4 ARTICLE 2: TURNING TITANIUM METAL MATRIX COMPOSITES (TI-MMCS) WITH CARBIDE AND CBN INSERTS

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The International Journal of Advanced Manufacturing Technology (2018) 97:253–265

<https://doi.org/10.1007/s00170-018-1926-9>

Received: 23 November 2017 /Accepted: 15 March 2018 /Published online: 29 March 2018, # Springer-Verlag London Ltd., part of Springer Nature 2018 (**cited by 35 as of 4/29/2023**)

Abstract

Metal matrix composites (MMCs) are composed of non-metallic reinforcements (i.e. ceramic) in metal matrices that feature high toughness, wear, and fatigue resistant and relatively low density. 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 within a vast number of products and industrial sectors, including automotive and aerospace industries. Despite excellent mechanical and physical features, due to the presence of hard and abrasive ceramic particles in metal matrices of Ti-MMCs, various issues have emerged in the area of machining and machinability of Ti-MMCs. One of the principal machinability attributes is tool wear that requires further studies. Knowing that only a very few studies are available on adequate machining of Ti-MMCs, this work intends to report the tool wear and surface roughness when turning Ti-MMCs with carbide and cubic boron nitride (CBN) tools under various cutting conditions. The flank wear

(VB) and average surface roughness (R_a) were considered as the measure of the tool wear and surface quality. The main wear modes observed on the flank side of the tested tools were adhesion, abrasion, and oxidation. According to experimental results, the surface roughness and the flank wear rate when using carbide and CBN tools can be controlled by the cutting parameters used, in principle cutting speed.

Keywords: Tool wear; Ti-MMC; Composite, Machinability, Turning.

4.1 Introduction

According to the literature review, the performance of the individual family of tool materials (i.e. PCD, carbide, and CBN) may vary under different machining operations and cutting parameters. High cutting energy and temperature cause several complications in the cutting process, including reduced strength, hardness and wear resistance of the cutting tool; degraded the dimensional accuracy of the workpiece as well as thermal damage to the machined surface [1]. This, therefore, recalls further investigations regarding the effects of cutting parameters on machining attributes when machining hard to cut materials. One the most respected hard to cut materials with superior features is titanium metal matrix composite (Ti-MMC), which can be however considered as an alternative to superalloys such as Inconel. Based on the review of literature, despite of numerous works on machinability of titanium alloys [2, 3], only a few studies are reported on machining Ti-MMCs with traditional and non-traditional approaches [4-11]. Among, the tool wear and surface roughness are the major machinability attributes which are of prime importance in scientific research works.

Severe tool wear, short tool life and poor surface finish (quality) are considered as the main concerns in machining Ti-MMCs. Due to the very low thermal conductivity of Ti-MMCs, very high local temperatures are generated in a tiny area around the cutting edge that results in high tool wear rate [8]. Moreover, oxidation and chemical wear mechanisms are involved, and tool life reduction is expected. The high affinity of almost all tool materials to Ti-MMC's matrix and elevated temperature in the tool-workpiece engagement leads to the chemical reaction, material diffusion and adhesion in the cutting tool [12]. Consequently, even at high material removal rate, the chips cannot evacuate the massive thermal loads [13]. Moreover, the tool slides than cutting the workpiece at a low shear angle; therefore, as similar as friction, the cutting zone temperature and pressure arise [14]. Then, the scraped materials melt and adhere to the tool tip. The hot adhered

particles in the vicinity of oxygen turn into fragments including TiO_2 and V_2O_3 [15]. Therefore, the abrasive particle and high resistance to plastic deformation in Ti-MMC compel high energy load to the tool-workpiece engagement.

One of the major components affecting the surface quality and the tool wear mode is the chip formation morphology. Bejjani et al. [6] studied the chip formation and microstructure evolution in the adiabatic shear band in machining (Ti-MMCs). It was concluded that a high dislocation density characterizes the grains located at the lightly strained areas within the chip segment. It was declared that no phase transformation appears inside the adiabatic shear band (ASB). The microstructure inside the ASB was found to be composed of elongated nano-size grains. Moreover, it was observed that segmentation mechanism of chips is initiated from a crack on the material free surface ahead of the tool, not at the tool tip. Furthermore, the hard particles inside the matrix were found not to be hindering or retarding the ASB formation.

Though there are currently a few studies found on the comprehensive comparison between the various tool materials used in machining Ti-MMCs, including turning operation. Furthermore, except these few works available [4-7], the main tool wear modes when turning Ti-MMCs with commercial tools as aforementioned are not yet reported in the open literature. Two main types of tool wear are flank wear and crater wear. Flank wear can be created by the abrasive particles in the workpiece, whereas crater wear can be considered as a complex combination of two or more wear mechanisms such as abrasion, adhesion, dissolution, and diffusion. Contact conditions, the interface between the tool and workpiece, and cutting temperatures are thought to be the most efficient factors on the wear mechanisms [16].

Kamalizadeh [5] focused on initial tool wear in turning of Ti-MMCs using carbide tools. It was observed that the first transition time of tool wear occurs in the first second of machining. A direct correlation was found between the transition time in tool wear progression charts and the cutting force diagrams. As noted in [5], the preliminary wear mechanism during the initial moments of machining Ti-MMC is abrasion and the dominant wear mechanism is adhesion.

CBN as one of the hardest tools after PCDs exhibit superior characteristics such as high hardness at elevated temperature (i.e. 1200°C), high melting point and ability to keep sharpness, could be employed to machine Ti-MMCs with acceptable surface roughness. However, CBN tools are more expensive than carbides, but due to their superior characteristics, these tools are widely used in the

industry especially at aerospace [28]. Basically, two types of CBN are produced by manufacturer: low content (50% of total volume) and high content (80-90%) CBN [29]. To sinter the ingredients, the binder-assisted-sintering method is normally used, and some binders such as Al, Mg, Co, and Ni elements or TiC, TiN, and Al_2O_3 materials are added [30]. In reference to state of the art in this domain, Aramesh et al. [4] observed a unique wear morphology of CBN tools during machining of Ti-MMCs. They noted that the entire adhered material consists of the Ti, Al, and V elements and a black zone. The zone separated the inside and the outside of the contact area and sounded by a white zone containing Mg and O. They found out that the Mg coming from tool or workpiece material might be oxidized during machining and perform this white zone.

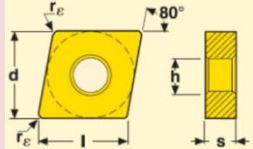
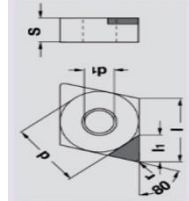
In general, due to the presence of hard and abrasive particles in Ti-MMCs, flank wear is considered as the commonly observed wear mode when machining Ti-MMCs. Within the most of the reported work in the literature, the tool wear was quantified by measuring the flank wear of the tools and plotting it versus cutting time [8, 17]. Unfortunately, not much information is available regarding the flank wear rate when machining Ti-MMC with different cutting tools. Furthermore, using various cutting tools, the generated surface quality, in principle surface roughness of Ti-MMC workpiece when is not yet reported. The primary objective of this work is to present the tool wear modes in turning Ti-MMC when using carbide and CBN tools. Furthermore, the controllability of the flank wear by changing cutting parameters used will be investigated. Finally, the effects of cutting parameters and different tools on the recorded values of the surface roughness will be studied on the basis of statistical evaluation.

4.2 Experimental plan

This study consists of three sets of turning tests with one replication on carbide tool TH1000 (CNMG 120404-MF1) and CBN tool (CNMA-432TW-MC-PBC 10) as shown in Table 4-1. It is to underline that the TH1000 is a coated carbide tool of WC sintered strut with a nano-laminated PVD-coat of TiSiN-TiAlN. The manufacture, SECO Inc., provided both types of the tools. As regards to their catalogs, they offer TH1000 tools to be used in turning of materials with high toughness and hard surface components especially in semi-finishing of titanium alloys. A hard-deposited coating on the surface can decrease abrasion wear mechanism and protect the surface of scratching and grooving by the work material hard particles. Meanwhile, the low content CBN tool contains TiC particles, SiC whiskers, and Al_2O_3 ceramic binders. These binders reinforce tool by

increasing the toughness, wear, and fracture resistance. Although thermal conductivity of the tool is relatively low (i.e. 40–50 W/m·K) due to the binder Al_2O_3 , but yet it has a very high hardness (i.e. 30 GPa).

Table 4-1: Characteristics of the carbide and CBN tools used in turning tests (Becker)

Item	Grade	d	d1	r	l	l1	s	schematics	Coating
CNMG 120404-MF1	TH1000	12.7	---	0.4	12.9	---	4.76		PVD TiSiN-TiAlN coated carbide with W and Co as core and binder
CNMA-432-MC	PBC-10	12.7	5.1	0.8	12.9	2.8	4.8		Uncoated standard CBN, with TiC particles, SiC whiskers, and Al_2O_3 ceramic binders

The workpiece was a 140-mm diameter cylindrical Ti-MMC made of Ti-6Al-4V with 10-12% volume fraction of TiC particles with uneven shapes and 10-20 μm size. A precise elemental composition of the workpiece material (Ti-MMC) is presented in Table 4-2.

The CNC turning center MAZAK Nexus 200 was used in turning tests (Figure 4-1). The flank wear and surface roughness measurements were conducted on the optical microscope and profilometer Mitutoyo SV-C4000 (Figure 4-2).

Table 4-2: Elemental composition of Ti-MMC

Chemical Analysis of Ti-MMC	Aluminium (Al)	Vanadium (V)	Carbon (C)	Oxygen (O)	Iron (Fe)	Nitrogen (N)	Hydrogen (H)	Titanium (Ti)
Mass %	5.55	3.84	0.97	0.26	0.004	0.21	< 0.003	Remainder (89.163)

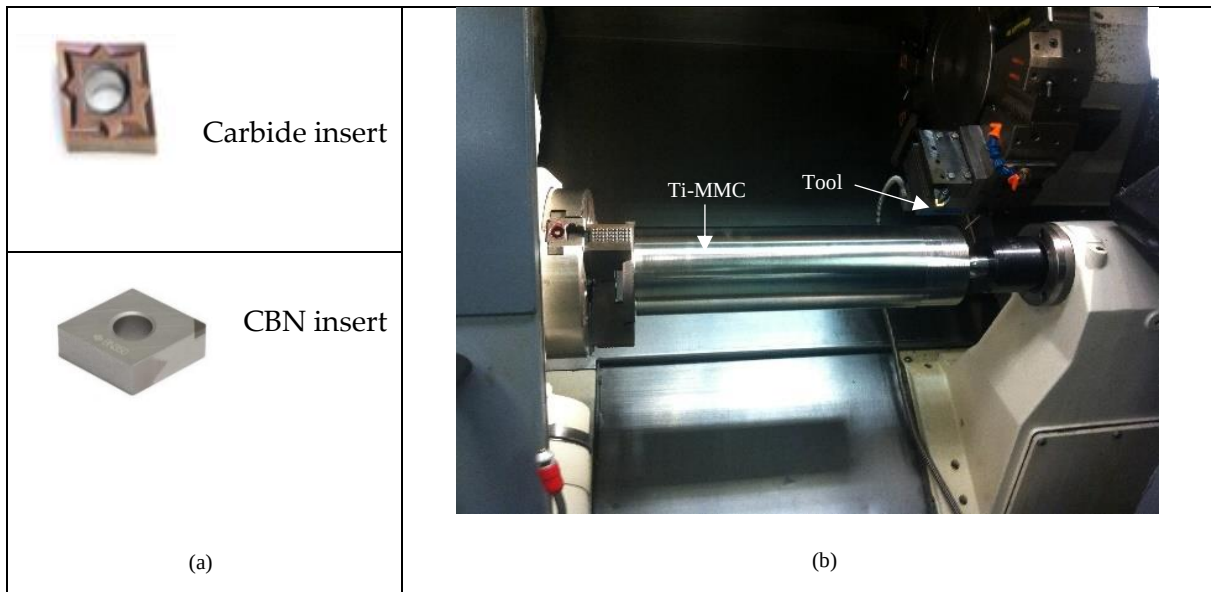


Figure 4-1: (a) Inserts used; (b) The CNC turning center MAZAK Nexus 200

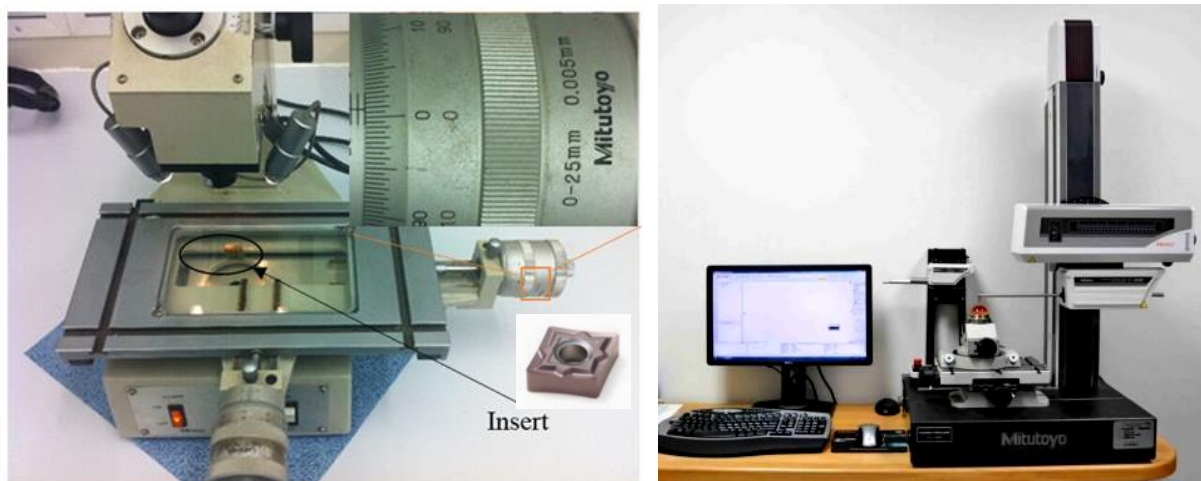


Figure 4-2: (a) Optical microscope (b) Profilometer Mitutoyo SV-C4000

The cutting conditions used are presented in Table 4-3. The orthogonal array $L_9(3^4)$ design of experiment was used to build up experiments carried out with CBN tools, while $L_{27}(3^{13})$ was used on those tests conducted with carbide tools (Table 4-3). Due to lack of information on turning Ti-MMCs as aforementioned, the cutting conditions were selected based on the tool manufacturer's recommendations for industrial usages.

Table 4-3: Cutting conditions and two types of tools used

Cutting tool	Experimental factors and levels		
	v_c (m/min)	f_r (mm/ rev)	a_p (mm)
Carbide (CNMG 120404-MF1)	40, 60, 80	0.15, 0.25, 0.35	0.5, 1, 1.5
CBN (CNMA-432TW-MC-PBC 10)	150, 175, 200	0.3, 0.45, 0.6	0.5, 1, 1.5

The statistical approaches such as analysis of variance (ANOVA) were used to define the factors governing wear rate on the tool's flank. To that end, the statistical parameters including R^2 , R^2_{adj} , P-value, and F-ratio were employed for result analysis. An extensive overview of the statistical tools and terms used is presented in [18].

To study the tool wear mechanisms, elemental analysis and quantitative mapping were performed using Jeol JSM 7800F FEG-SEM equipped with an Oxford X-ray detection system (Aztec EDS). The micrographs of the microstructures were captured at the low and high magnifications. To avoid the coolant effects, wear investigation tests were conducted under dry condition. However, to avoid temperature effects on the functionality of the workpiece and tools performance, an appropriate coolant was used during surface roughness investigation.

4.3 Results and discussions

4.3.1 Turning tests with carbide tools

The effects of cutting parameters on the flank wear rate recorded when using carbide tool TH1000 is presented in Table 4-4. It can be exhibited that cutting speed is the only statistically significant factor on the flank wear rate. This is in agreement with observations during turning titanium alloys and MMCs [10, 19-22]. However, $R^2 = 0.57$ states that the flank wear rate cannot be statistically controlled by process parameters used. This is also in agreement with reported works in the literature [10, 23, 24]. The low controllability of flank wear rate could be attributed to the rubbing effect of the hone/edge radius when machining Ti-MMC. In fact, the sparks were observed in the cutting zone. Similarly, as can be seen in Table 4-4, all cutting parameters used are statistically significant parameters on the recorded values of R_a under similar cutting conditions.

Table 4-4: ANOVA table of turning tests when using carbide tools

Experimental factors		Tool wear		Surface roughness R_a	
		F	P	F	P
(1)	v_c	10.411	0.0008	8.788	0.0018
(2)	f_r	1.957	0.1674	9.476	0.0013
(3)	a_p	0.987	0.3902	7.208	0.0044
		$R^2 = 0.572$; $R^2_{adj} = 0.443$		$R^2 = 0.78$; $R^2_{adj} = 0.72$	

Furthermore, the experimental results denote that factors governing optimum or near optimum tool wear and surface roughness are not identical. This implies the use of advanced optimization tools for adequate simultaneous multiple response optimization. This is not however within the scope of this work. Further investigations in these regards are presented in following article currently under preparation. Two photos of the flank face after 60 seconds of machining with different cutting parameters were shown in Figure 4-3. The difference between the worn surfaces can be clearly seen. Machining with higher speed and federate but lower depth of cut caused severe tool wear. Figure 4-4 shows the SEM micrographs of flank face, rake face and deposited layer on the flank face near the nose. Scratches and grooves on the deposited layers might be caused by TiC particles during the interaction between tool and workpiece showing the abrasion mechanism. Another possibility is that since this is a coated tool, the harder coating particles might disintegrate the tool surface. The SEM micrographs show clearly that the deposited materials smear on the flank face and the thin adhered layer has the appearance of spread butter.

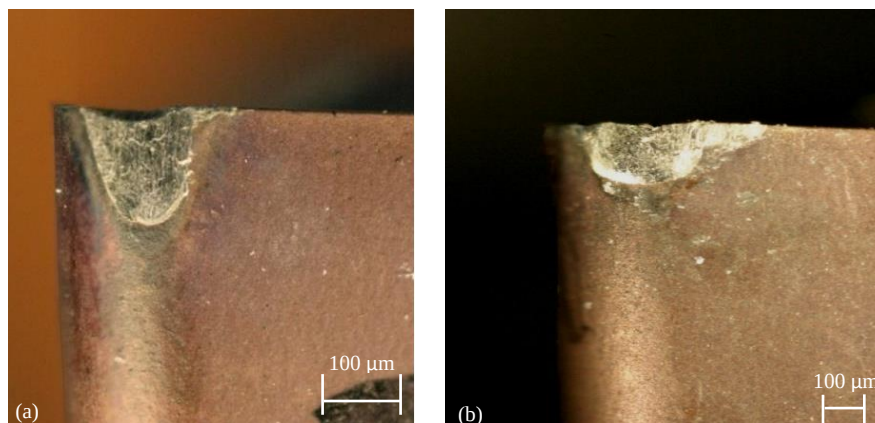


Figure 4-3: The flank wear on the carbide tool when

a) $v_c = 80$ m/min; $f_r = 0.35$ mm/rev; $a_p = 0.5$ mm; b) $v_c = 60$ m/min; $f_r = 0.25$ mm/rev; $a_p = 1$ mm

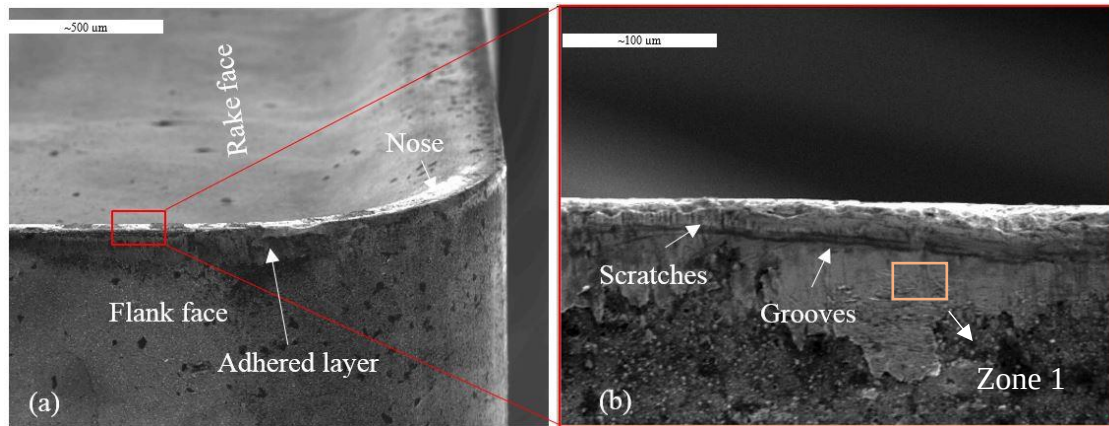


Figure 4-4: (a) SEM micrograph of flank face, rake face and deposited layer observed on the flank face near the nose (b) highly magnified flank face shows scratches and grooves caused by TiC particles

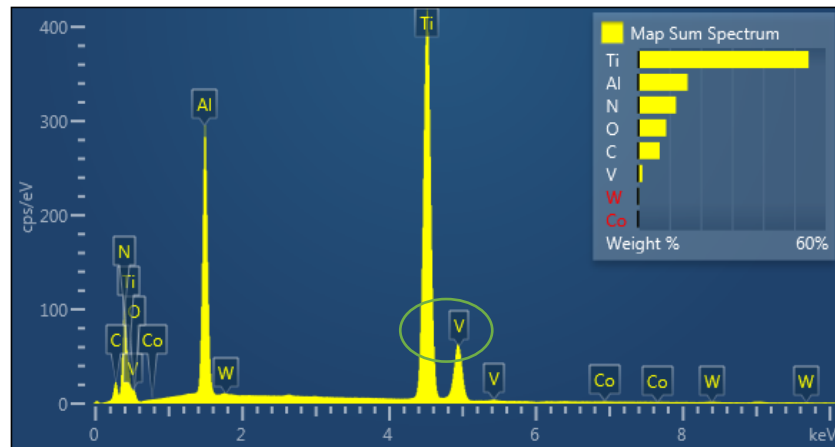


Figure 4-5: An EDS spectrum of the deposition layer on the flank surface of the carbide tool (Zone 1 in Figure 4-4b) along with the element content table showing the existence of vanadium

The corresponding chemical compositions of the Zone 1 (Figure 4-4b) on the worn flank face detected by EDS are presented in Figure 4-5. The elements such as aluminum (Al), carbon (C), and titanium (Ti) exist in both tool and workpiece elements (Table 4-1). Tungsten (W) and cobalt (Co) are the tool elements as core and binder (Table 4-1). Nitrogen (N) could come from the tool coating (again Table 4-1). No trace of magnesium (Mg) was seen in this analysis. Besides, the existence of vanadium (V) is suggested to belong the Ti-6Al-4V transferred from the workpiece material (Table 4-2) showing adhesion mechanism.

4.3.2 Turning tests with CBN tools

According to Table 4-5 and based on statistical results of flank wear rate and surface roughness when using CBN tools (Table 4-6), it could be inferred that both responses are statistically significant to the variation of the cutting parameters used. The variation of flank wear rate and surface roughness are highly affected by cutting speed (P-values 0.033 and 0.0081). This is in agreement with the findings in the literature [25-27]. The correlation of determination (R^2) denotes that both flank wear rate and surface roughness can be controlled by 99% and 94% under similar levels of cutting parameters used. Knowing that the presented cutting parameters in Table 4-5 were selected according to tool's manufacturer recommendations, it can be underlined that CBN tools revealed good performance in machining Ti-MMC. Machining duration was 2 minutes for each test.

Table 4-5: Turning tests with CBN tools

Test No.	Experimental parameters			Responses	
	v_c (m/min)	f_r (mm/rev)	a_p (mm)	$V_{B\max} \times 10^{-1}$ (mm)	R_a (μm)
1	150	0.3	0.5	1.05	1.03
2	150	0.45	1	1.14	1.00
3	150	0.6	1.5	1.93	1.56
4	175	0.3	0.5	1.07	2.10
5	175	0.45	1	3.10	1.75
6	175	0.6	1.5	1.16	1.42
7	200	0.3	0.5	3.72	4.78
8	200	0.45	1	2.36	1.79
9	200	0.6	1.5	1.61	5.16

No severe failure was observed on the cutting tests. Smooth layers of high-temperature resistant coating on the tools edges are used to protect the tool against the abrasive particles and wear.

Table 4-6: ANOVA table of results recorded in turning by carbide and CBN tools

Experimental factors		Tool wear		Surface roughness R_a	
		F	P	F	P
(1)	v_c	29.131	0.033	11.295	0.287
(2)	f_r	8.044	0.110	2.484	0.0081
(3)	a_p	62.178	0.015	3.161	0.240
		$R^2 = 0.99$; $R^2_{adj} = 0.94$		$R^2 = 0.94$; $R^2_{adj} = 0.88$	

Experimental results based on ANOVA denote that low levels of cutting speed, feed rate and depth of cut led to low wear rate. Furthermore, at higher levels of cutting speed, and moderate depth of

cut, reduced surface roughness can be obtained. This can be related to easier chip formation in the cutting zone as a result of higher speed which tends to facilitate the plastic deformation in the shear zone. This is in agreement with observations made in the literature [3]. A SEM image of the serrated chip formed at the speed of 150 m/min, feed 0.3 mm/rev and depth of cut 0.5 mm was shown in Figure 4-6c. As also presented in Table 4-6, however, the effects of cutting speed and depth of cut are not significant. In fact, the feed rate is mostly a governing factors on the feed rate when turning Ti-MMCs with CBN tool. As similar as the case of turning with carbide tools, the experimental results denote that factors governing optimum or near optimum tool wear and surface roughness are not identical. This implies the use of advanced optimization tools for adequate simultaneous multiple response optimization.

It should be noted that presence of hard particles and dislocations in the Ti-MMC structure intensifies the thermal and mechanical stresses on the tool surfaces. Based on experimental results, high abrasive and strong mechanical properties of Ti-MMC degrade all tools within the first few seconds of cutting operations, in particular under high levels of cutting speed where elevated temperature and abrasive particles are the essential problems (Figure 4-6b). This, therefore, implies that the tool/insert must resist the high abrasion and thermal loads (i.e. CBN). At a low level of cutting speed, the matrix behavior and hydrostatic pressure of the cutting edge play prominent roles. In this case, the tool may acquire enough hardness to prevent abrasion and present adequate resistance against the deflection forces (Figure 4-6a).

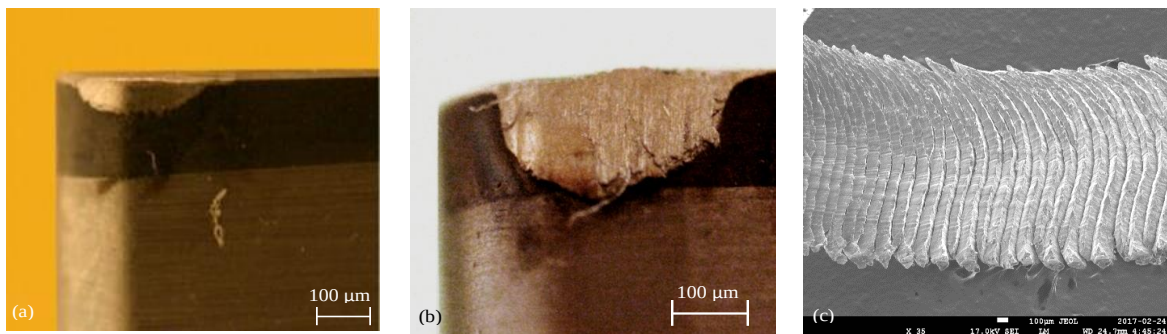


Figure 4-6: Flank wear of CBN tools under cutting tests (a) $V_c = 150$ m/min; $f_r = 0.3$ mm/rev; $a_p = 0.5$ mm (b) $v_c = 200$ m/min; $f_r = 0.45$ mm/rev; $a_p = 0.75$ mm and (c) SEM image of a serrated chip

Therefore, despite the tool used, moderate to high levels of feed rate must be chosen. This reveals that the cutting tools require adequate hardness and rigidity to resist the reinforced particles. Likewise, the tools need sufficient toughness to tolerate the fluctuated forces, spring back and impacts that may occur due to the matrix toughness, elasticity, and inhomogeneity.

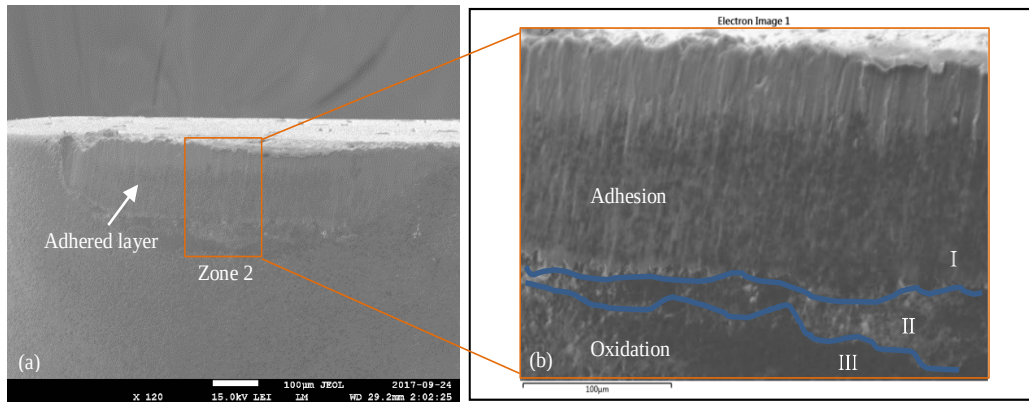


Figure 4-7: (a) SEM image of tool flank face after dry machining with $v_c = 150$ m/min, $f_r = 0.3$ mm/rev, and $a_p = 0.5$ mm, machining time 30 s; (b) magnified image of the zone 2 in image a, no trace of holes or grooves

In order to understand the tool wear mechanism of the CBN tools, EDS analysis was employed on the selected zone 2 as a typical area of flank wear. EDS reveals the key elements, their distributions, and locations via mapping. Figure 4-8 shows the corresponding maps of Figure 4-7b. Titanium (Ti), aluminum (Al), exist in both tool and workpiece materials, but vanadium (V) is just workpiece element (Table 4-2) which shows the adhesion mechanism. As can be seen in Figure 4-8 d & e, magnesium (Mg) and oxygen (O) are the two elements outside of the contact region.

This is in agreement with the Aramesh et al. studies [4]. However, in their study they suggested that Mg might be the workpiece element, but based on the chemical analysis (Table 4-2), magnesium might not come from the workpiece material. Magnesium also was not observed in the carbide tool chemical analysis. It may be the tool element as a catalyst or manufacturing process additive [31]. EDS analysis also suggests that the top layer is shaped by the adhesion mechanism and second region is formed based on the abraision mechanism.

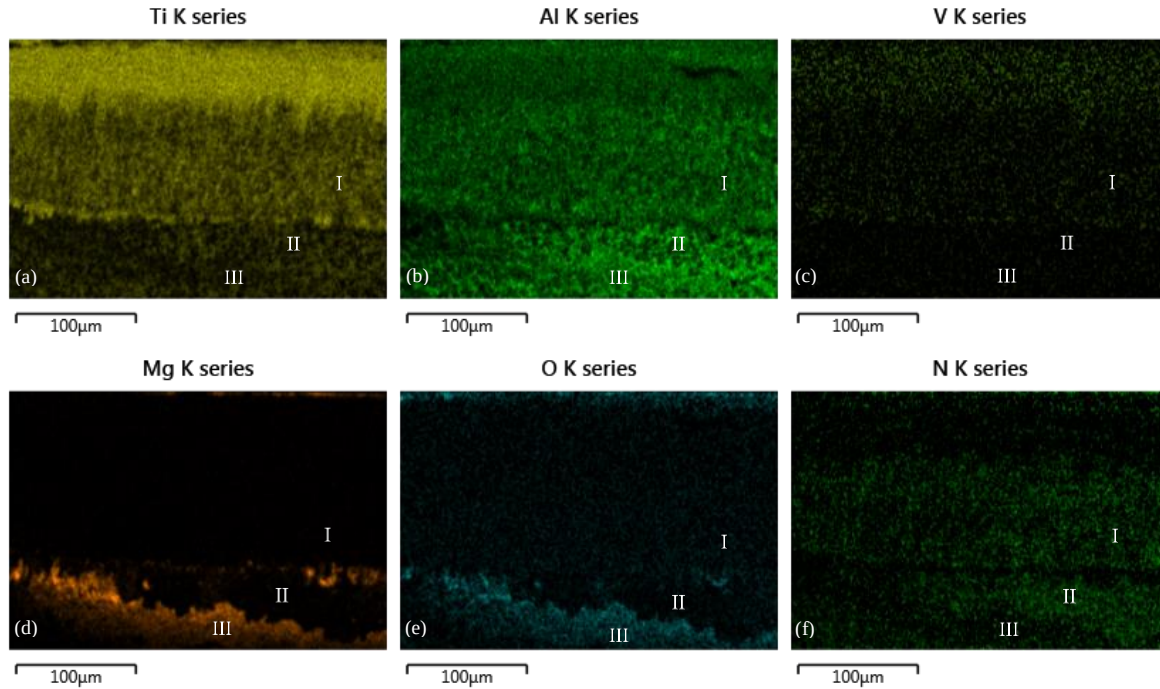


Figure 4-8: Elemental maps of the entire zone 2 (a) titanium, (b) aluminum, (c) vanadium (d) magnesium (e) oxygen and (f) nitrogen.

As can be seen in Figure 4-8b, Al is all over the analyzed region due to the high amount in both workpiece (as Ti-6Al-4V) and tool (as Al_2O_3). Comparison of Figure 4-7b and Figure 4-8d&e shows three distinct regions with different elements. Region I, containing Ti, Al, and V, represents the adhesion area where the sticking phenomenon is the main mechanism. Region II at the boundary of the contact zone mostly contains Ti, Al, and N. Besides, the high concentration of Mg and O at region III could be due to oxidation of Mg which comes from the tool material. Meanwhile, the high affinity of Mg to be oxidized and the concentration of the high temperature at a tiny area due to the low thermal conductivity of Ti-MMCs (around $5.8 \text{ W/m}\cdot\text{K}$) result in the oxidation as dominant wear mechanism at this region.

4.4 Conclusions

The turning tests were conducted on Ti-MMCs workpiece using carbide and CBN tools. Cutting parameters were selected according to manufacturer's recommendations. Despite the tool used, the main wear phenomenon observed was flank wear. Therefore, it was selected as the main wear component when turning Ti-MMC and the flank wear rate, denoted as the tool wear rate was

recorded in the course of this study. However, during high-speed machining, the rake face was also affected by the wear modes such as abrasion and adhesion.

- The typical wear mode observed in the carbide tools were mainly abrasion and adhesion. However, CBN tools were also mostly suffered from adhesion as well as oxidation.
- As noted earlier, cutting speed and feed rate are the governing cutting parameters on the flank wear rate during turning Ti-MMCs with carbide tools.
- Despite the tool used, cutting speed is the governing factor on the flank wear. Depth of cut is another key determinant of the flank wear rate when turning Ti-MMC with CBN tools. Furthermore, despite of the tool used, moderate to high levels of feed rate must be selected to accommodate an acceptable tool life.
- The rigidity and suitability of the cutting tool and tool holder have important roles in the stability of the cutting process and successful reduction of the fluctuated forces effects, particularly under high levels of cutting speed.
- Elevated temperature and abrasive particles were discovered as the essential problems observed under high-speed machining of Ti-MMCs. Thus, the tool/insert should resist the high abrasion and thermal loads (i.e. CBN). At a low level of cutting speed, the matrix behavior and hydrostatic pressure of the cutting edge play prominent roles. In this case, the cutting tool acquires sufficient hardness to prevent abrasion and resists against the deflection forces.

Acknowledgment

Authors would like to appreciate the financial support received from Fonds Québécois de la Recherche sur la Nature et les Technologies (FQRNT) and NSERC Canadian Network for Research and Innovation in Machining Technology (CANRIMT).

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CHAPTER 5 ARTICLE 3: THE USE OF TOPSIS METHOD FOR MULTI-OBJECTIVE OPTIMIZATION IN MILLING Ti-MMCS



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Received: 30 August 2022 / Revised: 3 October 2022 / Accepted: 19 October 2022 / Published: 24 October 2022

Abstract: This paper presents the use of TOPSIS, a multi-criteria decision-making model combined with the Taguchi method to find the optimum milling parameters. TOPSIS is the Technique for Order Preference by Similarity to the Ideal Solution and shows the value of closeness to the positive ideal solution. This study shows the optimum combination of process parameters using the shortest distance from the ideal solution. The surface roughness and flank tool wear were considered the objectives for simultaneous optimization. After converting multiple responses into a single response, the Taguchi method was used to analyze and determine the optimum machining parameters. According to reported studies, the initial wear behavior and initial cutting conditions have significant effects on the tool wear progress. Several initial cutting parameters can contribute to tool life and therefore can be used to improve both tool life and surface roughness. However, the cutting speed may significantly affect tool wear and ultimate tool life. In this study, an innovative solution was proposed for interrupted machining with two different cutting speeds. The first level cutting speed was used for 1 s and the second level was used for the rest of the process. The experimental results indicate that the initial speed and feed rate significantly affects tool life. In addition, using the proposed strategy with different levels of cutting speed during machining operations led to improved tool life and surface roughness compared to conventional machining with uniform cutting speed throughout the entire process.

Keywords: Ti-MMC, Machining, tool life, initial tool wear, cutting speed, optimization

5.1 Introduction

5.1.1 Background

Numerous studies and publications were reported on optimizing the cutting parameters and proposing the model for the relationship between cutting parameters and responses. Garg et al. [1] developed an empirical model that optimized machining parameters to minimize power consumption. They also studied the influence of machining parameters on energy consumption and their model reduced the power consumption of machine tools. Kant and Sangwan [2,3] developed a predictive and optimization model to predict the optimal value of machining parameters and minimize surface roughness. Their model was capable of determining the optimum machining parameters. Pusavec et al. [4] also studied the effects of the cutting process as inputs on the cutting forces, surface roughness, and tool wear. They also provided a chip breakability model in machining high-temperature Inconel 718. Their results showed a significant improvement in the machining process by optimizing parameters combined with sustainable alternative cooling and lubrication conditions.

Furthermore, several researchers have optimized cutting criteria, such as cutting forces, power consumption, surface roughness, and tool life. However, finding the optimal cutting parameters for certain objectives or responses requires machining knowledge and an adequate understanding of the relationship between the input parameters and the responses [5]. Although single-objective optimization has been broadly used, it has a major limitation when used in machining. It shows the optimum cutting parameters for a particular response and ignores the other objectives. However, unlike a single objective, in the multi-objective optimization method, all important objectives are simultaneously targeted by finding the optimum value of the input factors. Hence, a multi-objective method is more accurate and practical for this study. In 2016, Bilga et al. [6] reported the single-objective optimization of energy consumption for turning EN 353 alloy steel using the Taguchi method with Analysis of Variance (ANOVA). They optimized the cutting parameters individually for each response. The results show different optimum values in each case. One year later, Kumar et al. [7] repeated the similar work reported in [6] but for multi-response optimization, and optimized six responses using TOPSIS (Technique for Order Preference by Similarity to Ideal Solution). This approach was introduced by Hwang and Yoon in 1981 [8] to find the best

alternatives with the shortest separation from the positive ideal solution and farthest distance from the perfect negative solution. The method is thoroughly discussed in Section 4.

Multi-criteria decision making (MCDM) is a method that evaluates and addresses decision issues by combining the effects of each criterion for multiple decision criteria, resulting in an optimal solution. The application of MCDM methods in machining process improvement has steadily increased. In the literature [9], three main groups of MCDM methods are:

- Full aggregation methods, such as the analytic hierarchy process (AHP). This method assigns a weight to each criterion to show its importance. Then, the value of each alternative is determined and the highest positive value shows the best fit. The draw-back is the complexity and time-consuming process depending on the inputs' numbers.
- Outranking methods, such as the ELimination Et Choix Traduisant la REalité (ELECTRE). In this method, to rank the alternatives, each pair of alternatives is compared for each criterion. The drawback is that this method needs several technical parameters, which are sometimes complex and hard to understand.
- Goal, aspiration, or reference level methods, such as the TOPSIS method. The most significant advantage of this method is that it needs only a few inputs and its output is easy to understand. This makes the process pretty straightforward and comprehensible. This is the main reason for using TOPSIS for this study.

The responses found in [7] were power consumption, power factor, surface roughness, material removal rate, energy efficiency, and active energy consumption. Rao et al. [10] focused on the parametric optimization of cutting speed, feed rate, and cut depth in turning AA 6351 alloy using carbide tool. Their objective was to maximize the machining rate while minimizing surface roughness using the TOPSIS method. Their results showed a significant improvement for the responses. They found that the major process parameter affecting the multi-responses is cutting speed with a contribution of 38.68%. The contribution of feed rate was 34.51% and the depth of cut contribution was 21.91%. Mandal et al. [11] conducted several experiments to optimize electro-discharge machining using MOPSO_TOPSIS with four controlling components. They adopted Taguchi L9 orthogonal array for the experiments and TOPSIS to find the most desirable controlling parameters.

The Taguchi method is one of the most popular and powerful methods to analyze machining parameters and to determine the best process control factors. One of the main advantages of this method over the other methods is that more quantitative results can be obtained by performing less experiments, which also reduces the amount of experimentation and, consequently, the experimental costs. Taguchi's method is also pretty straight-forward and easy to apply to the machining process. However, it is a single-response optimization method and is not a proper method for simultaneously optimizing several responses. The other drawback of this method is that the results are strongly dependent on and relative to the number of input parameters and do not test all variable combinations. Despite these disadvantages, Taguchi's method is extremely useful for experimental design. Titanium-based metal matrix composites (Ti-MMCs) are relatively new materials for both industry and academia, and many uncertainties exist about the difficulties and restrictions in their production, formation, and machining. Therefore, an overview of the machinability attributes of MMCs is introduced in the following sections. High tool wear rate, short tool life, and poor surface quality are the main concerns in machining Ti-MMCs. Due to the very low thermal conductivity of Ti-MMCs, very high local temperatures are generated in a tiny area around the cutting edge, resulting in a high tool wear rate [12]. Indeed, flank wear is a major machining issue because of the hard and abrasive particles in Ti-MMCs. For the successful and high production of components made of Ti-MMCs, such as engine parts of airplanes or cars, sometimes having a suitable surface finish is more critical than machining costs. Theoretically, two factors can play the more important roles in surface roughness: feed rate and tool geometry [13]. However, the high affinity of almost all tool materials to Ti-MMC's matrix, especially at elevated temperatures in the tool-workpiece engagement, leads to a chemical reaction, material diffusion, and adhesion in the cutting tool [14]. Consequently, even at a high material removal rate (MRR), the chips cannot evacuate the massive thermal loads [15]. Moreover, the tool mostly slides more than cuts the workpiece at a low shear angle; therefore, similar to friction, the cutting zone temperature and pressure increase [16]. Then, the scraped materials melt and adhere to the tooltip. The hot adhered particles in the vicinity of oxygen turn into fragments, including titanium oxide and vanadium oxide [17]. It is worth mentioning that there are many studies [18] showing that the type of tool and its nose radius can impact the surface roughness. As a rule of thumb, when other factors, such as machining speed, work material, coolant, etc., are not taken into consideration, a larger nose radius results in better surface roughness. Liang et al. [19] studied the effect of the

welding thermal treatment on the microstructure and mechanical properties of nickel-based superalloy fabricated by selective laser melting. Their results quantified the respective contributions of the four conventional strengthening mechanisms. Zhong et al. [20] studied the microstructure and mechanical properties in the lap weld. They found that the number of cracks in the lap joint positively correlates with the size of the Ti_2Ni region of the brittle intermetallic compound. Usually, tool life is identified based on a typical tool wear curve versus cutting time. This curve shows three regions: the primary or initial, the steady state, and the accelerated wear period. Most of the research studies focus on the steady-state zone, which is more practical for traditional materials. However, due to the short tool lifetime, the initial moments of machining become more critical when it comes to difficult-to-cut materials. In other words, except for limited studies, the effects of the first moment of machining on tool life and initial tool wear mechanism have not been clearly determined and this field is open to more investigation. Amongst reported works, Troung [21,22] performed several experimental studies on the initial tool wear in the machining of Ti-MMCs and investigated the effect of the initial tool wear and initial cutting conditions on tool wear progression and tool life. Furthermore, the sensitivity of tool life to the initial cutting conditions was studied. It was exhibited that initial cutting conditions, such as initial speed, feed rate, and depth of cut within the first tool wear period improved tool life while turning Ti-MMCs. In addition, Troung [21,22] discovered a protective layer forming in the first stage of tool wear, which could influence tool life. This so-called brace shield is a protective layer for the steady wear region. The formation of the brace shield provides a better explanation for the tool wear rate during the first wear period due to the accelerated cutting force and temperature concentrated in a tiny area. Finally, he suggested a chaos theory to explain the formation mechanisms of wear-protective tribo-films. However, the formation mechanisms of the protective tribo-films are not yet fully understood due to the complex chemo-mechanical interactions at the contact region and the limited three-dimensional resolution of many typically used characterization methods. In 2019, Aramesh et al. [23] was granted a US patent on an ultra-soft cutting tool coating and coating method. The cutting tool contains a substrate with a cutting surface and an ultra soft coating adhered to the cutting surface in a solid state. This soft metal can melt and work as an in-place liquid lubricant. Their method also provides a practical way of shaping a tribo-film between the workpiece and the cutting tool. In two different studies, Abdelali, Beste, and colleagues [24,25] showed that when machining starts in a very short period, the cutting forces increase drastically

and, consequently, so does the friction between two new surfaces where the relative sliding speeds are close to zero. This leads to high stress in a small area at the tool–workpiece interface. This very rapid initial increase in the cutting forces, which results in an immediate increase in cutting temperature, happens within one second and is followed by a slow but constant rate of increase during the second wear period [26,27]. According to standard in machining Ti-MMCs, contact conditions, the interface between the tool and workpiece, and cutting temperatures are the most influential factors in the wear mechanisms [28]. In [28], with a speed of 90 m/min, feed rate 0.2 mm/rev, and depth of cut 150 μm , machining has the optimal conditions, meaning less tool wear and better surface roughness.

In contrast, Troung [29] found that at lower speeds, i.e., 50 m/min, tool wear is less than that at higher speeds. In addition, a new theory was presented to relate the initial moments of machining to the rest of the process. Still, some of the observations and conclusions made by the authors of [29], such as the initial wear mechanism, are dissimilar to observations made by Bejjani [28] and Aramesh [30]. Asgari et al. [31] observed that the carbide tools demonstrate an acceptable tool wear rate despite a bit of vibration during the milling of Ti-MMCs. Their study showed that the optimum machining parameters are: cutting speed (V_c) = 45 m/min, feed rate (f) = 0.2 mm/rev, and depth of cut (a_p) = 0.16 mm for the X500 carbide tool, and V_c = 70 m/min, f = 0.35 mm/rev, and a_p = 1.5 mm for the X400 carbide tool. Based on their results, cutting speed is the main factor influencing the tool wear rate for the PCD tool.

Finally, Kamalizadeh et al. [26] focused on initial tool wear in turning Ti-MMCs using carbide tools. It was observed that the first transition time within the tool wear curve occurs in the first second of machining. Furthermore, a favorable correlation was found between the transition time in tool wear progression charts and the cutting force diagrams. As noted in [26], the primary wear mechanism during the initial moments of machining Ti-MMC is abrasion and the dominant wear mechanism is adhesion. The literature allows us to state that few studies are available on Ti-MMCs, mainly when dealing with the milling of Ti-MMCs, which is more costly and complex than turning. Therefore, an adequate selection of optimal milling parameters has evolved.

5.1.2 Contribution of this Work

This paper presents a multi-objective optimization model to optimize the milling parameters in the milling process using the Technique for Order Preference by Similarity to the Ideal Solution

(TOPSIS). The surface roughness and flank tool wear were considered simultaneous optimization objectives. To the best of the authors' knowledge, the initial cutting speed and its effects on the tool wear morphology when machining Ti-MMC has not yet been studied and no work was observed by means of tool life improvement when changing cutting speed at initial moments of cutting operation. To that end, it was also noted that the use of the TOPSIS method in the machining of Ti-MMCs is relatively new as the authors did not find any study that used this model, neither for ranking machining parameters nor for multi-objective optimization of the machining process.

Experimental results confirm that the initial machining conditions significantly affect ultimate tool life. In addition, the significant effects of initial and secondary cutting speed on the tool wear progress and ultimate tool life were noticed. Moreover, the strategy of cutting with two different speeds, mainly the initial and the secondary cutting speed, improved wear rate by 105.5% and surface roughness by 143.2% compared to readings made in traditional machining with a constant cutting speed. The structure of the paper is as follows: Experimental methodology is described in Section 2. Then, the results and the approach used to convert multi-response into single response using TOPSIS and determine optimal cutting parameters using the Taguchi method are presented in Section 3. The next section presents a discussion of the results. Finally, conclusions are presented in Section 5.

5.2 Materials and Methods

This study presents a multi-objective optimization model to optimize the machining parameters in milling Ti-MMCs using carbide tools. Two surface roughness (R_a) and tool flank wear values were the main machinability attributes for optimization purposes. In addition, the initial cutting speed, secondary cutting speed, and feed rate were input parameters. TOPSIS is used to identify the optimal milling parameters. Furthermore, the Taguchi method was used to determine the optimum machining parameters after converting multiple responses into a single response. According to previous studies [22,26], the initial moments of machining and initial tool wear behavior significantly affected tool life. Hence, the initial condition strategies were applied for 1 s of machining. Furthermore, based on two studies performed in 2017 [26,29], this initial period was sufficient to see the positive value of a scattered wear exponent. However, these researchers also found that the wear rate at lower speeds is pretty constant during the steady wear period after only one second of machining time, especially when the protective layer, the so-called brace shield, is

shaped. Since not much data are available on proposed cutting process parameters for machining Ti-MMC, especially regarding the milling process, some main parameters governing other machinability attributes (in principle R_a) are unclear. Hence, the statistical tools and approaches were used in this study to assess the controllability of R_a and V_{Bmax} under various cutting conditions.

Machining Tests

Dry milling tests were conducted on a three-axis milling machine (Mitsui Seiki, Franklyn lakes, New Jersey, USA). The experiment setup is shown in Figure 5-1. A cubic shape of Ti-6Al-4V alloy matrix reinforced with at 10–12% volume fraction of TiC ceramic particles was used in this study. The elemental composition of Ti-MMC is shown in Table 5-1.

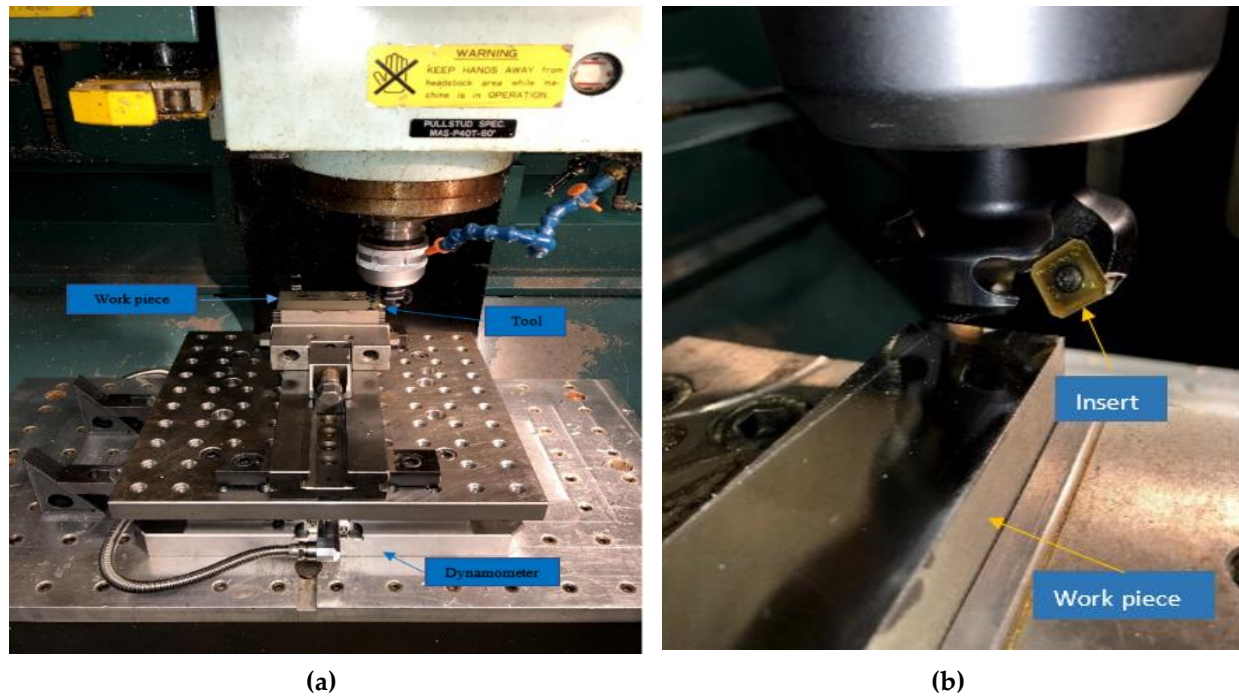


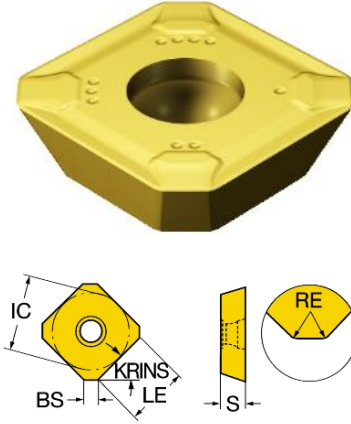
Figure 5-1: (a) Milling experimental setup and (b) the insert.

Table 5-1: Elemental composition of Ti-MMC [32].

Chemical Analysis of Ti-MMC	Aluminum (Al)	Vanadium (V)	Carbon (C)	Oxygen (O)	Iron (Fe)	Nitrogen (N)	Hydrogen (H)	Titanium (Ti)
Mass %	5.55	3.84	0.97	0.26	0.004	0.21	<0.003	Remainder (89.163)

CoroMill 245 TiAlN + TiN nano-laminate Physical Vapor Deposition (PVD) coated carbide grades (Sandvik R245-12 T3 K-MM 2030) was utilized for this study, as shown in Table 5-2. These tools can be used in the milling process of hard-to-cut alloys, such as Ti-MMCs, showing high levels of toughness and complex surface components, especially in the semi-finished process. In addition, a hard PVD deposited coating on the tool surface can decrease the abrasion wear mechanism and, at the same time, protect it from scratching and grooving by the work material's tough TiC particles. Moreover, the difference between the price of TiAlN+TiN PVD-coated tools and other superior tools, such as CBNs or diamonds, makes this type of tool an excellent candidate for experimental studies. However, the machining process used in this study should not be very long due to the high cost of the Ti-MMC sample. This may gradually increase the experiment's cost with less benefit.

Table 5-2: CoroMill 245 -12T3 carbide tool

CoroMill 245 PVD TiAlN+TiN	Insert Specifications
	Inscribed circle diameter (IC) 13.4 mm
	Cutting edge effective length (LE) 10 mm
	Insert rake angle (GAN) 15 degree
	Corner radius (RE) 1.5 mm
	Coating (COATING) PVD TiAlN+TiN
	Substrate (SUBSTRATE) HC (coated hard metal)

The work part surface roughness and tool flank wear were measured after each test using an optical microscope (Mitutoyo Corp., Tokyo, Japan) (Figure 5-2a) and a surface profilometer Mitutoyo SV-C4000 (Mitutoyo Corp., Tokyo, Japan) (Figure 5-2b).

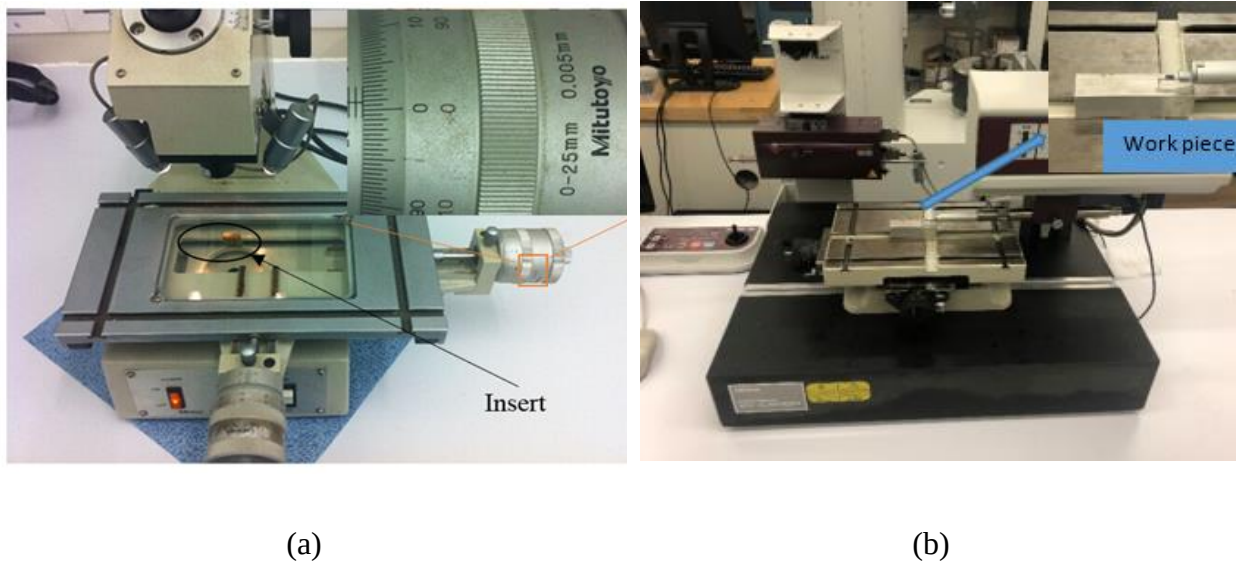


Figure 5-2: (a) Optical microscope (b) Profilometer Mitutoyo SV- C4000

The arithmetical mean roughness value R_a was used to characterize surface roughness (Figure 5-3). Tool wear was measured according to the ISO standard $V_{B \max}$ as a common quantitative parameter. To measure $V_{B \max}$ (Figure 5-4), the cutting tool worn-out length (b) was measured using a toolmaker optical microscope (Figure 5-2a) with a precise measurement of 0.005 mm. Then, near zone N (equal to $b/4$), the distance between the rake face and the end of the worn-out region, $V_{B \max}$, was measured.

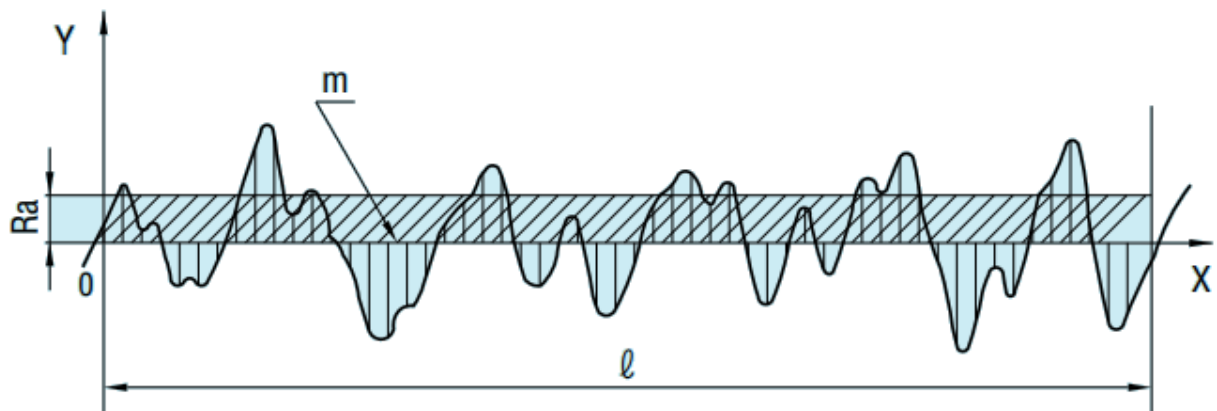


Figure 5-3: Mean roughness value R_a .

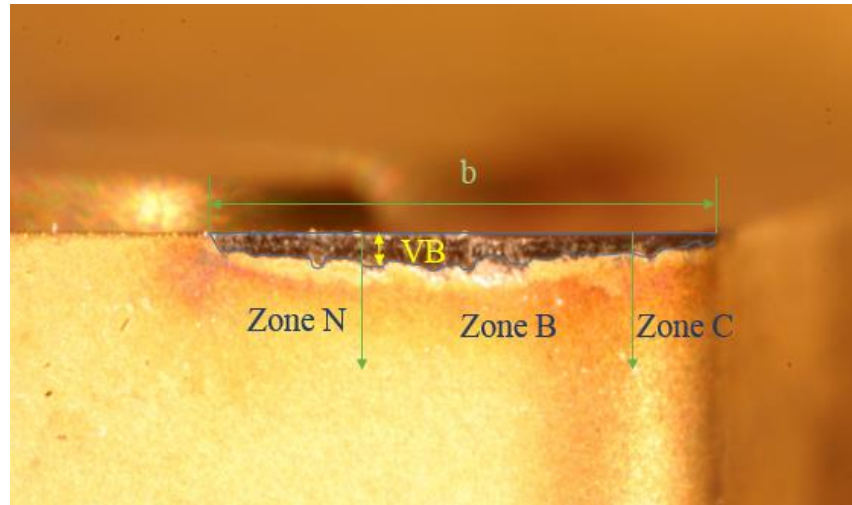


Figure 5-4: A typical tool wear, $V_{B \max}$ and different wear zones [26]

The smaller the R_a , the smoother the machined surface. For each insert, sequential milling tests were performed and $V_{B \max}$ and R_a were measured for each edge of the tool. In order to have very accurate results, each test was performed with a new and sharp edge of the insert, which amounted to a total of 4 tests for each insert. To avoid the effects of the previous cutting on the workpiece and tool elements, every new test was conducted using an unused edge of the tool. All tests were repeated two times to ensure that the tests were correctly carried out. For the surface roughness measurements, since our profilometer was placed in a temperature-controlled room and all measuring parameters are based on the ISO 4278 routine calibration procedure, these conditions guarantee the result accuracy.

A Kistler dynamometer was used to monitor and record the cutting force signals in three directions related to the thrust force (FR), feed force (FF), and cutting force (FC), as depicted in Figure 5-5b. The sampling frequency of 10,000 Hz was used to analyze the cutting force signals. The cutting forces were analyzed in both time and frequency domains to evaluate the machining tests' vibrational modes (chatter and forced) (Figure 5-5a). Minor tool vibration was observed in several tests, especially in those with higher levels of cutting speed (i.e., 80 m/min). However, despite vibration, the major difference in wear rate or surface roughness was not observed during the tests. No tool breakage was observed. Moreover, except in minor cases, an acceptable tool wear rate was observed in all cutting tests.

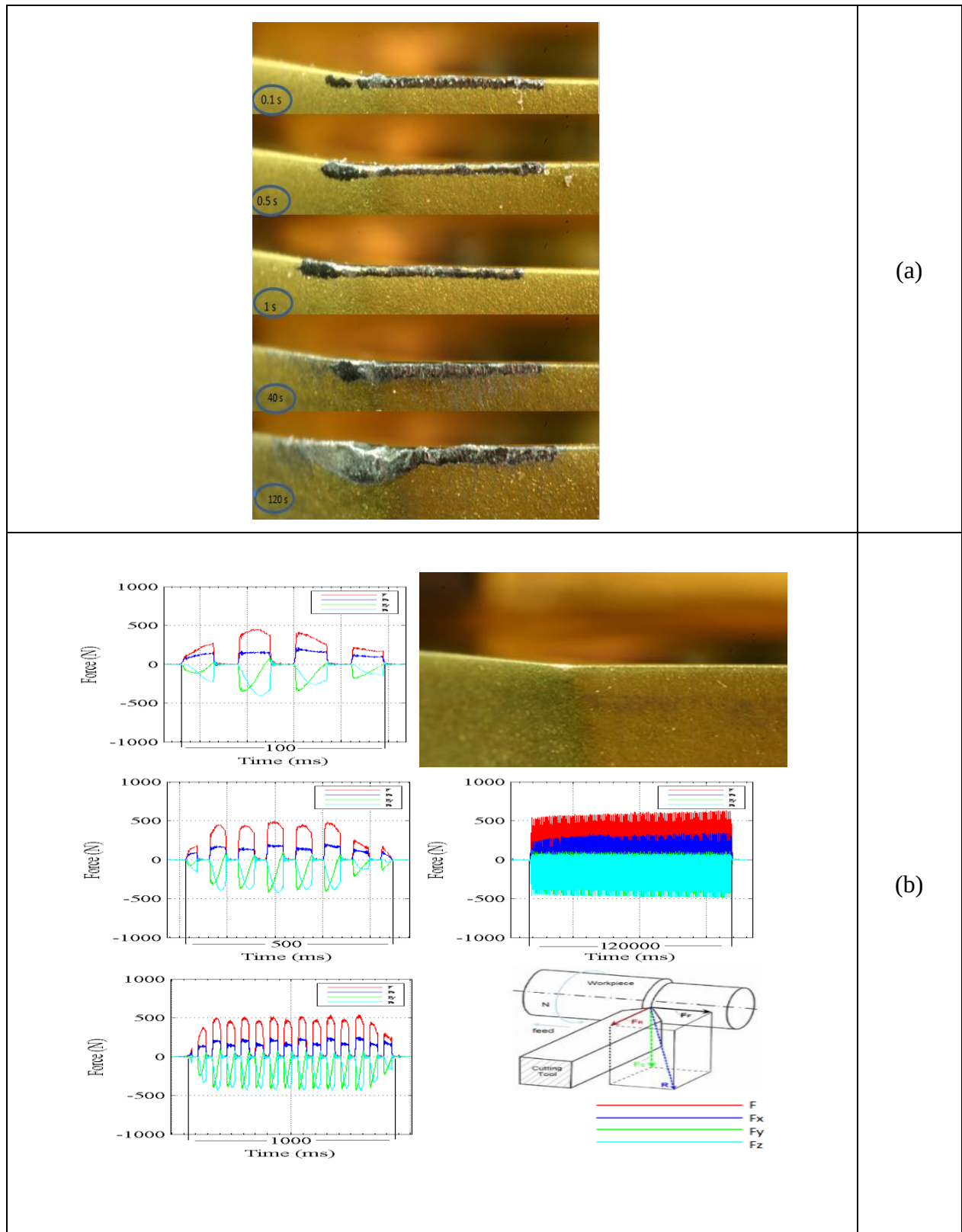


Figure 5-5: Tool wear after different moments of machining, b) corresponding captured cutting forces

5.3 Results

5.3.1 Cutting conditions and experimental results

According to previous studies, cutting speed and feed rate are the most crucial parameters in machining Ti-MMCs [21]. Therefore, in this study, to see the main effects of the initial cutting conditions on tool life, two different cutting speeds were used, including the initial speed for 1 s and the secondary cutting speed used in the rest of the machining operation. The constant cutting time of 120 s was selected based on previous studies [12]. According to preliminary investigations, it was found that severe tool wear occurs around this machining time, and flank tool wear passes 250 μm , which is considered a tool wear threshold. Various feed rates were also considered based on industrial recommendations, machine tool capacity, and previous studies. The proposed levels of feed rates are tabulated in Table 5-3. According to the proposed cutting speeds and feed rate levels, the experiments were designed as an L27 full factorial orthogonal array (shown in Table 5-4). Moreover, machining tests were conducted four times for each cutting condition to present a more accurate tool life curve and the average recorded values were considered for additional studies.

Table 5-3: Considered input cutting parameters

Levels /Parameters	Initial cutting speed V_1 (m/min)	Secondary cutting speed V_2 (m/min)	Feed rate f (mm/rev)
I	40	40	0.1
II	60	60	0.15
III	80	80	0.2

Table 5-4 also shows tool wear rates $V_{B \max}$ (μm) and surface roughness R_a (μm) under different cutting conditions. At certain level for the initial cutting speed V_1 , secondary cutting speed V_2 , and feed rate, the best conditions were obtained with acceptable productivity and cutting volume. Depth of cut was 0.2 mm.

Table 5-4: Input cutting parameters and their responses

Experimental Run	Experimental parameters			Responses	
	V ₁ (m/min)	V ₂ (m/min)	f (mm/rev)	R _a (μ m)	V _{B max} (μ m)
1	40	40	0.1	1.907	220.2
2	40	40	0.15	1.999	232.2
3	40	40	0.2	1.776	194.2
4	40	60	0.1	1.684	179
5	40	60	0.15	1.902	138
6	40	60	0.2	1.769	159
7	40	80	0.1	3.685	296.3
8	40	80	0.15	4.185	228.6
9	40	80	0.2	3.983	283.6
10	60	40	0.1	1.284	114.5
11	60	40	0.15	1.257	123.5
12	60	40	0.2	1.517	153
13	60	60	0.1	2.514	204.5
14	60	60	0.15	2.884	162
15	60	60	0.2	2.194	151.7
16	60	80	0.1	3.687	299.3
17	60	80	0.15	3.318	271.2
18	60	80	0.2	3.447	243.5
19	80	40	0.1	1.683	166.3
20	80	40	0.15	1.483	150.4
21	80	40	0.2	1.565	119.2
22	80	60	0.1	1.023	95.4
23	80	60	0.15	1.028	75.4
24	80	60	0.2	1.083	81.3
25	80	80	0.1	3.43	187.5
26	80	80	0.15	3.381	189.4
27	80	80	0.2	3.574	201.3

The cutting conditions were selected based on recommendations by the tool manufacturer. Machining tests were conducted several times for each cutting condition, and the average values of responses were used. This makes tool life curve more accurate. The statistical approach (i.e., TOPSIS and Taguchi) was used to define the factors governing flank wear of the tools $V_{B \max}$ and the surface roughness R_a of the machined parts. Due to the lack of space and technical scope of the presenting work, no comprehensive overview of statistical tools (mostly the Taguchi method) and analysis procedures based on statistical tools is presented in this work.

5.3.2 Conversion of multi responses into a single response using the TOPSIS method

This study used the TOPSIS approach to convert multiple responses into one. Then, the Taguchi method was used to optimize the objectives. The TOPSIS approach was introduced by Hwang and Yoon [8] in 1981 to find the best alternatives with the shortest separation from the positive ideal solution and farthest distance from the negative ideal solution. The following steps are commonly applied to transfer the multiple responses into a single response [33]:

Step 1:

In the first step, the experimental decision matrix (a_{ij}) which is usually called an “evaluation matrix” was created. In this matrix, each row (i) represents the alternative (experimental run number), and each column (j) represents the criteria (responses).

$$a_{ij} = \begin{bmatrix} a_{11} & a_{12} & a_{1j} & \cdots & a_{1m} \\ a_{21} & a_{22} & a_{2j} & & a_{2m} \\ a_{i1} & a_{i2} & a_{ij} & & a_{im} \\ \vdots & & \ddots & & \vdots \\ a_{n1} & a_{n2} & a_{nj} & \cdots & a_{nm} \end{bmatrix} \quad (1)$$

In this matrix for our case, i is the number of experiments that is 27, and j is the number of responses that is equal to two R_a and $V_{B \max}$. The experimental values listed in Table 5-4 were used for the experimental decision matrix a_{ij} elements as mentioned earlier in equation (1). All the calculations are also rounded up to four digits after the decimal.

Step 2:

In this step, the evaluation matrix was normalized. Therefore, the responses were normalized for a limit of 0-1. This is to put them on a simple scale and removes the variation of their measuring units. The higher its value, the better the metric. The following equation was used to obtain the normalized matrix α_{ij} and all the values are listed in Table 5-5.

$$\alpha_{ij} = \frac{a_{ij}}{\sqrt{\sum_{i=1}^n (a_{ij})^2}} \quad (2)$$

Step 3:

Now, the weighted normalized decision matrix (x_{ij}) was calculated by multiplying each normalized metric from step 2 by the assigned weight of their respective response (w_j). It should be noted that each criterion must have its weight, all of which sum up to one.

$$x_{ij} = \left[w_j \alpha_{ij} \right] \quad (3)$$

Both performance characteristics (responses) are considered equally important in this case. Hence, for each response, the relative weight of 0.5 is given and using equation (3), the weighted normalized matrix x_{ij} is calculated, which is shown in Table 5-5.

Table 5-5: Normalized, weighted values of the responses

Experimental Run	Normalized Value		Weighted normalized value	
	R_a (mm)	$V_{B \max}$ (mm)	R_a	$V_{B \max}$
1	0.1439418	0.220542	0.0719	0.1102
2	0.1508861	0.232561	0.0754	0.1162
3	0.1340538	0.194502	0.0670	0.0972
4	0.1271096	0.179278	0.0635	0.0896
5	0.1435644	0.138214	0.0717	0.0691
6	0.1335255	0.159247	0.0667	0.0796
7	0.2781466	0.029676	0.1390	0.1483
8	0.0315887	0.228955	0.1579	0.1144
9	0.3006399	0.028404	0.1503	0.1420
10	0.0969173	0.114678	0.0484	0.0573

11	0.0948793	0.123692	0.0474	0.0618
2	0.1145043	0.153238	0.0572	0.0766
13	0.1897587	0.204818	0.0948	0.1024
14	0.2176865	0.162252	0.1088	0.0811
15	0.1656048	0.151936	0.0828	0.0759
16	0.2782976	0.299765	0.1391	0.1498
17	0.2504452	0.271621	0.1252	0.1358
18	0.2601822	0.243878	0.1300	0.1219
19	0.1270341	0.166558	0.0635	0.0832
20	0.0111938	0.150634	0.0559	0.0753
21	0.1181274	0.119385	0.0590	0.0596
22	0.0772168	0.075517	0.0386	0.0377
23	0.0775942	0.079724	0.0387	0.0398
24	0.0817457	0.081426	0.0408	0.0407
25	0.0258899	0.187791	0.1294	0.0938
26	0.2552005	0.189694	0.1276	0.0948
27	0.2697683	0.201613	0.1348	0.1008

Step 4:

In this step, the ideal positive (best) (x_j^b) and ideal negative (worst) (x_j^w) alternative for each criterion (response) were gained by using equations (4) and (5). The idea is to find the maximum and minimum value of each metric. In all cases, surface roughness and flank tool wear are best when minimum meaning the smallest is the best.

$$x_j^b = \{ \sum_i^{max} x_{ij} / j \in L, \sum_i^{min} x_{ij} / j \in L', i = 1, 2, 3, \dots, 27 \} \quad (4)$$

$$x_j^w = \{ \sum_i^{min} x_{ij} / j \in L, \sum_i^{max} x_{ij} / j \in L', i = 1, 2, 3, \dots, 27 \} \quad (5)$$

In these equations, L , ($l = 1, 2, 3, \dots, 27$) | l was linked to beneficial characteristics or positive impact. L' , ($l = 1, 2, 3, \dots, 27$) | l was linked to non-beneficial characteristics or negative impact. In this work, the values of (x_j^b) and (x_j^w) for surface roughness are 0.0386 and 0.1579, whereas (x_j^b) and (x_j^w) for flank tool wear are 0.0377 and 0.1498, respectively.

Step 5:

In this step, the Euclidean geometric distance between the target alternative and the best/worst alternatives (d_i^b, d_i^w) was calculated amongst all for the ideal positive (x_j^b) and ideal negative (x_j^w) using equations (6) and (7).

$$d_i^b = \sqrt{\sum_{j=1}^N (x_{ij} - x_j^b)^2} \quad (6)$$

$$d_i^w = \sqrt{\sum_{j=1}^N (x_{ij} - x_j^w)^2} \quad (7)$$

In our case:

$$d_i^b = \sqrt{\sum_{j=1}^{27} (x_{ij} - x_j^b)^2} \quad (i=1, 2, \dots, 27)$$

$$d_i^w = \sqrt{\sum_{j=1}^{27} (x_{ij} - x_j^w)^2} \quad (i=1, 2, \dots, 27)$$

In Table 5-6, the values of separation measures (d_i^b) and (d_i^w) are shown. The values of (d_i^b) and (d_i^w) were calculated using equations (6) and (7) values of the (x_j^b) and (x_j^w), which were estimated in the previous step.

Table 5-6: Separation measures, closeness coefficient, and signal-to-noise ratios

Experimental Run	Separation measures		Closeness coefficient	Signal-to-noise ratio
	d_i^b	d_i^w	s_i	S/N
1	0.0796	0.0947	0.5431	-5.302
2	0.0865	0.0891	0.5072	-5.8952
3	0.0658	0.1051	0.6149	-4.22267
4	0.0574	0.1120	0.6610	-3.5956
5	0.0455	0.1181	0.7216	-2.83334
6	0.0503	0.1151	0.6957	-3.15058
7	0.1492	0.0189	0.1126	-18.9671
8	0.1417	0.0355	0.2005	-13.9564

9	0.1526	0.0110	0.0677	-23.3833
10	0.0218	0.1434	0.8677	-1.23165
11	0.0255	0.1413	0.8467	-1.44461
2	0.0430	0.1245	0.7433	-2.57565
13	0.0856	0.0790	0.4800	-6.37498
14	0.0824	0.0845	0.5062	-5.91241
15	0.0583	0.1054	0.6438	-3.82474
16	0.1504	0.0187	0.1110	-19.0889
17	0.1306	0.0356	0.2145	-13.3704
18	0.1242	0.0395	0.2416	-12.3371
19	0.0517	0.1156	0.6906	-3.21494
20	0.0412	0.1263	0.7537	-2.45495
21	0.0299	0.1338	0.8172	-1.75247
22	0.0099	0.1571	0.9404	-0.53337
23	0.0001	0.1636	0.9988	-0.01039
24	0.0036	0.1601	0.9775	-0.19727
25	0.1067	0.0629	0.3709	-8.6133
26	0.1056	0.0629	0.3733	-8.55673
27	0.1150	0.0543	0.3209	-9.87205

Step 6:

In this step, for each alternative, the similarity to the ideal solution, the closeness coefficients (s_i), was calculated using the equation (8). The obtained results are TOPSIS scores, which are shown in Table 5-6.

$$s_i = \frac{d_i^w}{d_i^w + d_i^b} \quad (8)$$

Now, the closeness coefficient (s_i) represents a single response by converting the two responses (i.e. surface roughness and flank tool wear) into a single response. This will be used for further analysis as a single objective function in the Taguchi method.

Step 7:

Finally, it is required to rank alternatives according to the TOPSIS score in descending order. The metrics closest to the best obtain the highest score and consequently will be higher in our ranking. Now, a ranked set of alternatives based on specified criteria is shown in Table 5-7.

Table 5-7: Responses for signal-to-noise ratios (larger is better)

Level	V ₁	V ₂	f
1	-9.034	-3.122	-7.436
2	-7.351	-2.937	-6.048
3	-3.912	-14.238	-6.813
Delta	5.122	11.301	1.387
Rank	2	1	3

5.3.3 Determination of optimum cutting parameters using Taguchi approach

After converting multiple responses into a single response, the Taguchi method was used to determine the optimum machining parameters.

Minitab 19 was used to calculate the signal-to-noise ratios of the closeness coefficients. S/N results are listed in Table 5-6. The larger value of closeness coefficients means the least distance from the ideal outcome; thus, the maximization (the larger is better attribute) of the closeness coefficient (s_i) is considered to determine S/N via the Taguchi method (larger is better). The S/N ratio is calculated from Equation (9):

$$S/N = -10\left(\frac{1}{x}\right)\log_{10} \sum_1^x \frac{1}{Y_{ij}^2} \quad (9)$$

where x is the number of replications and Y_{ij} is the measured observations.

Table 5-7 shows the responses for signal-to-noise ratio for the larger is better condition. As can be seen in this table, V_2 has the highest value and is the most significant factor for the signal-to-noise ratios. However, more importantly, V_1 has a higher value and impact on the process than the feed rate. As per previous studies [34], feed rate has a higher effect on cutting forces and less effect on surface roughness in the milling of titanium alloys. However, cutting speed has a higher effect on temperature. This aligns with our results: ranking feed rate is the less important machining

parameter among all the inputs. Delta in Table 5-7 is the difference between the highest and lowest average response values for each factor.

5.4 Discussion

As mentioned earlier, high tool wear rate, short tool life, and poor surface quality are some major issues in machining Ti-MMCs. In addition, the very low thermal conductivity of Ti-MMCs results in very high local temperatures in a small area around the cutting edge, causing a high tool wear rate. This is escalated by tough and abrasive TiC particles dispersed in Ti-MMC, resulting in scratching and grooving of the cutting tools. All of these factors result in a non-linear tool wear rate with three distinctive periods: initial, steady, and accelerated wear (Figure 5-6a):

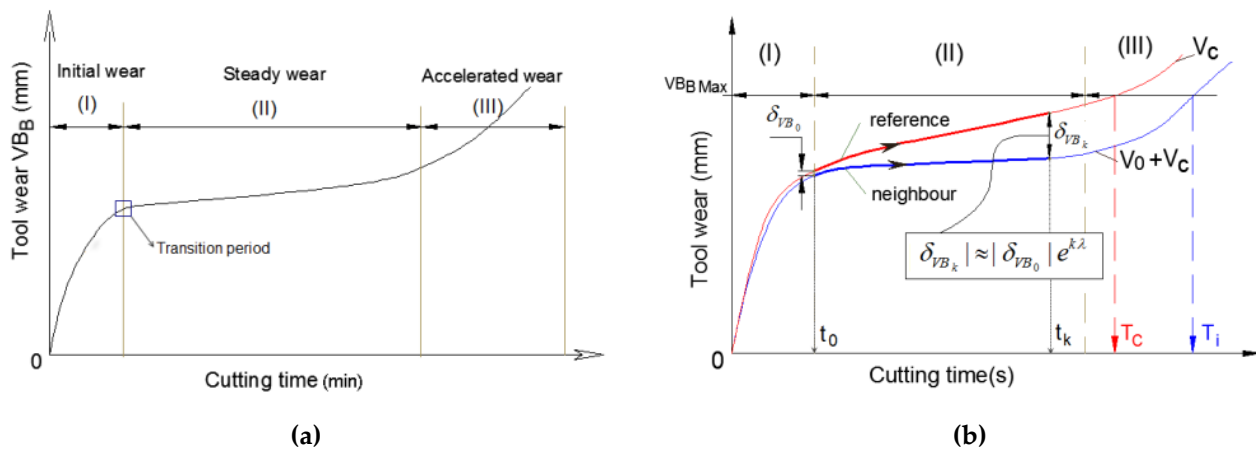


Figure 5-6: (a) Three distinctive tool wear periods; (b) chaos theory: a small change in the initial period can result in a big change in the entire process [21].

As shown in Figure 5-6b, a slight change in the initial period can significantly change the entire process. This is the foundation of the methodology of this experimental research. Our results show that the initial cutting speed is one of the most critical factors affecting the wear rate and surface roughness over time. This would align with the previous studies [21,35] and a related patent [23], proposing that a protection layer during initial machining is shaped and protects the tool from severe damage and adhesion. In other words, forming a brace shield or a protection layer in the first second of machining is the answer to why tool wear and surface roughness are low with two different cutting speed strategies.

In Figure 5-7, the mean S/N ratios of the corresponding machining parameter levels for the closeness coefficient (s_i) is presented. In the main effect plots, when the line is parallel to the x-

axis (horizontal), there is not any main effect and the effects of each factor are the same. However, when the line is not horizontal, the effects of each input factor are different and the sharper the slope, the higher magnitude of the main effect. Based on the Taguchi approach, each level of the machining parameters related to the maximum means of the S/N ratios is taken as the optimum setting of the input parameters. As seen in Figure 5-7, the values of the optimum cutting parameters are identified as the levels (V_1 – V_2 – f) and their respective values are $V_1 = 80$ m/min, $V_2 = 60$ m/min, and $f = 0.15$ mm/rev. As shown in this plot, with increasing initial speed V_1 from 40 to 80 m/min, S/N increases. However, increasing the secondary speed (V_2) from 40 to 60 m/min increases S/N and from 60 to 80 m/min decreases S/N . Similarly, with an increasing feed rate from 0.1 to 0.15 mm/rev, S/N increases, and from 0.15 to 0.20 mm/rev, S/N decreases. These results align with other studies [26,29], showing that feed rate affects tool wear less than surface finish. Moreover, a high feed rate can decrease tool wear because of the better heat transfer from the cutting zone to the workpiece.

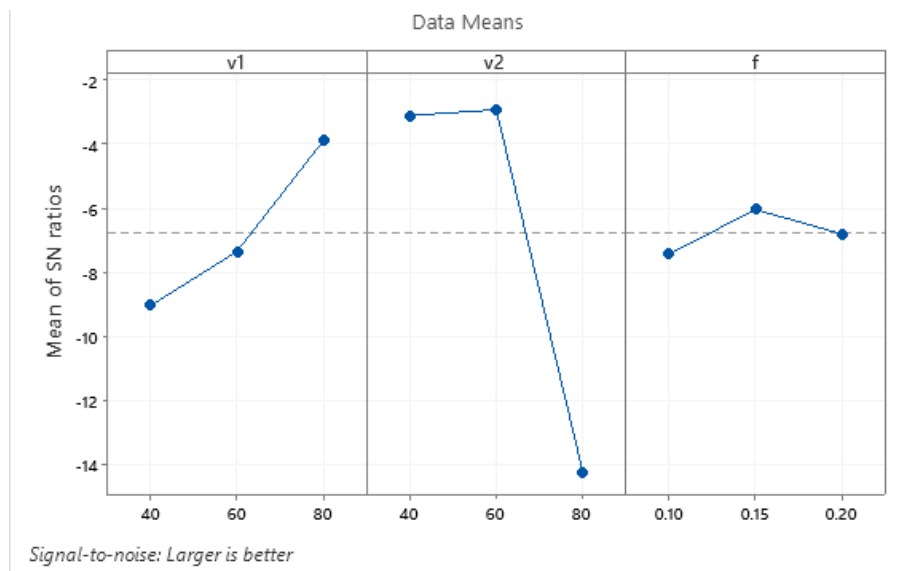


Figure 5-7: Main effects plot for signal-to-noise ratio (S/N) for closeness coefficients

Probability Plots

The probability plot (Figure 5-8) shows the distribution of experimental data, as previously presented in Table 5-4 also shows tool wear rates VB_{max} (μm) and surface roughness R_a (μm) under different cutting conditions. At certain level for the initial cutting speed V_1 , secondary

cutting speed V2, and feed rate, the best conditions were obtained with acceptable productivity and cutting volume. The Anderson Darling Test (ADT) is a standard statistical tool to validate the normality of assumptions. It shows and detects the outlier from normality [36,37]. The probability plot in Figure 5-8 confirms that the experimental data for all responses fall near the fitted line and the ADT static values are relatively low (0.361). Furthermore, the p -value (0.422) of the test is also greater than 0.05, meaning that deviation from the null hypothesis is not notable, and the null hypothesis is not rejected. Therefore, it is assumed that the experimental data align with normal distribution and confirm that the study is on the right track.

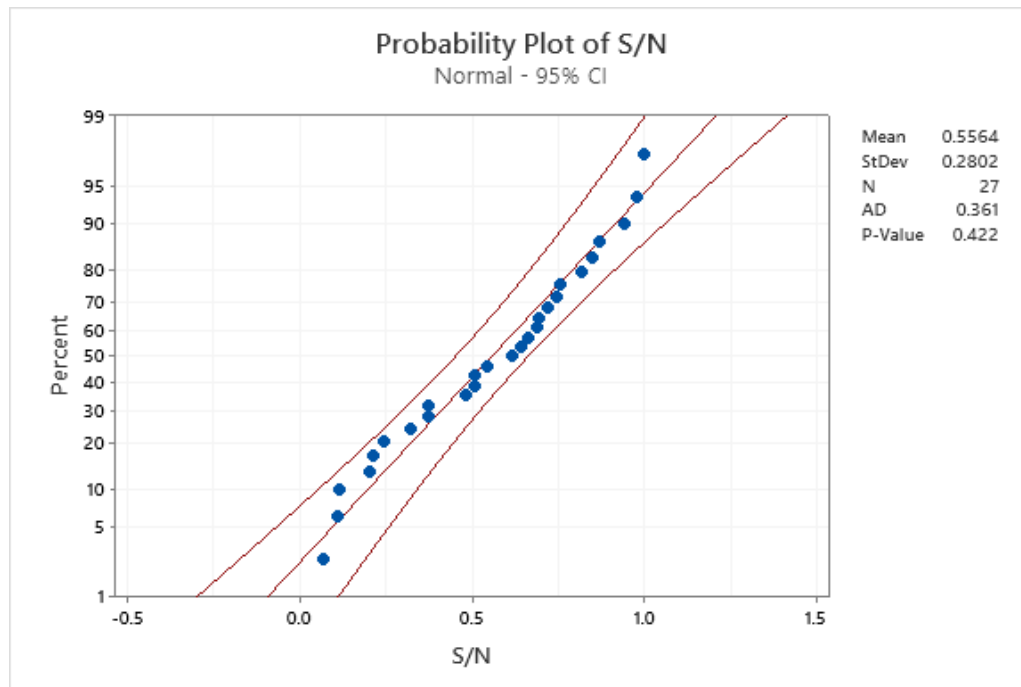


Figure 5-8: Probability plot of S/N, data points (blue dots) are relatively close to fitted normal distribution lines

Figure 5-9 shows the tool wear curves for all 27 cutting conditions. As can be seen, initial cutting speed can significantly affect the tool wear rate. The average of the three lowest tool wear amounts (84.03 μm) is with an initial cutting speed of 80 m/min, secondary cutting speed of 60 m/min, and different feed rates. Traditional machining with 60 mm/min speed and different feed rates has an average tool wear of 172.73 μm . Hence, the strategy of cutting with two different speeds, initial and secondary, can improve tool wear rate by 51.3% compared to traditional machining with a constant cutting speed. Figure 5-10 also shows the surface roughness results for all 27 cutting conditions. As can be seen, initial cutting speed can also significantly affect surface roughness. The

average of the three lowest surface roughness amounts is $1.04 \mu\text{m}$, with an initial cutting speed of 80 m/min, secondary cutting speed of 60 m/min, and different feed rates.

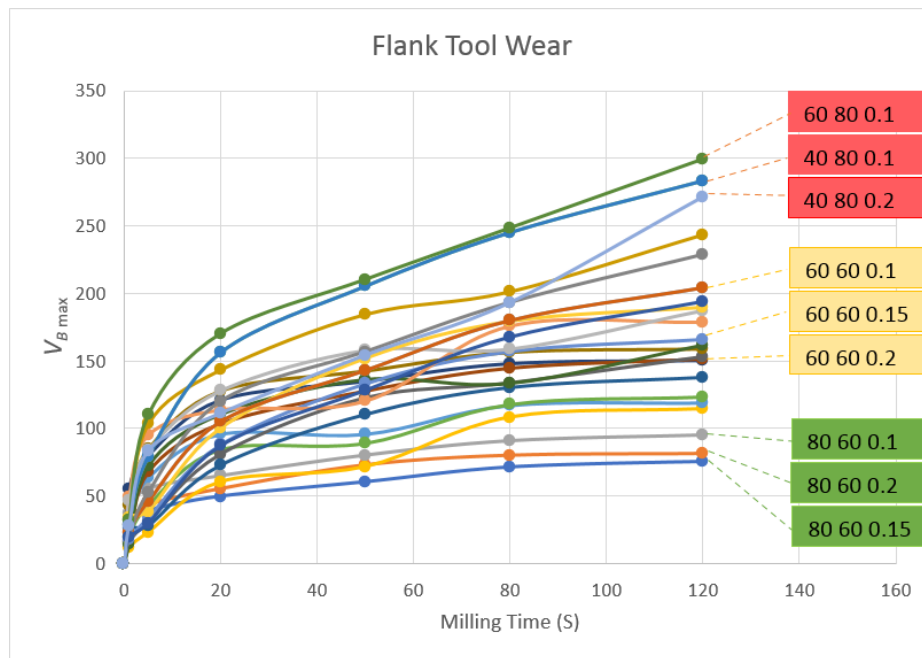


Figure 5-9: Tool wear curves for different cutting conditions

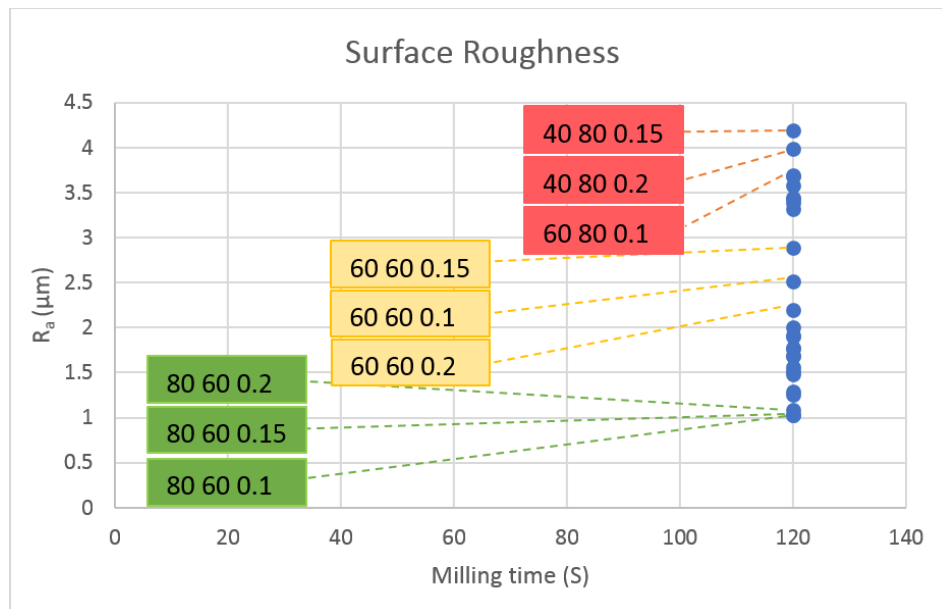


Figure 5-10: The recorded values of surface roughness under different cutting conditions

Regular machining with 60 m/min speed and different feed rates has an average surface roughness of $2.53 \mu\text{m}$. Hence, the strategy of cutting with two different speeds, initial and secondary can

improve surface roughness by 58.9% compared to regular machining. Additionally, based on the optimization results, $V_1 = 80$ m/min, $V_2 = 60$ m/min, and $f = 0.15$ mm/rev are the optimal cutting conditions. It is worth mentioning that the highest tool wear rate is for the secondary cutting speed of 80 m/min and feed rate of 0.1 mm/rev. However, a low initial cutting speed V_1 (40 m/min) places two of the experiments among the three highest tool wear rates. Furthermore, the recorded value of surface roughness amount at an initial cutting speed of 40 mm/min, the secondary cutting speed of 80 m/min, and feed rate of 0.15 mm/rev is the highest amount and is similar to tool wear. Low initial cutting speed places two cutting conditions in the highest amounts for surface roughness.

5.5 Conclusions

This study provides a reliable and structured approach to secure a multi-objective optimization model using the TOPSIS method. The proposed approach led to optimized flank tool wear $V_{B \max}$ and surface roughness R_a when milling Ti-MMC. The Taguchi method was used to determine the optimum machining parameters. A L_{27} full factorial orthogonal array was selected to cover an extensive range of the observed input parameters.

During this work, and within each experimental test, a constant feed rate and different cutting speeds (mainly, initial speed for 1 s (V_1) and the secondary (V_2) cutting speed for the rest of the machining operation for 120 seconds, were used. Flank tool wear $V_{B \max}$ and surface roughness R_a were the responses. By changing the initial cutting condition for the first second of machining, tool life and surface roughness were improved in all cases of the proposed strategies. It was also found that the values of the optimum cutting parameters are identified as the levels ($V_1 - V_2 - f$) and their respective values are $V_1 = 80$ m/min, $V_2 = 60$ m/min, and $f = 0.15$ mm/rev. Moreover, based on the signal-to-noise ratio responses, V_2 has the highest impact on the responses and V_1 has the second highest impact, meaning it has a higher impact than even the feed rate. Moreover, the strategy of cutting with two different speeds, mainly the initial and the secondary cutting speed, improved wear rate by 51.3% and surface roughness by 58.9% compared to readings made in traditional machining with a constant cutting speed. The observations made in this work align with previous studies on forming a brace shield at the very first moments of machining, acting as a protection layer.

Experimental results confirm that the initial machining conditions significantly affect ultimate tool life. In addition, the significant effects of the initial and secondary cutting speed on the tool wear

progress and ultimate tool life were noticed. One of the limitations of the applied methodology is the Taguchi method used to analyze and determine the optimum machining parameters. As mentioned earlier, a L_{27} full factorial orthogonal array was selected. Therefore, the results are strongly dependent upon the number of the input parameters and do not test all variable combinations. The other limitations are the effects of other machining parameters, such as depth of cut, which has not been studied in this paper. This would be another topic for future work.

Author Contributions: Validation, S.K.; formal analysis, S.K.; investigation, S.K.; writing—original draft preparation, S.K.; writing—review and editing, S.A.N., S.T., and M.B.; supervision and writing—review and editing, S.A.N., S.T., and M.B. All authors have read and agreed to the published version of the manuscript.

Data Availability Statement: Data sharing is not applicable.

Acknowledgments: The authors would like to appreciate the financial support received from the Natural Sciences and Engineering Research Council of Canada (NSERC) and NSERC Canadian Network for Research and Innovation in Machining Technology Network (CANRIMT).

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study, in the collection, analyzes, or interpretation of data, in the writing of the manuscript, or in the decision to publish the results.

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CHAPTER 6 GENERAL DISCUSSION

This section provides a general discussion of the thesis in light of what has been learned. In addition, some unsuccessful approaches are presented in the thesis, which is not involved in the published articles. Next is a summary of the scientific results of the research. Then, there is a discussion of how the proposed approaches in this thesis contributed to tool life and surface roughness improvement during the machining of Ti-MMCs. Finally, some limitations of the work. A complementary analysis was also performed to find the optimum cutting conditions, which resulted in minimum tool wear and surface roughness while keeping the efficiency high. The input parameters were cutting speed, feed rate, and depth of cut. The response parameters were the surface roughness and the tool wear rate. The TOPSIS and Taguchi methods fit the model to the response parameters. This was an innovative multi-objective optimization, and for the first time, initial speed was used as one of the optimization inputs. This has not been done on this material before. Thus, this information could be considered precious data for manufacturers.

6.1 Guiding principles

Due to the direct effects of tool wear on the tool life and, therefore, machining costs, the primary purpose of this study was to carry out some experimental tests and deeply characterize the different aspects of machining of Ti-MMCs. As mentioned in the introduction, high tool wear rate, short tool life, and poor surface quality are major issues in machining Ti-MMCs. In addition, the very low thermal conductivity of Ti-MMCs results in very high local temperatures in a small area around the cutting edge, causing a high tool wear rate. This is escalated by tough and abrasive TiC particles dispersed in Ti-MMC, resulting in scratching and grooving of the cutting tools. These factors result in a non-linear tool wear rate with three distinctive periods: initial, steady, and accelerated (Figure 6-1).

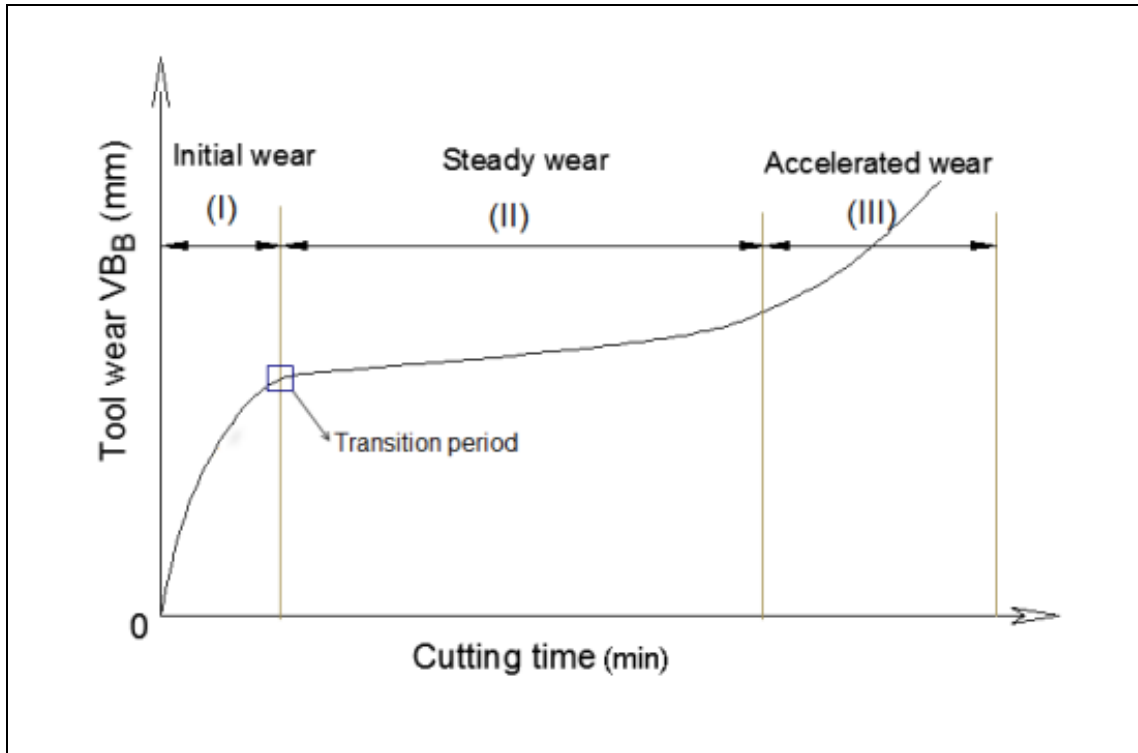


Figure 6-1: Three distinctive tool wear periods [11]

Although cutting speed is believed to be the principal affecting cutting parameters on complete tool life, the cutting parameters' influences were also investigated. Based on previous research [11, 14], a brace shield, or protective layer is formed during the initial moments of the machining. It reduces the friction and, consequently, the cutting force. We can see that this is a beneficial material to use, and we can get a lot longer tool life. Therefore, the right conditions to form and engineer a protective layer can result in better tool life and less machining costs. The outcome would be a tool with the best optimization and productivity achieved. Thus, the self-generation of that protective film becomes beneficial. A built-up edge is generally avoidable by running at a reasonable speed, but sticking is still one of the major wear mechanisms, even at higher speeds.

6.2 An unsuccessful approach

Throughout the work leading to this thesis, an unsuccessful approach was attempted. This approach used tomography to see and analyze different layers of the worn-out region. The strategy and method that were used are explained here.

Tomography

Early in the research, to analyze the tool wear region and characterize the wear profile, a computerized tomography (CT) scan was carried out (Figure 6-2).

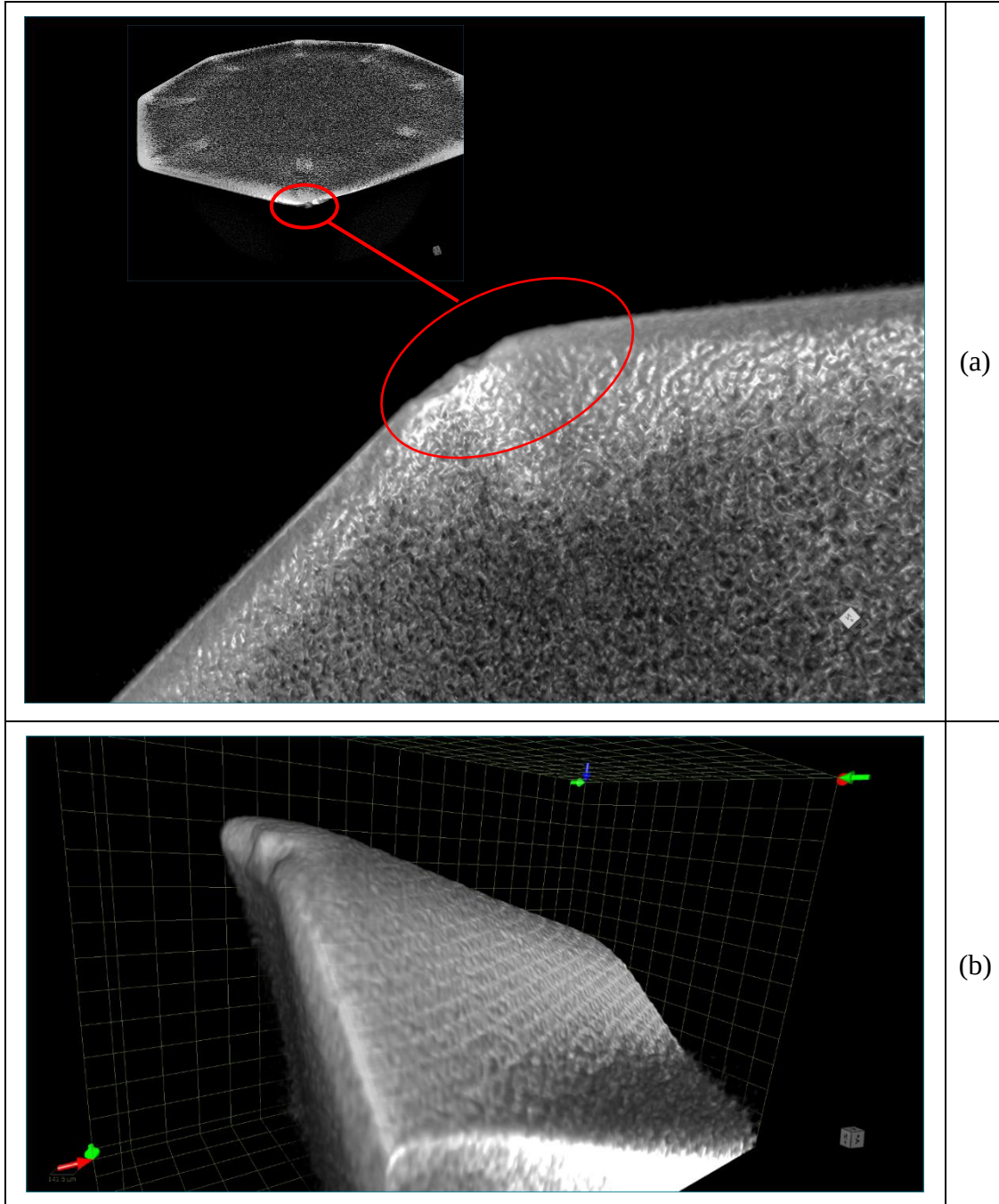


Figure 6-2: (a) Tool wear region and wear profile characterization using CT scan (b) another view of the wear region

X-ray computed tomography (CT) is a non-destructive testing method that can effectively inspect volume defects and complex geometry inside a part. With CT we can inspect local defects near the surface and a part's external surface. The objective of using CT was to inspect the different layers near the surface and ideally see a tribological or so-called protective layer [21].

As the first attempt, unfortunately, the results were not as expected. The tool density was too high, and the X-ray could not penetrate the surface. There is always the problem with the lack of penetration of the sample. The density seems to be problematic for such samples.

6.3 Confocal microscopy

Confocal Laser Scanning Microscopy (CLSM) was applied to increase the worn-out region's optical resolution and contrast. Optical sectioning captures multiple two-dimensional pictures at different depths of the workpiece surface, and three-dimensional structures are reconstructed. The idea is to determine and measure the amount of adhered work material layers onto the tool surface and see their form. The edge of the tool and the region with some built-up materials are shown in Figure 6-3a.

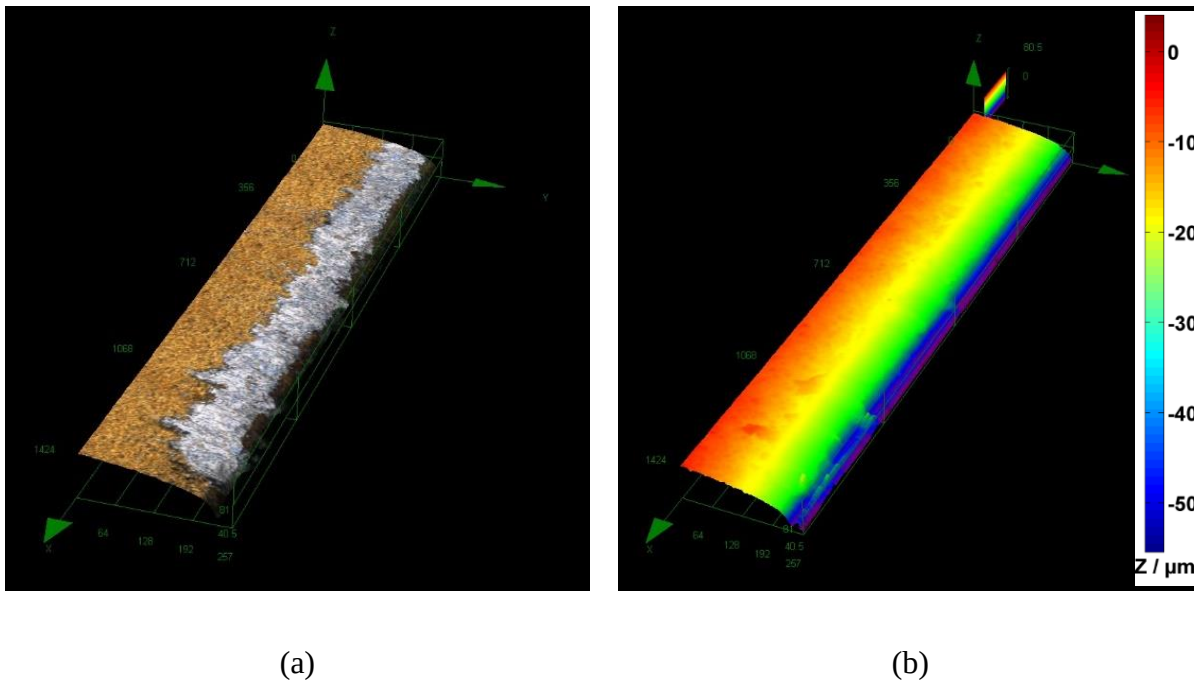


Figure 6-3: (a) An image of the worn-out zone using CLSM (b) a colored 3D profile of cutting edge and worn-out region

With these preliminary results, the adhered layer was observed on the surface.

6.4 Main discussion

Phase I

The first phase of this project's goal was to characterize tool wear in Ti-MMC high-speed milling with carbides. Initially, we conducted several preliminary experimental tests in order to provide practical and optimal cutting parameters for Ti-MMC machining. Because this material is commonly manufactured close to the net shape, the finishing operation is being investigated. The data obtained from the machining tests were then analyzed. Then, we ran our experiments at very low speeds to better understand how that built-up edge forms and behaves during the tests. The following step was to investigate the morphology and composition of various elements on the tool surface area. Severe tool vibration was observed in several tests, particularly those with higher feed rate and cutting speed levels. Despite the monitored vibration, however, a high wear rate was only observed in two individual tests. Nonetheless, acceptable tool wear was observed in all cutting tests, with some exceptions.

In contrast, no specific failure, in principle, tool breakage or chatter vibration, was observed when the carbide tool X500 was used. The most significant influences on tool wear rate are cutting speed and depth of cut, while feed rate has no statistically significant effects on tool wear rate. This could be attributed to the severe effects of cutting speed on the temperature generated within the cutting zone, which directly increases tool wear rate. Because of several interrupted cutting tests, no statistical analysis was performed to assess the sensitivity of machining responses to cutting parameter variation when using carbide tool X400. These findings could have helped us to improve tool life by better understanding the initial moments and their effects on the entire milling process of Ti-MMCs.

6.4.1 Face milling tests with carbide tools

SEM/EDS analysis was performed to better understand the morphology and composition of various elements surrounding the workpiece/tool interaction area. The SEM micrograph shows that the deposited materials smear on the flank face and that the thinly deposited layer resembles spread butter. Figure 6-4c depicts the chemical compositions of the worn flank face detected by EDS. The

presence of vanadium (V) in the elements deposited in zone 1 (Figure 6-4a) indicates that the Ti-6Al-4V transferred from the work-piece material has an adhesion mechanism. The high strain-hardening coefficient and heat resistance of Ti-MMCs are thought to cause a significant colour change around the tool-workpiece interaction area (Figure 6-4a). When exposed to oxygen, the elevated temperature produced during machining causes titanium to oxidize outside the tool/chip contact region (Figure 6-4c). As a result, oxidation is proposed as a secondary wear mechanism during machining.

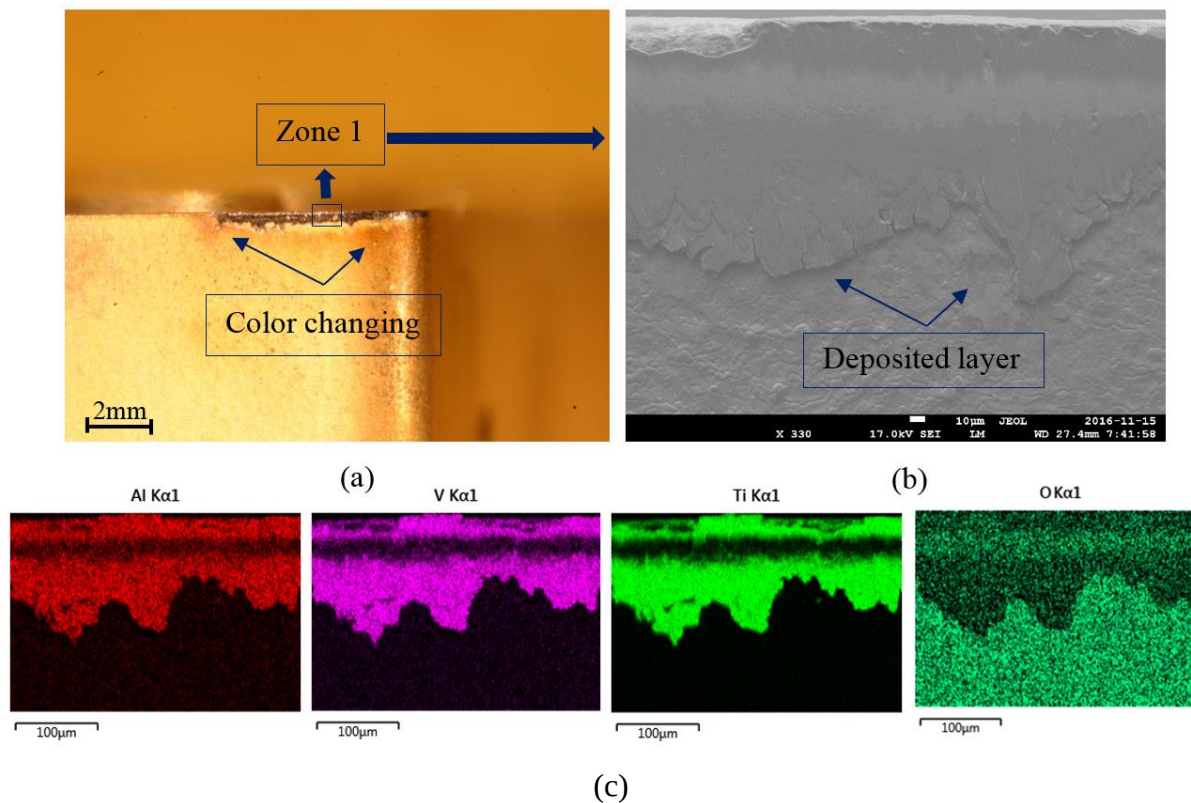


Figure 6-4: a) X500 Carbide tool wear in milling of Ti-MMC with $V_c = 95$ m/min; $f_r = 0.1$ mm/rev; $a_p = 1.6$ mm b) SEM micrograph of flank face, and deposited layer observed on flank face near the nose with the appearance of spread butter (c) EDS elemental mapping analysis of SEM micrograph

6.4.2 Face milling tests with PCD tools

The final round of face milling tests was carried out with the previously mentioned PCD tools. Unfortunately, no systematic database of allowable cutting parameter levels for milling Ti-MMC with PCD tools exists. Tool breakage occurred during milling tests with PCD tools at high cutting

speeds (350-600 m/min). As a result, lower levels of cutting speed were used in subsequent tests, with satisfactory results. Nonetheless, acceptable tool wear rate was observed at low levels of depth of cut and speed and high levels of feed rate. Generally, at low cutting speeds, the matrix behaviour and hydrostatic pressure of the cutting edge provide enough hardness to prevent abrasion and resist deflection forces. The experiments demonstrated that interaction effects between cutting parameters highly control surface roughness variation in milling with PCD tools. Unlike the surface roughness results, the cutting speed has the most significant effect on the tool wear rate, followed by the depth of cut. Furthermore, the findings of this study revealed that variation in process parameters, particularly cutting speed, strongly influences tool wear rate. This could be attributed to the intense effects of high-speed machining, which raises the temperature in the cutting zone and at the tool-work part interface, reducing tool life. It was also noticed that an acceptable tool wear rate can be observed at very low depths of cut and high feed rates. Furthermore, the optimum cutting volume and productivity values were achieved at a specific cutting speed under a constant depth of cut (0.05 mm). Promising tool wear rates were also observed at low cutting speeds and high cutting feed rates. Despite chatter vibration in cutting tests, high wear rates were only observed in two tests.

Edge chipping was observed after two minutes of machining. This could be due to the workpiece material's hard TiC particles and the high hardness of PCD tools. The presence of Ti, N, Al, V, and Co elements is demonstrated by line scan analysis. The workpiece elements exhibiting the adhesion mechanism are suggested to be Ti, Al, and V. Although some material adhesion was observed, the main mechanisms on the PCD tools are edge chipping, peeling, and abrasive wear. Additional research is required into modelling cutting temperature in the shear zone and chip-tool contact zone when machining Ti-MMCs. It is also necessary to comprehend the effects of the abrasive particles on temperature generation and variation.

Phase II

The second phase of this research looked into tool wear mechanisms and surface quality evaluation when turning Ti-MMCs with carbides and CBNs. Because of the lack of information on turning Ti-MMCs, the cutting conditions were chosen based on the tool manufacturer's recommendations for industrial applications.

6.4.3 Turning tests with carbide tools

Elemental analysis and quantitative mapping were performed on the tool wear mechanisms using a Jeol JSM 7800F FEG-SEM equipped with an Oxford X-ray detection system (Aztec EDS). Microstructure micrographs were captured at low and high magnifications. Wear investigation tests were carried out in a dry environment to avoid coolant effects. However, an appropriate coolant was used during the surface roughness investigation to avoid temperature effects on the functionality of the workpiece and tool performance. To define the factors governing the wear rate on the insert's flank, statistical approaches such as analysis of variance (ANOVA) were used. To that end, statistical parameters such as R^2 , R^2_{adj} , P-value, and F-ratio were used to analyze the results. (Table 6-1).

Table 6-1: ANOVA table of turning tests when using carbide tools

Experimental factors		Tool wear		Surface roughness R_a	
		F	P	F	P
(1)	v_c	10.411	0.0008	8.788	0.0018
(2)	f_r	1.957	0.1674	9.476	0.0013
(3)	a_p	0.987	0.3902	7.208	0.0044
		$R^2 = 0.572$; $R^2_{adj} = 0.443$		$R^2 = 0.78$; $R^2_{adj} = 0.72$	

As can be seen, the only statistically significant factor in the flank wear rate is cutting speed. $R^2 = 0.57$, on the other hand, indicates that the flank wear rate cannot be statistically controlled by the process parameters. The low controllability of flank wear rate during Ti-MMC machining could be attributed to complex chip formation. Sparks were indeed seen in the cutting zone. Furthermore, the experimental results show that the factors that govern optimal or near-optimal tool wear and surface roughness are different. This necessitates sophisticated optimization tools to achieve adequate simultaneous multiple-response optimization. Scratches and grooves on the deposited layers could be caused by TiC particles during the tool-workpiece interaction, demonstrating the abrasion mechanism. Another possibility is that because the carbide tool TH1000 is coated, the harder coating particles disintegrate the tool surface. The SEM micrographs clearly show that the deposited materials smear on the flank face, and the thin adhered layer resembles spread butter. It was also discovered that the tool/particle interaction during cutting can take three different forms.

The particles can be cut at the surface and pushed inside the material. There was no evidence of particle debonding. After analyzing the deposition layer on the tool's flank surface, no trace of magnesium (Mg) was found. Furthermore, the presence of vanadium (V) is suggested to be associated with the Ti-6Al-4V transferred from the workpiece material exhibiting an adhesion mechanism.

6.4.4 Turning tests with CBN tools

Again, statistical approaches such as analysis of variance (ANOVA) were used to identify the factors influencing wear rate on the flank of the tool. According to the findings of this study, both responses (flank wear rate and surface roughness) are statistically significant to the variation of the cutting parameters used. Cutting speed impacts the variation of flank wear rate and surface roughness (P-values 0.03 and 0.008 (Table 6-2). The correlation of determination (R^2) indicates that under similar cutting parameters, both flank wear rate and surface roughness can be controlled by 99% and 94%, respectively.

Table 6-2: ANOVA table of results recorded in turning by carbide and CBN tools

	Experimental factors	Tool wear		Surface roughness R_a	
		F	P	F	P
(1)	v_c	29.131	0.033	11.295	0.287
(2)	f_r	8.044	0.110	2.484	0.0081
(3)	a_p	62.178	0.015	3.161	0.240
		$R^2 = 0.99$; $R^2_{adj} = 0.94$		$R^2 = 0.94$; $R^2_{adj} = 0.88$	

ANOVA results show that low cutting speed, feed rate, and depth of cut resulted in a low wear rate. Furthermore, reduced surface roughness can be obtained at higher cutting speeds and moderate depths of cut. This can be attributed to easier chip formation in the cutting zone due to increased speed, facilitating plastic deformation in the shear zone. When turning Ti-MMCs with CBN tools, the feed rate is the most important factor. The experimental results show that the factors governing optimum or near-optimum tool wear and surface roughness are not identical, as in the case of turning with carbide tools. This necessitates sophisticated optimization tools to achieve adequate simultaneous multiple-response optimization. Hard particles in the Ti-MMC structure increase the thermal and mechanical stresses on the tool surfaces. According to experimental

results, the high abrasive and robust mechanical properties of Ti-MMC degrade all tools within the first few seconds of cutting operations, especially at high cutting speeds where elevated temperature and abrasive particles are major issues. As a result, the tool/insert must withstand high abrasion and thermal loads. The matrix behaviour and hydrostatic pressure of the cutting edge are important at low cutting speeds. In this case, the tool may harden enough to prevent abrasion and adequately resist deflection forces. As a result, regardless of the tool used, moderate to high levels of feed rate must be selected. This demonstrates that the cutting tools must be sufficiently hard and rigid to withstand the reinforced particles. Similarly, the tools must be tough enough to withstand the fluctuating forces, spring back, and impacts caused by matrix toughness, elasticity, and inhomogeneity. EDS analysis was used on a selected zone of flank wear to understand better the tool wear mechanism of the CBN tools.

EDS uses mapping to reveal the key elements, distributions, and locations. Titanium (Ti) and aluminium (Al) are both tool and workpiece materials, but vanadium (V) is only a workpiece element that demonstrates the adhesion mechanism. This is consistent with the previous study [10]. However, in their study, they suggested that Mg might be the workpiece element, but this study showed that magnesium (Mg) might not come from the workpiece material based on the chemical analysis. Magnesium was also not detected in the chemical analysis of the carbide tool. It could be a tool element such as a catalyst or a sintering additive. Because of the high concentration of Al in both the workpiece (as Ti-6Al-4V) and the tool, it is present throughout the analyzed region (as Al_2O_3).

Phase III

The TOPSIS method was used to find the optimum cutting conditions in the final approach used in this research project. This resulted in minimal tool wear and surface roughness while maintaining maximum productivity. This study looked into the main effects of initial cutting conditions on tool life. To accomplish this, two different cutting speeds were used: the initial speed for 1 s and the secondary cutting speed used for the remainder of the machining operation. Based on previous research [14], a constant cutting time of 120 s was chosen.

According to preliminary research, severe tool wear occurs around this machining time, with flank tool wear exceeding 250 μm , considered a tool wear threshold. Various feed rates were also considered based on industrial recommendations, machine tool capacity, and previous research. The TOPSIS method was used in this study to combine multiple responses into one. The Taguchi

method was then used to optimize the goals. The two responses were flank tool wear (V_{Bmax}) and the arithmetic mean roughness value R_a .

A complementary chip formation and morphology analysis during the initial moments of machining Ti-MMCs was also performed. The goal was understanding how chip formation varies during the early machining stages. The initial moments were captured using a high-speed camera. Six different types of chips were observed after analyzing different frames, but all of them were segmented and discontinuous due to the chip breaker on the tool. We discovered that the depth of cut is insufficient for shaping the chip (less than the tool nose radius) before 100 milliseconds (ms) of machining, and the materials are ploughed up. At 200 ms, when the force of sheared material from the work-piece is strong enough to break the previously piled-up materials, the chip begins to shape, and some short and narrow chips are formed. Curly chips are shaped at this time because the workpiece material has sufficient ductility and due to the very low thermal conductivity of Ti-MMC and instant strain relaxation after chip removal from the workpiece material. Chips are discontinuous at an irregular rate at 300 ms, and chip removal does not take a consistent form. Furthermore, the relative direction of the chip flowing over the tool changes constantly between 300 and 400 ms of cutting (see Figure 6-5a, 400 ms). However, the general direction of chip flow (see Figure 6-5b, 500 ms) does not change after 400 ms of machining.

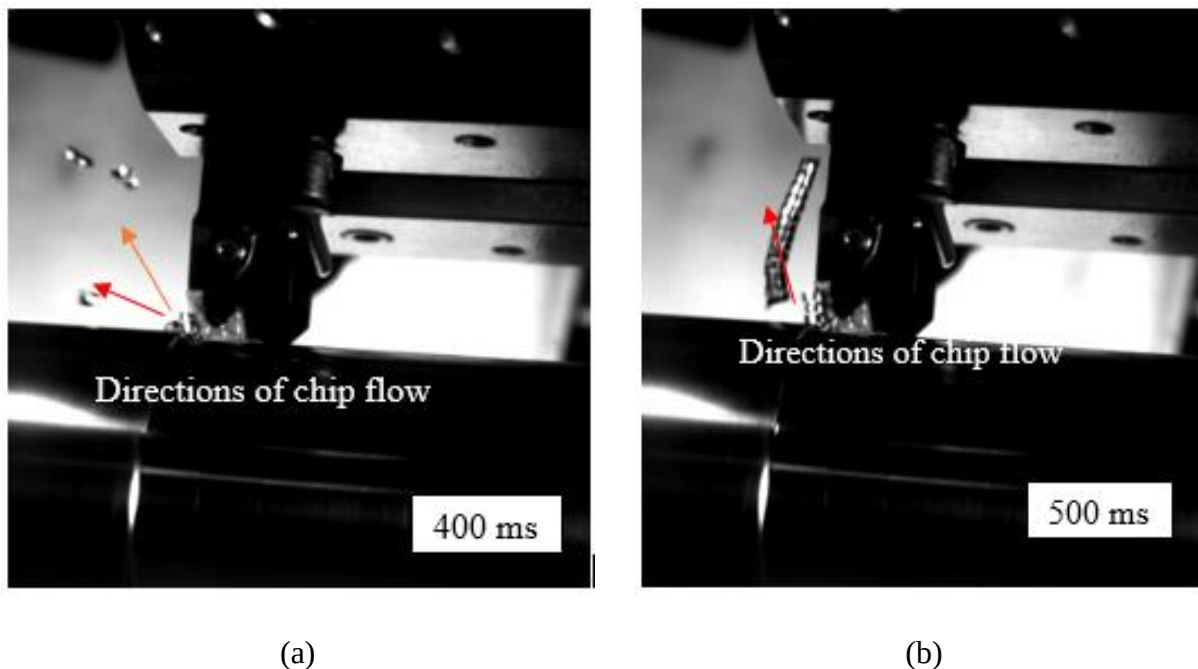


Figure 6-5: Chip formation at (a) 400 ms and (b) 500 ms of machining

Compared to previous images, the chip is longer at 500 ms. It is proposed that the workpiece material experienced severe strain hardening in the chip formation zone at 500 ms and that this high strain hardening effect was transferred to the chips, resulting in relatively long chips. These long curling chips gradually took the place of discontinuous chips. Two distinct chip types were observed on the chips' free (serrated type) and back (smooth and shiny) surfaces. It is suggested that the combined effects of high contact pressures, temperature, and frictional forces cause a smooth and shiny back surface. High shear stresses and contact cause deformation, resulting in a smooth back surface when the back surface slides onto the tool rake face. It is important to note that chip serrations occur across the width of the chips, and these teeth are referred to as "primary serrated teeth." Serrated elements were found on the upper and lower edges of the chips. Secondary serrated teeth is the name given to these larger elements. While the tool advances during machining, some intense localised deformations occur before the cutting edge, resulting in a different chip compression ratio in two main zones, A_1 and A_2 (Figure 6-6). the deformation line and flow direction can be seen in this picture.

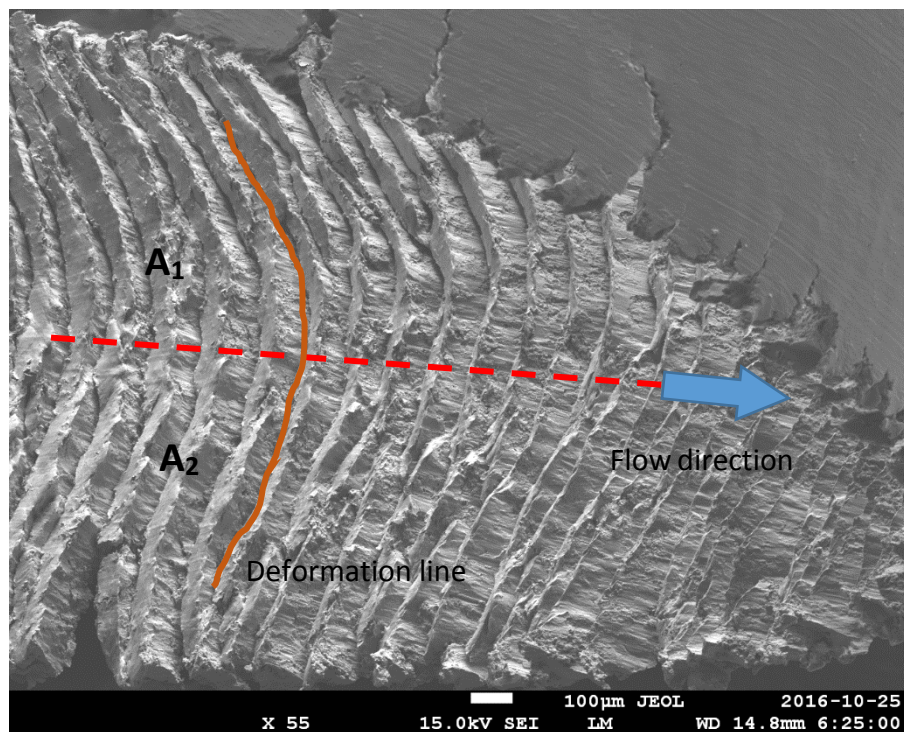


Figure 6-6: Two distinct zones in a chip, deformation line, and the flow direction

This deformation could be related to the nonlinear movement of chips over the rake face, demonstrating the relative motion between the already formed chip and the segment being formed.

Another reason for having two main zones could be excessive heat at the tool chip interface. This heat has the potential to change a portion of the chips. A higher serration level indicates a more violent shear slip action in the cutting zone, resulting in a longer shear slip distance and slip angle. As a result, shear slip distance and angle correlated positively with cutting time. This is because the critical strain of tool materials affects the chip serration level. Because of the low cutting force, the critical strain of tool materials is relatively low at the start of machining. As a result, the chip serration level is low during this period. However, as the cutting time increases, so does the cutting and friction force on the tool/workpiece. As a result, the serration level rises steadily. In Ti-MMC machining, the heat generated by shear deformation in the shearing zone is highly centralised, and the temperature in the shearing band increases rapidly.

6.5 Novelty

The following are the main original contributions of this thesis:

- For the first time, a detailed analysis was performed to investigate carbide, CBN, and PCD tool's wear mechanisms during machining of Ti-MMCs. PCD tools are the hardest available tools for machining of Ti-MMCs. Yet, there is no reported work in the literature regarding the wear mechanisms of these tools during the machining Ti-MMCs. Therefore, an in-depth microstructural analysis was performed to discover the responsible wear mechanisms. CBNs, as the second hardest tools, could be considered a potential alternative to expensive PCD tools for machining Ti-MMCs. There is still limited literature regarding the wear mechanisms of these tools in machining Ti-MMCs. This study revealed two wear modes in machining Ti-MMCs: adhesion and oxidation, unlike carbides, which were abrasion and adhesion. The governing factors on the flank tool wear were ranked for the first time in this study. Cutting speed and feed rate were the main factors during turning Ti-MMCs with carbide tools. However, cutting speed and depth of cut are the main factors when turning Ti-MMC with CBNs (**Objective 1**).
- For the first time, a multi-objective optimization method using TOPSIS was performed to find the optimum cutting conditions that result in minimum tool wear and surface roughness while preserving the highest productivity during machining Ti-MMCs. Also, for the first time, initial and secondary cutting speeds were used as the input parameters for the optimization. Since the tool wears out drastically right after the machining starts, initial

cutting speed plays a vital role during machining. Thus, controlling and finding the optimum cutting parameters could result in cost reduction, better surface roughness, and productivity increase. Therefore, this study could be of prime interest to various academic studies, and outcomes could be used in multiple valuable data for industrial applications **(Objectives 2 and 3)**.

- For the first time, the Taguchi method was combined with TOPSIS to optimize the cutting conditions. The optimization resulted in tool wear reduction and surface roughness improvement **(Objective 3)**.

CHAPTER 7 CONCLUSION

This chapter summarizes the significant observations made in this study. The general conclusions drawn from experimental and analytical investigations are listed below:

- During milling of Ti-MMC:
 - With carbide tools, adhesion is the main wear component appearing on the flank side of the tool. Another main wear mode is oxidation which seems to occur due to the high temperature at the cutting zone.
 - With PCD tools, although a slight material adhesion was observed, edge chipping, peeling, and abrasion wear were the dominant mechanisms.
 - Despite sensible vibration occurring when using carbide tools, an acceptable tool wear rate was observed.
 - The PCD tools failed at a cutting speed range of 350-600 m/min, while optimum tool wear and productivity were observed under low feed rate and cutting speed levels. This could be attributed to the intense effects of matrix behaviour and hydrostatic pressure of the cutting edge at low levels of cutting speed, which provide sufficient hardness to prevent abrasion and resist deflecting forces.
 - The statistical investigations on the milling tests using carbide X500 and PCD tools led us to conclude that cutting speed and depth of cut are the major cutting parameters affecting tool wear rate. In contrast, surface roughness was not affected by the cutting parameters used when using the PCD tool and was only sensitive to feed rate variation when using the carbide tool X500.
 - The experimental results denote that the milling responses studied in this work, in principle, tool wear rate and average surface roughness, are affected by different cutting parameters. This means that the optimum selection of cutting parameters by simultaneous multiple response optimization techniques is a delicate subject that needs further investigation.

- During the turning of Ti-MMCs:
 - The typical wear mode observed in the carbide tools was mainly abrasion and adhesion. However, CBN tools also suffered from adhesion as well as oxidation.
 - Cutting speed and feed rate are the governing cutting parameters on the flank wear rate during turning Ti-MMCs with carbide tools.
 - Independent of the type of tool used, cutting speed is the governing factor on the flank wear. Therefore, the depth of cut is another crucial determinant of the flank wear rate when turning Ti-MMC with CBN tools. Furthermore, independent of the type of tool used, moderate to high levels of feed rate must be selected to accommodate an acceptable tool life.
 - The stiffness and suitability of the cutting tool and tool holder have essential roles in the stability of the cutting process and successful reduction of the fluctuated forces effects, particularly under high levels of cutting speed.
 - Elevated temperature and abrasive particles were discovered as the fundamental problems observed under high-speed turning of Ti-MMCs. Thus, the tool/insert should resist high abrasion and thermal loads (i.e. CBN). At a low level of cutting speed, the matrix behaviour and hydrostatic pressure of the cutting edge play prominent roles. In this case, the cutting tool acquires sufficient hardness to prevent abrasion and resists deflection forces.
- A multi-criteria decision-making model (TOPSIS) combined with the Taguchi method was used to find the optimum milling parameters. The surface roughness and flank tool wear were considered the objectives for simultaneous optimization. An innovative solution was proposed for interrupted machining with two different cutting speeds. The first level cutting speed was used for 1s, and the second level was used for the rest of the process. The experimental results indicate that the initial speed followed by the feed rate significantly affects tool life. In addition, using the proposed strategy with different levels of cutting speed during machining operations led to improved tool life and surface roughness compared to conventional machining with uniform cutting speed throughout the entire process.

- Initial moments of the chip formation during the turning of Ti-MMC were studied. Different types of chips are formed after starting machining. The reason could be due to the low thermal conductivity of Ti-MMC, the rapid increase of the temperature in the shearing band, and the changing friction coefficient between the chip and tool surface. Shear slip distance and slip angle showed a direct correlation with cutting time. This is because the chip serration level depends on the critical strain of tool materials. Two different zones on the free surface of the chip were observed. It could be related to the non-linear movement of chips over the rake face showing the relative motion between the already formed chip and the segment being formed. The back surface of the chips is pretty smooth and shiny, indicating that the workpiece material in the chip formation zone does not experience the overwhelming effect of strain hardening and thermal softening.

Finally, The effects of cutting parameters, including cutting speed and feed rate, on the initial tool wear mechanism, morphology, and size when machining Ti-MMCs were studied in this dissertation. Consequently, it was revealed that these parameters should be considered as the main machining factors governing the initial wear modes, reflected as flank wear modes in both initial moments of cut and exhausted tool (worn tool), and finally, the ultimate tool life. Subsequently, the initial levels of cutting parameters seem to have undoubtful effects on the ultimate tool life. Hence, the effects of initial cutting conditions considering various initial cutting speeds and feed rates on the ultimate tool life during the machining of Ti-MMCs were also investigated.

It is worth mentioning that the author of this thesis personally committed all the work described was done by himself. The author chose the research path, hypotheses, methods, experiment design, data acquisition setup measurements, application of and development of mathematical methods, analysis, illustrations, and paper and thesis writing. Exceptions are grant applications, machining, and the mechanical mounting of the accelerometer. In addition, several people have advised the author throughout the work. They are formally recognized in the main acknowledgements section.

CHAPTER 8 REFERENCES

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APPENDICES

APPENDIX 1 ARTICLE 4: FIRST MOMENTS OF THE CHIP FORMATION WHEN TURNING OF TITANIUM METAL MATRIX COMPOSITES

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The 6th International Conference on Virtual Machining Process Technology ©VMPT 2017

29 May-2 June 2017, Polytechnique Montréal, Québec, Canada

1. ABSTRACT

Due to their excellent combination of high-specific strength, low thermal conductivity and corrosion resistance characteristics, titanium metal matrix composites are widely used in different industries. Within a very short time after starting of the machining process, there are different mechanisms of chip formation with either long or short discontinuous chip flow and different flow directions. In this study, the complex changes that occur in the main deformation zone due to different chip morphologies were explained by multi-view characterizations (including free surface, back surface, and cross-section of the top surface). Two different zones on free surface of the chip were observed which could be related to the none-linear movement of chips over the rake face showing the relative motion between the already formed chip.

Keywords: chip morphology, chip formation, turning, titanium metal matrix composites

2. Introduction

Titanium metal matrix composites (Ti-MMCs) with the advantages of both TiC particles and titanium alloys, have excellent features such as high stiffness, high-performance mechanical properties, fairly high elastic modulus, high wear resistance, increased strength, and low density [1]. A lot of studies have focused on chip formation due to the importance of chip morphology and chip formation mechanism as other parameters in machining of difficult to cut materials such as cutting force and temperature, tool wear, machined surface finish, and surface integrity. As a

matter of fact, chip is produced from the workpiece material with removing by tool and it is obvious that tool condition can have direct relation in chip morphology. Two aspects that can define this relationship are tool wear and friction forces. Qiu et al. [2] had some investigation about the relation between chip morphology and tool wear for cermet tools in milling stainless steel and found that the tool boundary wear and the serrated chip formation are closely related to the mechanical fatigue crack formation. Poulachon et al. [3] found that the two most important factors affecting the chip morphology are the hardness of materials and cutting speed. Based on Yang et al. [4] study, the chip saw-tooth degree has the opposite relation with cutting speed, while it has the direct relation with feed rate. Dolinsek et al. [5] performed a research regarding chip shape, chip microhardness, and segmentation frequency and found that width and spacing of (Adiabatic shear Bands) ASBs decrease with the increase of cutting speed. Serrated chips are the most common form generated during machining of titanium alloys and could be related to high-stress focus.

Chip morphology has an important role in surface quality, machining accuracy and tool life [6]. Hence, characterizing chip formation could help to optimize cutting parameters and led to reducing the machining costs. The above overview indicates that serrated chip morphology in Ti-MMCs and the mechanisms, involved in the process, been well understood.

3. Methodology

In this work, the results are obtained by an optical microscope, a high-speed camera, and a scanning electron microscope (SEM). Also, the mechanism of serrated chip formation is discussed by analyzing the formation of serrated chip collected from turning of Ti-MMC. All the experimental tests were done using a 5-axis Mazak QT-Nexus-200, CNC turning center. The work piece material was Ti-6Al-4V with 10-12% volume fraction of TiC particles with irregular shapes and 10-20 μm size. The turning tests were performed using carbide TiAlN-TiN coated tools. Cutting parameters were constant for all tests: containing cutting speed 50 m/min, feed rate 0.1 mm/rev and depth of cut 1.5 mm. A divider was put between the cutting parts and the bed of the lathe machine to separate the chips of each pass. After each test, all the produced chips were collected and labelled with machining time. Then, the divider was cleaned and replaced. Slip angle ϕ and the shear slip distance were measured using a Toolmaker-Mitutoyo optical microscope.

4. Results and discussion

To understand how the chip formation varies during the first moments of machining, a Mikrotron Motion Blitz cube high speed camera with 400 frames/s, is used. After analyzing different frames, as shown in Figure 1, six different kinds of chips were observed, but all of them were segmented and discontinuous due to the chip breaker on the tool. As observed with the high-speed camera in the initial moments of machining operation, before 100 milliseconds (ms) of machining, depth of cut is insufficient for shaping the chip (less than tool nose radius) and the materials are plowed up. At 200 ms, when the force of sheared material from the work-piece is large enough to break the previous piled up materials, chip starts to be shaped and some short and narrow chips are produced. At this time, the workpiece material shows enough ductility and due to very low thermal conductivity of Ti-MMC and instant strain relaxation after the removal of chip from the workpiece material, curly chips are shaped. At 300 ms, chips are discontinuous at an irregular rate and chip removal is not a constant form. Moreover, between 300 and 400 ms of cutting the relative direction of the chip flowing over the tool is constantly changing (see Figure 1, 400 ms). However, after 400 ms of machining the general direction of chip flow (see Figure 1, 500 ms) does not change. At 500 ms, in comparison with previous images the chip is obviously longer. It is suggested that at 2600 ms the workpiece material experienced severe strain hardening in the chip formation zone, and this high strain hardening effect could be transferred to the chips resulting in the formation of relatively long chips. These long curling chips gradually took the place of discontinuous chip.

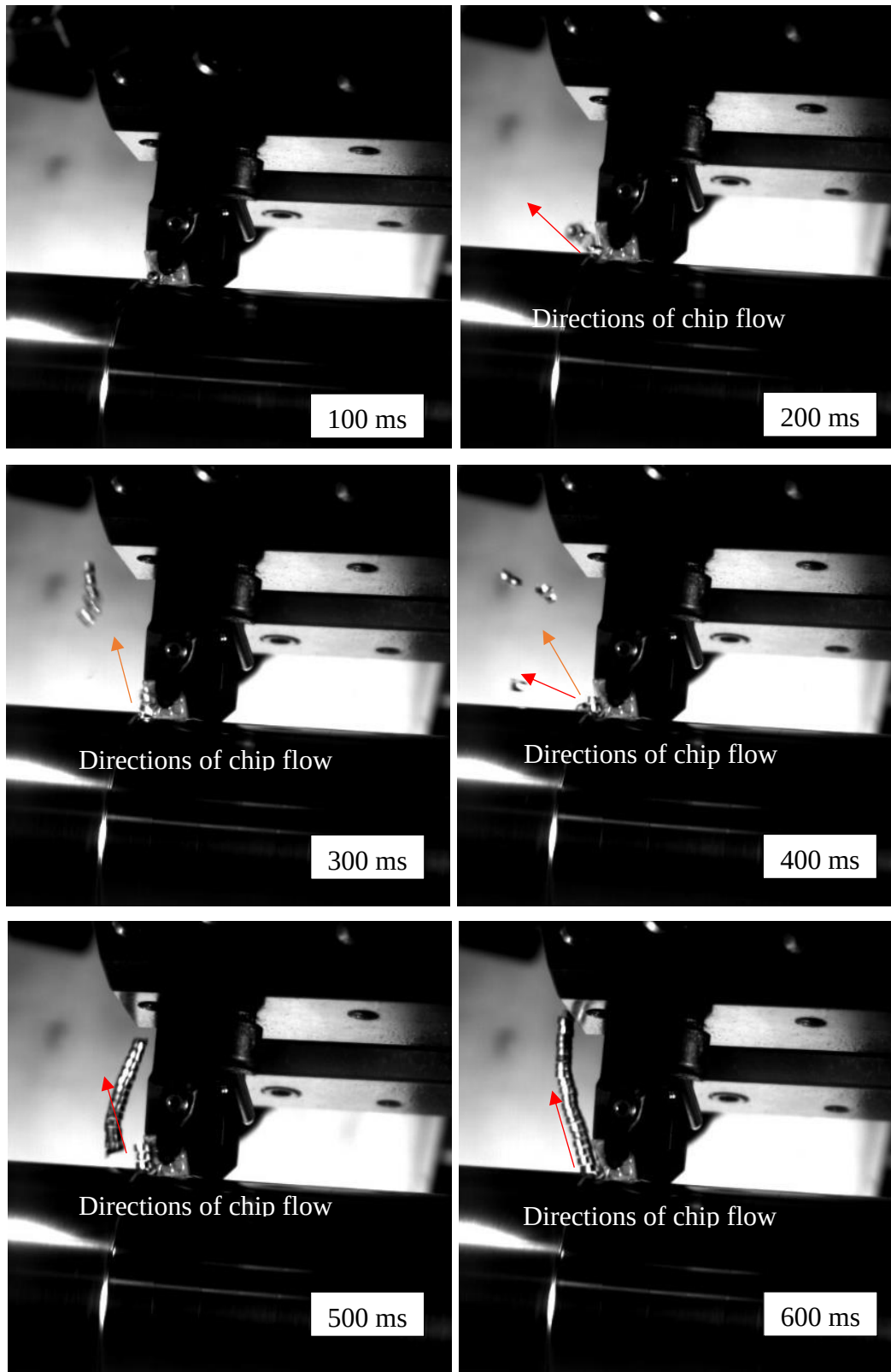


Figure 1: Different types of chip formation over time at the very beginning of machining

5. Chip morphology of initial moments of machining

Two different chip morphologies were observed at the free (serrated type) and back (smooth and shiny) surface of the chips as seen in Figures 2a and 2b. It is suggested that the reason for back surface being smooth and shiny is due to the combined effects of high contact pressures, temperatures and frictional forces. When the back-surface slides onto the tool rake face, high shear stresses and contact cause the deformation and lead to the smooth back surface. It is worth to know that chip serrations occurred across the width of the chips and these teeth are named as ‘primary serrated teeth’. At the upper or lower edge of the chips, serrated elements were observed. These larger elements are named as ‘secondary serrated teeth’ (see Figure 2a). As observed in Figure 2c, there are two different zones A_1 and A_2 which indicate the deformation line and the flow direction. This type of deformation could be related to the none-linear movement of chips over the rake face showing the relative motion between the already formed chip and the segment that is being formed.

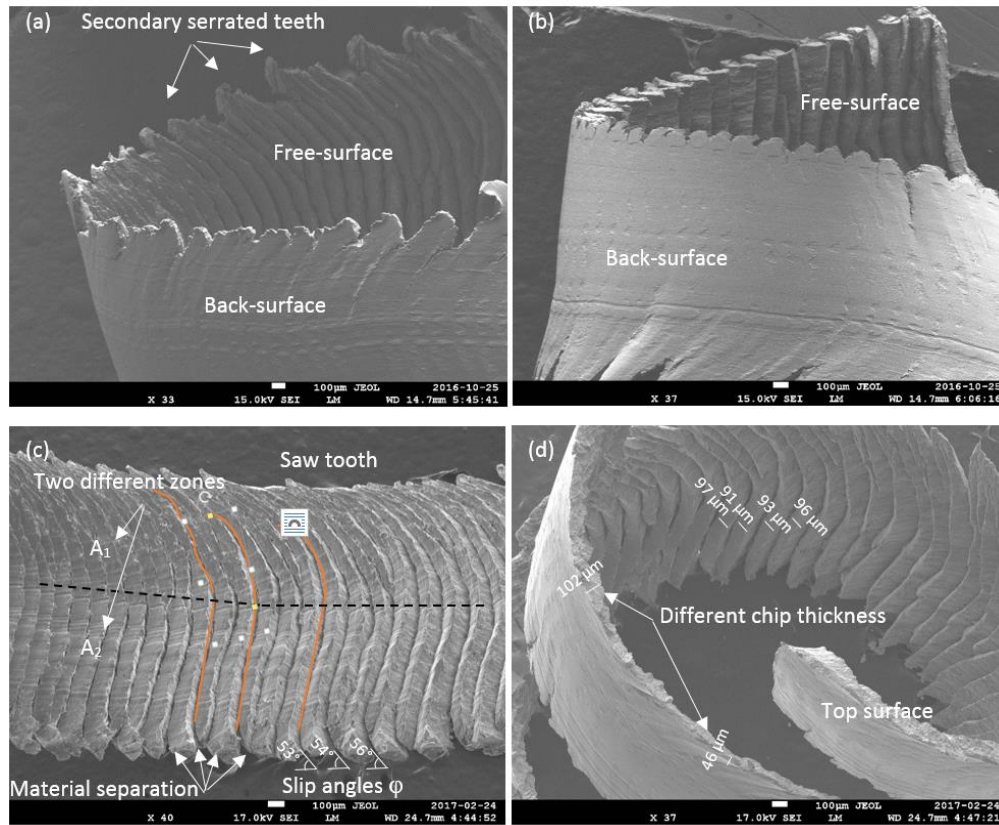


Figure 2: Different chip morphologies (a) secondary serrated teeth (b) back and free surface (c) two distinct zones and (d) different chip thicknesses and shear slip distances

During machining, while advancing the tool some intense localized deformations happen in front of the cutting edge resulting in different chip compression ratio in two main zones (Figure 2c, zones A_1 and A_2). A_2 is the curved zone where an intense shear band is formed by catastrophic shearing during the failure stage of the segment formation. The other reason for having two main zones could be due to high temperature at the tool chip interface. This heat can modify a partial of the chips.

6. Shear slip distance and slip angle

The observed shear slip distance and slip angle are shown in Figure 2c and 2d. Due to variation of shear slip distance and slip angle over time within each chip, data were measured in different locations several times and the average value was taken. After regression analysis of the measured data, the final results were obtained are shown in Figure 3. From the chip geometry, it appears that slip angle ϕ (Figure 3a) increases slightly over time. The similar evolution is observed for the Shear slip distance Δx (Figure 3b).

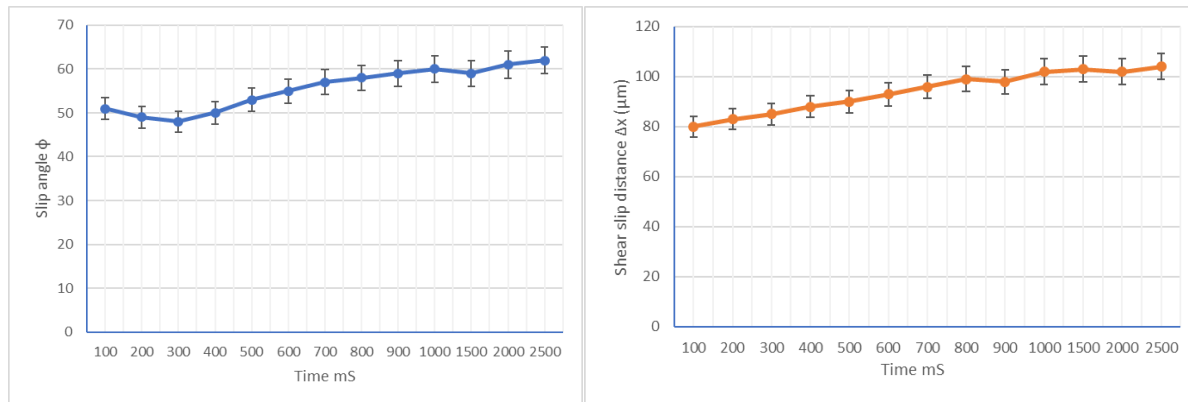


Figure 3: The changing rules of shear slip morphology (a) slip angle against cutting time (b) shear slip distance against cutting time

A greater serration level means a more violent shear slip action in the cutting zone, which will cause a greater shear slip distance and slip angle. As a result, shear slip distance and slip angle showed a positive correlation with cutting time. This is attributed to the fact that the chip serration level depends on the critical strain of tool materials. At the beginning of machining, the critical strain of tool materials is relatively small because of the little cutting force. So, the chip serration level is slight in this period. However, as the cutting time increases, the cutting force

and friction force on tool/workpiece increases rapidly. Thus, the serration level becomes more and more serious. The heat generated by shear deformation in shearing zone is highly centralized during machining of titanium metal matrix composites, and the temperature in shearing band increases rapidly.

7. Conclusion

This study was performed to understand the initial moments of chip formation better. Different types of chips are formed after starting of machining. The reason could be due to the low thermal conductivity of Ti-MMC and rapid increasing of the temperature in shearing band and changing in friction coefficient between chip and tool surface. Shear slip distance and slip angle showed a direct correlation with cutting time. This is attributed to the fact that the chip serration level depends on the critical strain of tool materials.

Two different zones on the free surface of the chip were observed. It could be related to the non-linear movement of chips over the rake face showing the relative motion between the already-formed chip and the developed segment. In addition, the back surface of the chips is pretty smooth and shiny, which indicates that the workpiece material in the chip formation zone does not experience the overwhelming effect of strain hardening and thermal softening.

8. Acknowledgements

The authors would like to take this opportunity to acknowledge the financial support of the Natural Sciences and Engineering Research Council of Canada (NSERC) Canadian Network for Research and Innovation in Machining Technology (CANRIMT).

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APPENDIX 2 ARTICLE 5: DEFINITION OF TRANSITION TIME IN MACHINING TITANIUM METAL MATRIX COMPOSITES (TI-MMCS)



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Characterization, Fabrication, and Application (CCFA-8)

Dec. 20-21, 2022

Iran University of Science and Technology, Tehran, Iran

Definition of Transition Time in Machining Titanium Metal Matrix Composites (Ti-MMCs)

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CERTIFICATE OF CONFERENCE

IS HEREBY GRANTED TO

Kamalizadeh, Saeid, Niknam, Seyed Ali, Turenne, Sylvain, Balazinski, Marek.

To certify attendance at the 8th International Conference on Composites: Characterization, Fabrication, and Application (CCFA-8) on 20-21 Dec.2022, at Iran University of Science and Technology, Tehran, Iran, as "Oral Presenter" of the paper titled:

**"Definition of Transition Time in Machining
Titanium Metal Matrix Composites (Ti-MMCs)"**

Mahmood M. Shokrie

Afshin Zeinedini

1. Abstract

Titanium metal matrix composites (Ti-MMCs) have broad applications in the biomedical and aerospace industries. Although reinforcing elements in MMCs matrix improves the physical, mechanical, and thermal properties; however, rapid tool wear and deteriorated surface finish are the common observations in machining MMCs. In addition, the interaction between the tool and abrasive reinforcing particles induces complex deformation in the MMC structure. Initial wear, steady wear, and rapid wear are three wear zones. In this regard, a comprehensive understanding of the estimated total time spent in each state called sojourn time, and the transition times between each zone are helpful to achieve a better tool life. This work will study the transition time in machining Ti-MMC under different cutting conditions and cutting tools.

Keywords - Metal matrix composites (MMCs); Ti-MMC, Flank wear; Transition Time; Machining

2. INTRODUCTION

A lack of information is still observed in machinability evaluation of superalloys, mainly when longer tool life is demanded. Furthermore, no adequate and reliable knowledge exists on the effects of initial cutting conditions on the ultimate tool life when machining Ti-MMCs. Hence, controlling the initial wear behaviors can improve the tool life and surface roughness. In light of the literature survey, although many research studies were reported on the steady-state wear period, initial tool wear and its significant influences on tool life have not been studied at an acceptable rate. The initial wear period of a cutting tool arises very fast at a high wear rate and has an essential role in system productivity. It is believed that the duration of initial tool wear and various wear morphologies in the initial moments when machining Ti-MMCs have intense effects on the ultimate tool life. Therefore, those factors governing initial tool wear must be analyzed, followed by determining the transient time where the initial tool wear ends and the steady-state wear region starts. In this regard, Kamalizadeh [1] focused on initial tool wear in turning Ti-MMCs using carbide tools. It was observed that the first transition time within the tool wear curve occurs in the first second of machining. Furthermore, a good correlation was found between the transition time in tool wear progression charts and the cutting force diagrams. As noted in [2], the primary wear mechanism during the initial moments of machining Ti-MMC is abrasion, and the dominant wear mechanism is adhesion. Since this study aims to obtain information about the transition time between different wear states, each state on the tool wear curve must be first analyzed as a separate

case. Hence, a failure criterion needs to be assigned separately for each zone. Kamalizadeh [3] observed that the first transition time of tool wear occurs in the first second of machining. A direct correlation was found between the transition time in tool wear progression charts and the cutting force diagrams. As noted in [3], the preliminary wear mechanism during the initial moments of machining Ti-MMC was abrasion, and the dominant wear mechanism was adhesion. In addition, a good correlation was found between the transition time in tool wear progression charts and the cutting force diagrams. The literature allows us to state that few studies are available on milling Ti-MMCs, which is more costly and complex than turning. Therefore, an adequate selection of optimal milling parameters has evolved.

3. Discussion

As shown in Figure 1 and Figure 2, a slight change in the initial period can significantly change the entire process. The obtained results by authors indicate that the initial cutting speed is one of the most critical factors affecting the wear rate and surface roughness over time. This would align with the previous studies [3-6], proposing that a protection layer during initial machining is shaped and protects the tool from severe damage and adhesion. In other words, forming a brace shield or a protection layer in the first second of machining is the answer to why tool wear and surface roughness are low with two different cutting speed strategies.

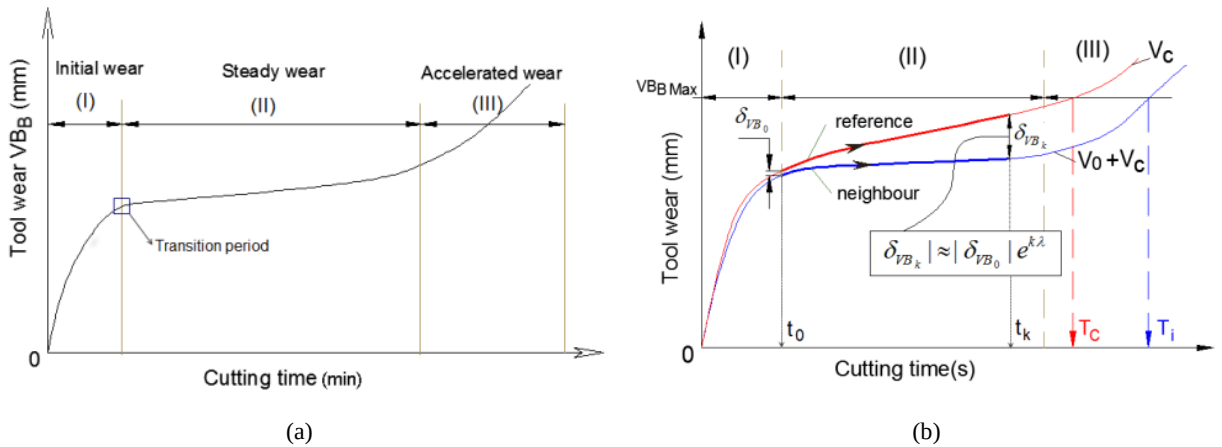


Figure 1: (a) Three distinctive tool wear periods; (b) chaos theory: a small change in the initial period can result in a big change in the entire process

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tool from severe damage and adhesion. In other words, forming a brace shield or a protection layer in the first second of machining is the answer to why tool wear and surface roughness are low with two different cutting speed strategies.

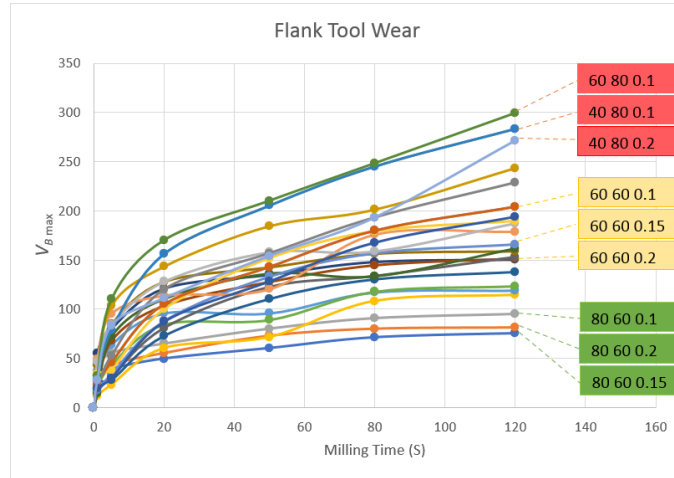


Figure 2: Tool wear curves for different cutting conditions

4. CONCLUSION

- Experimental results confirm that the initial machining conditions significantly affect ultimate tool life. In addition, the significant effects of initial and secondary cutting speed on the tool wear progress and ultimate tool life were noticed.
- It was observed that the first transition time within the tool wear curve occurs in the first second of machining.
- Based on previous research studies, a brace shield or protective layer can be formed during the initial moments of the machining. It reduces the friction and, consequently, the cutting force. Additional works are still needed to characterize the brace shield under various cutting conditions and cutting tools. Additional studies are still needed to optimize the tool life by adequate selection of cutting parameters in the initial conditions.

ACKNOWLEDGMENT

The authors would like to thank the Natural Sciences and Engineering Research Council of Canada (NSERC) and the NSERC Canadian Network for their financial support for research and innovation in machining technology (NSERC-CANRIMT).

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