Effect of micro texture on the performance of cutting tools for aluminium

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**EFFECT OF MICRO TEXTURE ON THE PERFORMANCE OF CUTTING
TOOLS FOR ALUMINIUM**

SHANMUGASUNDARAM DURAIRAJ

SCHOOL OF MECHANICAL AND AEROSPACE ENGINEERING

2020

EFFECT OF MICRO TEXTURE ON THE PERFORMANCE OF CUTTING TOOLS FOR ALUMINIUM

SHANMUGASUNDARAM DURAIRAJ

School of Mechanical and Aerospace Engineering

A thesis submitted to Nanyang Technological University
in partial fulfilment of the requirement for degree of
Doctor of Philosophy

Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research, is free of plagiarised materials, and has not been submitted for a higher degree to any other University or Institution.

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[25/03/2020]

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A handwritten signature in black ink, appearing to read 'Lam Yee Cheong', written in a cursive style.

Prof. Lam Yee Cheong

Authorship Attribution Statement

This thesis contains material from [x number] paper(s) published in the following peer-reviewed journal(s) / from papers accepted at conferences in which I am listed as an author.

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The contributions of the co-authors are as follows:

- A/Prof S. Castagne and A. Aramcharoen provided the initial project direction.
- I prepared the manuscript drafts. The manuscript was revised by S. Castagne and G. Jiang.
- I designed the study and performed all the laboratory work at Precision Lab at School of Mechanical and Aerospace Engineering, NTU. I also analyzed the data.
- All microscopy, including sample preparation, was conducted by me in the Materials Lab at School of Mechanical and Aerospace Engineering, NTU and SimTech, Singapore.

[24/03/2020]

Date

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Abstract

Due to environmental obligations on manufacturing industries, there has been a continuous effort to develop new methodologies targeting sustainable manufacturing. One such effort is shifting from flooded lubrication to minimum quantity lubrication and dry machining. It is estimated that almost 25 to 60% of energy is wasted in the tool-chip and tool-workpiece interaction zones. The major loss of energy in the interaction zones is due to friction. The use of lubricants and/or coolants could potentially solve this problem, but practically it is difficult for the fluid to penetrate between the interfaces during machining.

To address this problem, micro-texturing of the tool surface has been proposed. This solution can be beneficial in two ways; firstly, the texture acts as a reservoir of lubricants in the interaction zone and secondly, it reduces the actual contact area. Thus, tribological properties are modified by surface texturing and are utilised to improve the performance of the cutting tool by reducing the energy losses due to friction. In this work, surfaces very near to the cutting edge in the rake face of the tool are textured using micro-EDM and laser micromachining. Experimentally it has been demonstrated that textures can be used to improve the cutting performance of the tool in certain conditions. There are many investigations of employing texture tools for the cutting of steels and titanium alloys indicating the beneficial effects of the texture tools. There are few investigations on the cutting of aluminium, although the cutting of aluminium occurs extensively. Due to their differences in material properties, unfortunately, the same conclusion of beneficial outcomes of using a texture tool for cutting of steel and titanium may not be translated directly to aluminium without further investigations. As such, this investigation focuses on the use of texture tool for cutting of aluminium.

The rake face textures are found to induce significant improvement in the cutting performances in terms of cutting force decrement and chip morphology. However, such effects are not observed in flank face textures for the tested conditions. The texture effect is further investigated in this thesis under three sections: experimental study, simulation and acoustic emission.

In the experimental study, the influence of geometric texture parameters, such as texture shape and size, depth, pitch and distance of the features from the cutting edge, was studied using statistical analysis. The Taguchi methodology of L9 Orthogonal Array was used for the experimental study of four texture parameters at three levels. ANOVA was then used to establish the percentage contributions of significant texture parameters to cutting forces. Furthermore, the Taguchi methodology was used to study the effect of the same texture parameters on other responses, including shear angle, contact area and percentage concentration of workpiece material on the cutting surface. The effect on all the responses was finally compared for the given texture parameters.

To understand the effect of micro-texture and its effective utilisation, finite element-based simulation using arbitrary ductile fracture for chip separation was conducted. Abaqus/Explicit software with the Lagrangian formulation was used for the simulation as it is capable of coupling material damage and its fracture energy. Simulation results showed a reduction in cutting forces and similar chip formation characteristics as in the experimental study. It is attributed that the reduction in cutting forces and chip curling effect in the rake textured tools are due to the presence of textures on the rake face, which cause smaller chip tool contact length, reduced friction coefficient and local lubrication effect.

The acoustic emission study focusses more on the cutting phenomena involved in the metal cutting process. Cutting involves three phenomena, namely rubbing, ploughing and cutting. Generally, rubbing and ploughing are undesirable effects that cause friction and heat, and thus wastage of energy supplied. The introduction of texture on the cutting tool surface can modify or reduce the amount of these undesirable phenomena. To identify these phenomena which are occurring in the cutting process, Acoustic Emission (AE) signals were used. The signals are extracted from the cutting process for non-textured tools, and the frequencies associated with each phenomenon are determined. The difference in the contribution of each phenomenon to the textured tool is then calculated. Such difference gives a measure of the influence of the texture on the cutting mechanisms, and this can be used to produce more effective textured tools.

In summary, the micro-texture effect on the cutting tool was demonstrated experimentally, and the contribution of texture geometry parameters and their distribution was estimated statistically. Furthermore, the FEM simulation study facilitates the understanding of the change in cutting mechanisms with the introduction of texture, which is difficult to observe experimentally. In addition, the utilisation of AE signals in estimating the change in cutting phenomena due to texturing of the cutting tool was proposed and evaluated. Finally, this study gives an overall in-depth analysis of the texture effect in improving the performance of cutting tools on aluminium.

Chapter 1: Introduction

Machining plays a significant role in the manufacturing sector. Most of the manufactured parts are machined before completion. In machining, the cutting tool forcefully removes material from the workpiece, and thus the process is associated with high-stress contact interactions between the tool and the workpiece. The interactions are in two regions: firstly, between tool-chip and secondly, between tool-workpiece. It is these tribological interactions that play a key role in the machining process in terms of machining efficiency, tool life and surface quality.

Although most of the machining processes, namely turning, milling and grinding, are generally termed oblique cutting processes with intricate three-dimensional cutting action, this thesis focuses instead the orthogonal cutting process. Figure 1.1 gives a better understanding of oblique and orthogonal cutting. Orthogonal cutting is considered for representing a two-dimensional cutting process. From this relatively simple two-dimensional process, the findings from orthogonal cutting can be extended to complex three-dimensional oblique cutting processes.

Figure 1.1: (a) Orthogonal cutting and (b) Oblique cutting [1]

Figure 1.2 shows a layer of the workpiece with a thickness t_0 , termed uncut chip thickness, which is removed from the workpiece by the tool. The tool is moving orthogonally towards the workpiece at speed ' V_c ', namely the cutting speed. The two interfaces on the cutting tool with chip and workpiece are shown in Figure 1.2. The chip of thickness ' t_c ' slides over the rake face of the tool, which is inclined at an angle ' α ' (the rake angle) to the cutting velocity direction. The rake angle can be negative or positive depending on the specific operation. The other face is the flank face that is in contact with the newly formed surface of the workpiece and is usually inclined at an angle (the clearance angle) to facilitate the formation of a smooth surface.

Figure 1.2: Two interfaces of orthogonal cutting

The thicknesses of the chip ' t_c ' are usually larger than the uncut chip thickness ' t_0 ' due to heavy shearing of workpiece material during the machining process. The deformation occurs mainly in two zones, namely the primary and secondary zones, see Figure 1.2. The deformation in the primary zone is mainly due to shear and is idealised as occurring in a thin plane called the shear plane. During machining, these deformation zones would undergo severe deformation with a strain range of 2–4 and strain rate range of 10^4 – 10^6 s⁻¹, and temperatures can reach the melting point of the workpiece for given cutting conditions [2].

Improving the machining process is certainly needed for many reasons, as even a small improvement can have an enormous impact at high production volume. These reasons include demand for more precise parts, the trend towards miniaturisation and the need for environment-friendly manufacturing process, as current machining process involves lubricants and cutting fluids that are not environmentally friendly. The performance of the machining process is associated with various aspects and is gauged based on many factors. Byrne et al. [3] in Figure 1.3 illustrate the interrelation of machining performance with tool life, accuracy, surface roughness, cutting force required and chip breakability.

Figure 1.3: Machining Performance (modified from [3])

1.1 Background and Motivation

The need for research in this area can be ascertained by raising the relevant research questions. These questions and the subsequent answers provided will give an overall idea and background of the research.

1. To what extent is there a need for sustainable techniques (such as utilisation of textured tool) in manufacturing, in particular for aluminium?
2. In what way are surface textured cutting tools beneficial, in particular for aluminium, as compared to other sustainable manufacturing technologies?
3. How do surface textures on the cutting tool affect the cutting mechanism in aluminium and in what way do they influence the cutting tool performance?
4. What are the limitations or negative effects of using texture effect for cutting tools for aluminium in manufacturing?

1.1.1 The need for sustainable techniques in manufacturing

Advancements in manufacturing technology are always needed to address the new challenges to machine new materials and make the machining process more efficient and environmentally friendly. Of late, there has been a need to machine materials with low thermal conductivity and high melting points. The problem with machining such materials is that a rapid rise in temperature in the cutting zone will ultimately lead to tool damage. This problem was addressed using a large amount of cutting fluids, namely flood cooling, which not only reduced the heat in the contact zones but also carried away the debris formed while machining. These cutting fluids could cause skin and lung diseases to machine operators and non-malignant respiratory problems. Cutting fluids are harmful not only to human health but also to the environment. The disposal of the used cutting fluids has become difficult with the stringent environmental obligations.

For addressing these problems, the industries are focussing on moving from flood lubrication machining to MQL (minimum quantity lubrication) and dry machining (which requires no lubrication). However, machining under such conditions involves high friction and

adhesion and thus will damage the tool earlier and result in a reduction of tool life. King et al. (2001) [4] reported that cutting fluid related costs in wet turning (including costs associated with the fluid purchase, maintenance disposal) were found to account for 20% of the total machining cost, whereas tool costs were found to account for only 3% of the production cost. It is not advisable to invest a larger portion of machining cost for the benefit of increased tool life. It is more advisable, and with cheaper cost, to accept a reduction in tool life instead of spending a larger amount on cutting fluids. Of course, the time spent for changing the damaged tool will result in extra operating cost; however, considering all factors, including the health and environmental hazards, there is a necessity to shift towards sustainable manufacturing that involves little or no cutting fluid.

1.1.2 Surface texturing is more beneficial than other sustainable technologies

Many attempts have been made to achieve sustainability, including improvement in tool material, tool geometry, lubrication, cooling, controlled environment machining, coating and vibration assisted machining. Though these attempts are efficient to some extent, the problem is not fully addressed. The major loss of energy in the tool-chip/workpiece interaction zones is due to friction. The use of lubricants and/or coolants helps to solve this problem to a certain extent, but practically it is difficult for the fluid to reach the interface zones during machining. It is estimated that 30–50% of the energy supplied is only used in machining and almost 25–60% [5] of the energy supplied is wasted in the interaction zone.

To address this problem and to achieve sustainable manufacturing, the texturing of the tool surface is proposed. The texture on the tool surface can be beneficial in two ways; firstly, the textures reduce the actual contact area of the interaction zone. Secondly, the textures can act as reservoirs of lubricants in wet cutting or as air pockets in dry cutting within the interaction

zone. Thus, the surface textured cutting tool is useful for reducing the energy losses due to friction and beneficial for tool based sustainable manufacturing technologies.

1.1.3 Mechanisms explaining how the texture effect improves the performance of cutting tools

It is expected that micro textured tools will contribute to improving the performance of cutting tools due to the following mechanisms:

- Reduction in friction by reducing the actual contact area in the textured cutting tool; the reduction in contact area is caused by an interruption of the area of texture units in the contact plane surface of the tool-chip contact. The textures were also found to contribute to reducing the contact length, and thereby, further reducing the contact area.
- Enhancement of the lubrication in the contact zone as the textures acts as micro-reservoirs for lubricants within the contact zones. The textures are filled with either liquid (wet cutting) or with solid lubricants (dry cutting) that will be released during the cutting process in the contact zone, which is otherwise impermeable. The release of lubricants will improve the frictional conditions between the contact surfaces. Even during absolute dry cutting (textures without any filled lubricants), the texture units are expected to act as air pockets in the contact zone and will result in a reduction in friction and a reduction in actual contact area and thereby increases the tool performance.
- Textures can be made in such a way that the overall tool surface has properties similar to that of hydrophilic surface with improved surface property against the sliding of the chip or workpiece material, as in the case of textured seals where the

textures acted as a hydrodynamic bearing and improved the load carrying capacity.

It is also possible in practice to mimic some of the naturally superior surfaces, say for instance a lotus leaf or snake scales or shark scales to harness the advantage of surface property. Such surface properties can be achieved by the application of textures.

- Textures are expected to reduce the cutting temperature by two mechanisms: friction reduction and heat dissipation. Reduction in friction due to the presence of textures will lead to less heat generation. In addition, the introduction of texture into the contact zone will increase the overall surface area which will facilitate faster heat dissipation, and thereby reduce the cutting temperature. The reduction in cutting temperature also influences the strength of work material (the higher the temperature, the lower the material's strength).
- Tool life is usually asserted based on the crater wear and flank wear depth; the presence of texture on these wear-occurring regions might provide not only anti-wear property but is also likely to offset the position of the maximum wear depth point.

1.1.4 Limitations or negative effects of using texture effect for cutting tools

- Texture can worsen the strength of the tool as a result of being made very near the cutting edge, which might lead to cracks or catastrophic failure.
- The texture edges can act as micro cutting edges or secondary cutting edges. Such edges on the rake and flank faces will waste energy for cutting the formed chip and might damage the newly formed surface on the workpiece.

- Texture can also result in a rougher surface due to more restriction to the chip flow; the chip flow restriction will be higher for adhesive material like aluminium and will increase friction in the contact zone. The increased friction ultimately might lead to an increase in cutting forces.
- In the course of the cutting process, the texture might be filled with work material and get clogged resulting in a nil effect.
- The cost and time spent on texturing the cutting tool should be reasonable compared to the resulting advantages. It should, however, be highlighted that the methodology used in this study for research purpose might seem to be costly, in terms of time taken for texturing and the equipment used. However, this cost will be greatly reduced when texturing is applied during the production of the tool itself.

1.2 Gaps identified and addressed in micro-texture utilisation in cutting tools

There are many investigations of employing texture tools for the cutting of steels and titanium alloys indicating the beneficial effects of the texture tools. There are few investigations on the cutting of aluminium, although the cutting of aluminium occurs extensively. Unfortunately, the beneficial outcomes of using a texture tool for cutting of steel and titanium cannot be assumed to be also applicable to aluminium without further investigation. This is because the mechanisms and issues associated with cutting of aluminium, a comparatively soft material, are rather different from the cutting of steel and titanium alloys (much harder materials). The major issue with aluminium cutting is adhesion, whereas the major issue with steel and titanium alloys is the high temperature in the cutting zone. As such,

it can be expected that this research will have significant impact if the range of texture geometry for having beneficial effects for given aluminium cutting conditions can be established.

Though micro-textures were utilised on the cutting tool, the science behind the texture effect has not been studied in detail. The optimized texture units in terms of their geometry and distribution are yet to be identified. To the best of the author's knowledge, the tribological behaviour changes during the cutting process caused by the introduction of textures were not reported; the change in the cutting mechanism with the presence of texture was not fully explained in the literature and the study of the micro-texture effect by numerical simulation was also not reported in detail. The simulation will help to understand, estimate and optimise the texture effect in terms of texture size, shape, placement, orientation and cutting conditions.

1.3 Objectives of the thesis

This research aims to study the influence of texture on cutting tools. The overall view of the research proposal is shown in Figure 1.4. It schematically shows the aim and the proposed scope as follows:

- To create micro-textures on the cutting tool surface close to the cutting edge without deteriorating the strength of the cutting tool edge.
- To understand the fundamentals and benefits of using textures in the cutting tool.
- To find the effect of texture size and distribution on the cutting tool performance parameters.
- To study the effect of texturing in the cutting process through simulation using Finite Element Analysis (FEA).

- To estimate the change in the tribological properties of the cutting tool surface under the actual high-stress condition of metal cutting. An experimental study is to be made in a tribometer using equivalent cutting conditions.
- To identify the changes in cutting phenomena when textures are present by the utilisation of acoustic emission signals.

1.4 Methodology and work scope

Micro-textures are created on cutting tool surfaces near the cutting edge either using EDM or laser micromachining. High speed steel and tungsten carbide tools have been textured. Texturing is done on rake, flank or both rake and flank faces of the tool. Dimples and stripes are the two types of textures investigated in this study. The textured tools are used to cut the workpiece orthogonally. Both strip cutting and tube cutting were conducted. An experimental investigation of the texture effect is done in terms of cutting forces, friction coefficient, shear angle, contact area and adhesivity of workpiece material on the tool surface. A detailed study of the geometric and distribution parameters of dimple textured tool is made with the help of the Taguchi methodology of experimental studies. A tribological study is made to study the improvement of friction conditions due to the texture in the contact zone at actual cutting conditions. A FEM (Finite Element Modelling) simulation model was developed to analyse the texture effect and study the change in chip formation due to texture introduction. The simulation model is validated for the observable phenomena, and the validated model has been used to explain and predict the trends of texture effect in terms of forces, temperatures, stresses and strains distribution. A new method for investigating the texture effect using acoustic emissions was proposed.

Figure 1.4: Aim and scope of the thesis

1.5 Thesis outline

- In Chapter 1, the thesis begins by introducing the cutting process with background and motivation about the research topic. This chapter formulates the research questions and their explanations followed by the objective and thesis structure.

- Chapter 2 introduces the relevant works that have been reported so far in the field of micro texturing of cutting tools. A table is presented as an overall summary and to compare the works reported. This chapter also discusses the agreements, disagreements and explanations offered by researchers who worked on the texture effect on cutting tool in terms of each parameter considered under the study.
- Chapter 3 describes the experimental details, machines and instruments used, the methodology used to measure the performance parameters, the experimental results and a discussion of the results obtained.
- Chapter 4 gives a statistical study on the influence of texture-geometric parameters (texture shape and size, depth, pitch and distance of texture from the cutting edge) using the Taguchi methodology and ANOVA.
- Chapter 5 demonstrates the change in chip morphology due to the introduction of texture on the rake face using the FEM simulation model. In this chapter, a comprehensive investigation is also conducted to study the effects of micro-textures in terms of parameters that are difficult to study using experimental methods.
- Chapter 6 presents the changes in the tribological behaviour of surfaces due to texturing under simulated cutting conditions. This chapter also gives an idea on how textures can be implemented effectively to reduce the friction between the contact surfaces.
- Chapter 7 proposes a new method, namely by employing Acoustic Emissions (AE), to study the change in cutting phenomena due to the texture introduction. AE signals are obtained from the cutting experiments for textured and non-textured tools and

are analysed to identify the changes in signal parameters to be correlated with the change in cutting phenomena due to textures.

- Chapter 8 concludes the thesis with an overall summary and recommendations for future work.

Chapter 2: Literature review

Surface textures have been effectively used in various applications. Surface texture can be used to modify cutting mechanisms and thereby, properties such as friction, wettability, reflectivity, absorptivity, adhesion and hydrophobicity. Research has shown the potential benefits of modifying surface topography in tribological contacts including for face seals, thrust bearings and piston rings. The benefits of surface texture include load-bearing capacity improvement [6], friction reduction [7], surface damage reduction [8] and service life increment [9]. Evans et al. [10] explained the functionalization of tool surfaces by textures. Recently a large number of investigations have been carried out utilising surface phenomena at micro/nano-scale to enhance the tribological advantage in machining operations. The mechanisms responsible for the improved performances are relative to the application and conditions in which surface texturing is utilised.

2.1 Performance of cutting tools

During the metal cutting process, any action that facilitates easy removal of material in the form of chips will improve the performance of the tool. The performance of the tool is usually assessed in terms of tool life, the amount of energy consumed to remove a specific amount of material and the finish quality of the newly formed surface. These factors are interdependent and are related to physical factors, such as friction and contact area. A very high friction occurs as the chip flows over the surface of the tool. The force exerted due to the relative motion during cutting causes an increase in contact area between the tool and the chip surface. Relative motion between the chip and tool surfaces produces frictional heating, resulting in high

temperature at their interface. Sliding speed, high temperature and high pressure in the interface will produce more wear in the tool. Many methods were tested to reduce friction and wear in contacting surfaces, which include improvements in tool geometry [11-13], materials [14, 15], tool coatings [16-20], cutting parameters [21], cutting fluids or lubricants [22], surface finishing [23] and surface texture enhancement [24-26], see Figure 2.1.

Figure 2.1: Factors influencing the tool performance

Surface texture utilisation seems to be attractive because it can make the manufacturing process more sustainable by reducing or eliminating the need for lubrication or cutting fluids. There is a possibility of even replacing the need for coating when textures are developed on the surface to have a friction coefficient less than the coated surface; such examples can be found in relation to biomimicking [27]. Micro-textures are utilised for improving the performance of the cutting tool with the expectation that the micro-textures will contribute to the followings:

- Reduce friction and improve the tribological conditions in the contact zone.
- Enhance lubrication conditions by acting as local reservoirs.
- Reduce the actual contact area.

- Facilitate debris entrapment.
- Reduce the cutting temperature.

2.2 Methods used to generate micro/nano textures

Micro/nano features or textures can be generated on the surface of the tool by many methods. A suitable method for texture generation must be determined based on the material, feature size, machine availability, processing time, cost, accuracy and repeatability. Table 2.1 lists the possible methods that are demonstrated to produce micro-features for different applications, which can be utilised for producing micro-texture in a cutting tool surface. The methods presented in the table are based on the generation principle by which the textures are produced, such as removal, addition, etching, ablation or deformation. Some of the references cited in the table demonstrate the texture generation on cutting tools.

Though many methods are available for micro-texturing, each has its advantages and disadvantages. Important requirement to produce a micro-texture tool is repeatability and controllability. Considering the minimum feature size, laser and focussed ion beam machining would be rather appropriate. However, the processing time and need of vacuum chamber for ion beam machining means that laser machining will be a better choice for micro/nanoscale textures. As texturing HSS and WC tools are the key candidates for cutting, both of which are conductive, EDM appears to be a good candidate in terms of micro size, repeatability and controllability. EDM is limited to microfeatures, whereas picosecond and femtosecond lasers could produce micro as well as nanoscale features. Out of all these methods for producing micro features, picosecond and femtosecond lasers and EDM seem to be promising methods and were selected to generate micro-textures.

Table 2.1: Methods demonstrated to produce micro/nano textures

Principle	Methods	References	Limitations / Advantages
1. Mechanical Force	Shot blasting	Nakano et al. 2007.[28]	Limitation in size, repeatability and accuracy of the features
	Machining: Shaper	Nakano et al. 2007. [28]	Limited to regular shapes
	Micro-grinding	Xie et al. 2012. [29, 30]	Limited to stripe texture
	Abrasive jet machining	Wakuda et al. 2003. [31]	Need mask and vacuum.
2. Material deposition	Laser-assisted chemical vapour deposition (LCVD)	Kadekar et al. 2005. [32]	Needs sophisticated reactor & vacuum system – Costly. Chemical and safety hazards
	Localized electrochemical deposition (LECD)	Kadekar et al. 2005. [32]	Inexpensive, reproducible. Maskless deposition of materials. Materials to be electrically conductive
3. Etching	Coating and selective etching, Lithography, Chemical etching.	Chouquet et al. 2010 ; Suh et al. 2010 ; Obikawa et al. 2011. [24, 33, 34]	Control of feature size is much difficult. Chemical usage is environmentally hazardous. The sequence of the process is needed.
	Electrochemical micro-machining / deposition / etching	Zhu et al.[35]; Tang, 2008.[36]	Difficult to control feature size and shape. Chemical and safety hazards.
	LIGA	Malek & Saile, 2004. [37]	Complicated process. The need of x-ray and vacuum make it costlier.
4. Replication	Die Sink EDM	Koshy & Tovey, 2011. [38]	Limited feature size. EDM is only for conductive materials.
	Impression by hardness tester	Jesudass et al, 2018[39]	Vickers and Rockwell hardness tester are used to make texture
5. Melting / Vaporization Thermal	EDM	Deng et al. 2011; Koshy & Tovey, 2011. [38, 40]	Only up to micro size and for conductive elements only.
	Focused ion beam (FIB) machining	Ali et al.2006,2010; Wirth, 2009. [41-43]	Can machine up to nanoscale size but requires a vacuum to process.
	Pulsed arc treatment	Moshkovith et al. 2007. [44]	Only for random texture.
	Cathodic arc vacuum evaporation	Basnyat et al. 2008. [45]	Needs sophisticated reactor & vacuum system
6. Ablation	Laser	Xing et al. 2016 [46] Sugihara et al. 2017[47].	Can process any material and can machine up to the size equal to the wavelength of the laser used.

2.3 State of the art in textured cutting tools research

This section explains the previous work reported by researchers on the surface texture effect on cutting tools. First, the experiments performed by the different research teams are presented. Their findings will then be organized by topics and summarized in the following sections. Initially, research in the field of surface texturing focused on tribological applications. It was only in 2009 that four different groups of researchers, Lei et al. [48], Kawasegi et al. [26], Deng et al. [49] and Sugihara et al. [25] started to report on the contribution of texture effect to cutting tools. Table 2.2 gives the timeline of the published works on texture effect on cutting tools. Based on the authors, the published work is categorised into 12 groups and explained briefly in that order.

Lei et al. [48] presented an experimental study on the performance of micro pool lubricated WC cutting tool (shown in Figure 2.2) for the machining of mild steel. They compared the experimental results of the non-textured tool (under dry and flood coolant conditions) with the micro-textured tool (under oil and solid lubrication conditions). With the use of FEM analysis, they also demonstrated that the strength or integrity of the cutting tool was not affected by the introduction of micro holes. Cutting forces, tool-chip contact length and chip morphology were taken as study parameters.

Figure 2.2: Texture tested by Lei et al. [48]

Kawasegi et al. [26] developed cutting tools (WC-Co) that had either micro or nano textures on their surfaces with depth and pitch ranging from tens of micrometres to hundreds of nanometers. The developed tools are shown in Figure 2.3. A femtosecond laser was used to fabricate micro and nano-textures by the phenomena of ablation and interference respectively. They compared the non-textured tool results from the turning of Al alloy with micro-textured and nano-textured cutting tools. The tools were textured in perpendicular, parallel and cross-patterned textures. Cutting forces and the direction of texturing were taken as study parameters.

Figure 2.3: Texture fabricated by Kawasegi et al. (a) Non-textured, (b) Parallel micro-textured, (c) Parallel nano-textured, (d) Side view [26]

Deng et al. [49] used EDM to make a single micro hole on WC/Co tool on either the rake or flank surface near the cutting edge and filled the micro hole with MoS₂ (solid lubricants). These tools acted as self-lubricated tools and are shown in Figure 2.4. They compared the results of dry cutting of hardened steel for non-textured with rake and flank micro hole self-lubricated tools in terms of cutting forces, flank wear and friction coefficient. Furthermore, in their subsequent publication [40], they increased the number of micro holes in WC/TiC/Co carbide tools and filled them with MoS₂ solid lubricants. They demonstrated that friction

coefficient was reduced for a textured surface filled with solid lubricant by reciprocating sliding tests and dry cutting tests.

Figure 2.4: Tools with micro holes on rake and flank filled with solid lubricants [49]

Song et al. [50] further explored the above study [40] for two more solid lubricants in addition to MoS_2 , see Figure 2.5. They compared the effect of textured tool filled with solid lubricants (MoS_2 , CaF_2 and Graphite) with the non-textured tool in dry condition. They found that a textured tool filled with solid lubricants possesses better cutting properties in terms of cutting forces and the average friction coefficient between tool and chip. It was shown that the improvement in the frictional properties for the tested solid lubricant is very much dependent on the cutting speed.

Figure 2.5: Textured tool filled with different solid lubricants [50]

Table 2.2: Timeline of contributed work on texture on cutting tool

	Group-1	Group-2	Group-3	Group-4	Group-5	Group-6	Group-7	Group-8	Group-9	Group-10	Group-11	Others
2009	Lei et al. [48]	Kawasegi et al. [26]	Deng et al.[49]	Sugihara et al.[25]								
2010				Enomoto et al.[51]								
2011			Deng et al. [40] Wenlong et al. [50]	Enomoto et al. [52]	Koshy et al. [38]	Obikawa et al. [24]						
2012			Deng et al. [53] Wu et al.[54]	Enomoto et al.[8] Sugihara et al.[55]			Xie et al. [30]					
2013			Deng et al.[56] Lian et al. [57] Wu et al.[61]	Sugihara et al.[58]			Xie et al. [29]	Fatima et al. [59]		Ma et al. [60]		
2014			Xing et al.[62] Xing et al.[63]					Fatima et al. [64]		Ma et al. [65]		
2015								Fatima et al.[66] Fatima et al. [67]	Kümmel et al. [68]	Ma et al. [69]		Kim et al. [70]
2016			Xing et al. [46]					Fatima et al. [71]		Ma et al. [72] Qiu et al.[73]	Arulkirubaka ran et al. [74] Arulkirubaka ran et al. [75]	
2017			Zhang et al. [76]	Sugihara et al.[47, 77]			Fang et al.[78]					
2018							Obikawa et al. [79]					Jesudass et al.[39] Gajrani et al.[80]

Deng et al. in their follow-up study [53] fabricated three types of surface textures on the rake face of WC/Co carbide tool filled with MoS₂. These three types of textures have different geometrical characteristics, namely elliptical, parallel grooves (to main cutting edge) and linear grooves, see Figure 2.6. These textured tools were compared with a non-textured tool in terms of cutting forces, temperature and friction coefficient.

Figure 2.6: Texture with different geometry characteristics [53]

Wu Ze et al. [54] studied both rake and flank textured tools (WC/Co tool) filled with MoS₂ for the cutting of Ti-6Al-4V. The flank and rake of the textured tool are shown in Figure 2.7. Parameters such as cutting forces, cutting temperature, chip thickness ratio, friction coefficient and tool wear were assessed to compare the performance improvement of the developed textured tools.

Figure 2.7: Texture on both rake and flank of the tool [54]

Deng et al. [56] further explored nano-textures effects while their previous studies were concerned only with micro-textures. They fabricated nano-textures on the rake face of carbide tools (WC/TiC/Co) and deposited WS₂ solid lubricant over the texture, as shown in Figure 2.8. They compared the performance of nanotextured tools with/without WS₂ coating with the non-textured tool. Lian et al. [57] and Deng et al. [56] presented similar experiments and results.

Figure 2.8: Nano-texture on rake face [56]

Wu et al. [61] proposed a novel method combining the idea of self-lubrication and self-cooling by micro-texture and pulsating heat pipe, respectively. Laser and EDM were used to produce their hybrid tools, illustrated in Figure 2.9. In their study, they developed three micro-textured tools: self-lubricating, self-cooling and self-lubricating with cooling enhancements.

The cutting performance was assessed in terms of cutting forces, cutting temperature, chip morphology and tool wear for the cutting of Ti-6Al-4V alloy in dry condition.

Figure 2.9: Hybrid-self-lubricating and cooling tools [61].

Zhang et al. [76], who conducted cutting experiments on AISI 1045 with TiAlN coated rake textured tools in the regimes of full and starved lubrication, reported that textured tools were more efficient under the full lubrication condition. Xing et al. [62] fabricated Al₂O₃/TiC tools coated with WS₂/Zr and three types of nano-textured tools, namely perpendicular, parallel and areal textures that were also coated with WS₂/Zr. The developed tools are shown in Figure 2.10. In their study, they compared non-textured tools with tools coated with WS₂/Zr and found that the coated tool is effective in terms of cutting force and friction coefficient. Then they compared the three coated nano-textured tools separately. Indeed, better comparison would have been made if the tools were compared together so that the coated-nanotexture effect could be observed effectively in comparison with the non-textured tool.

Figure 2.10: Three kinds of developed nano-textured tools [62]

Xing et al. [63] in their following study developed a combined nano/micro texture on the $\text{Al}_2\text{O}_3/\text{TiC}$ ceramic tool and burnished the textures with MoS_2 solid lubricants. They used a femtosecond laser to fabricate the micro-textures in different orientations, namely parallel, perpendicular and wavy-parallel to the cutting edge, and the nano textures were made only at the chamfer of the main cutting edge. The tools developed are shown in Figure 2.11. It was supposed that such a configuration would overcome the limitation that fully micro-textured tool where textured should be made only after a certain distance from the cutting edge in order not to affect the integrity of the cutting tool. Since nano textures will not affect the strength of the cutting tool, and to make use of texture effect on the region between micro-texture and the cutting edge, such a configuration was proposed. They conducted a cutting test with the developed tool on hardened steel and compared the cutting results with the non-textured tool.

Figure 2.11: Combined nano/ micro-textured tools [63]

Xing et al. in their very recent study [46] produced three types of textures on the rake surface of a cemented carbide tool that has different geometric features as shown in Figure 2.12. They conducted a dry orthogonal cutting test on Al 6061 using the developed textured tools and non-textured tools. The texture geometry effect on the cutting performance for the developed tools was assessed in terms of cutting forces, chip compression ratio, friction coefficient, shear angle, chip morphology, machined surface quality and tool adhesions.

Figure 2.12: Textured tool with different geometric features

Sugihara et al. in their series of papers [8, 25, 47, 52, 55, 58] experimentally studied the parameters of texture and their effect on the cutting process. They used a femtosecond laser to produce the nano/micro-texture on the surface of the cutting tool. Though aluminium alloys are easy-to-cut, it is to be noted that the cutting of aluminium alloys has serious challenges, such as low lubricity and strong adhesion to the cutting edge of the tool, which would lead to tool breakage. To counter these difficulties, Enomoto et al. [51] proposed a functionalization of the tool surfaces by textures as a solution with the idea to retain the cutting fluid and to reduce the actual contact area of the tool-chip interface. They fabricated nano/micro-textured on cemented carbide tools with grooves parallel and perpendicular to the main cutting edge after texturing the tool surface with DLC coating. They conducted the cutting test in both dry and wet conditions for the developed tools and the non-textured tools.

The anti-adhesive effect of the textured tool is further improved by banded nano/micro-textured tools [25]. The banded textured tool was fabricated in such a way that the band of nano/micro-texture is sandwiched between polished regions to retain the cutting fluids and to increase the fluid retention in the textured region, see Figure 2.13. They compared the previous published results with the newly developed tool for wet condition. In their subsequent publication, Enomoto et al. [52] used the same experimental results to discuss the mechanism for the improvement of anti-adhesive properties by texturing the cutting tool.

Figure 2.13: Banded nano/micro-textured tool [25]

Sugihara et al. demonstrated that nano/micro-textured surfaces coated with DLC significantly improved the anti-adhesive properties and the lubricity at the tool-chip interface in wet cutting, but the difficulty was not solved for dry cutting [55]. To overcome the chip adhesion problem in dry cutting, they designed nano/micro-textures on a cutting tool surface with a varying width of the convex and concave areas of the stripes. From their experiments, they demonstrated that the micro-textures could significantly improve the cutting performances

in terms of anti-adhesive properties not only in wet conditions but also in dry cutting without any surface coatings.

Figure 2.14: Tools with textures with different size and pitch [55]

Enomoto and Sugihara [8] extended their study to steel cutting by a textured tool with the idea of improving the tool life by reducing wear using the textured tool. They developed TiAlN-coated cutting tools with periodical stripe-grooves parallel and perpendicular to the cutting edge with varying depth and pitch, experimented with various cutting lengths and compared them with non-textured tool results. They reported that rake textured tools with periodic stripe-grooves displayed high crater wear resistance in steel cutting. In their subsequent study [58], cutting tools with both rake and flank surfaces textured with micro stripes were developed and were found to be effective in steel cutting of by suppressing both the crater wear and flank wear even under dry cutting conditions. In a recent study [47], they developed dimple-shaped textures only on the tool rake face to experimentally determined the effective texture dimensions and patterns. Dimple-shaped textures shown in Figure 2.15 were compared with groove-shaped textures to demonstrate the improvement in crater wear resistance caused by dimple textures in a severely lubricated environment.

Figure 2.15: Dimple textured tool [47]

Koshy and Tovey [38] used EDM to texture the rake face of the cutting tool. They demonstrated that textured cutting tools brought significant reduction in cutting forces by enhanced lubrication of the tool-chip interface in the machining of both steel and aluminium. Obikawa et al. [24] studied the micro-texture effect on the tool rake face in the orthogonal cutting of an aluminium alloy. They fabricated four types of microsurfaces on the rake face of a cemented carbide tool through spattering, photolithography and wet etching; the tools were also coated with either DLC and TiN. The developed tools shown in Figure 2.16 were tested and compared with the non-textured tool for the machining of aluminium alloy A6061-T6, for cutting forces, coefficient of friction and condition of the tool surface.

Figure 2.16: Textured tool with different geometric shapes [24]

Xie et al. [30] used micro-grinding to fabricate micro-groove textures on the tool rake surface. The fabricated tool is shown in Figure 2.17. They proposed micro-grooves on the tool

rake face as an alternative to coolant, to rapidly dissipate cutting chips and heat from the cutting zone for machining of titanium alloy. They conducted dry turning of titanium alloy with the developed orthogonal and diagonal micro-grooved tool. They compared the developed tool performance with the non-textured tool in terms of tool wear, surface roughness, chip topography and shear angle. In their subsequent study [29], they varied the micro-grooves depth and aspect ratio to understand their influence in cutting force and cutting temperature during turning of a titanium alloy under dry conditions.

Figure 2.17: Micro-grooved tool produced by grinding wheel [29]

Fatima et al. [64] used laser machining to fabricate micro and nano textures on tools rake faces to improve the tool-chip contact phenomenon. They conducted a systematic study on laser parameters to identify the best combination of parameters to produce the texture on carbide tools. They made a case study on steel cutting with textured tools and demonstrated the texture effect in terms of reduced cutting forces in comparison with the non-textured tool. Furthermore, an experimental study was conducted [59] on cutting tests based on the Taguchi experimental design to assess the texture dimension and distribution on the rake face of the cutting tool. They found that the distance of the texture from the cutting edge is the most

significant factor. They also reported that textures reduced the length of the sticking zone and weight percentage concentration of material transferred from the chip to the tool rake face.

In their subsequent study [66], they fabricated textures on both rake and flank faces of the cutting tool with a view of decreasing tool wear and cutting forces so as to reduce the power requirement. The effect of the textured tool was assessed in terms of cutting forces, friction coefficient and flank land wear rate by testing the developed textured tools in AISI/SAE 4140 cutting. In their recent study [71], they investigated the flank texture effect alone in cutting over a range of cutting speeds.

More interestingly, Fatima et al. [67] developed a bio-mimicked design for textures on the flank face. They obtained the nature-inspired design from ball python scales; these creatures have high resistance to damage because of their skin surface design feature. They replicated the scale design on the flank face and examined the performance of the developed tools in comparison with the conventional groove textured tools and non-textured tools. Results showed that nature-inspired design structures significantly reduced forces, temperature, compression ratio, contact length and power consumption. The nature-inspired textured flank tools developed By Fatima et al. are shown in Figure 2.18.

Figure 2.18: Flank groove textured tool [71] and bio-mimicked flank textured tool [67]

Jiang et al. [81] fabricated a bio-inspired textured tool (inspired from shark teeth and sea urchin surface architectures), but unlike all the other textured tools reported in this section, the texture was formed by an additive method. They produced a 3D textured coating surface formed with cubic boron nitride in soft titanium nitride matrix over the cutting tool surface, analogous to a sea urchin structure. The tool surface had serrated edges with a tip placed along their cutting edges like that of shark teeth.

Kümmel et al. [68] developed uncoated dimple, parallel and perpendicular channel textured tools as shown in Figure 2.19. They found that these textures on the rake surface changed the adhesion tendency of the BUE on the cutting tool, which is associated with tool wear and surface finish of the machined workpiece in the dry turning of steel SAE 1045.

Figure 2.19: Dimple, parallel and periductular channel textured tools [68]

Dinesh et al. [82] conducted an orthogonal turning study of ZK60 magnesium alloy with parallelly and perpendicularly textured WC cutting inserts under both dry and cryogenic conditions. They found that parallel textures under cryogenic conditions considerably reduced the contact area between the tool-chip interfaces, thereby minimising the frictional effects when compared to non-textured tools, owing to the coupled effect of micro-pool lubrication and the formation of thin-film lubrication.

Recently, Fang et al. [78] studied the effect of high-pressure jet coolant on flank textured tool made of CNMG120408 and in the cutting of Inconel 718. They analysed the flow patterns of coolant on the textured tool face using CFD and found that the textured tool increases the tool life. They attributed that the micro-textures increase the turbulent kinetic energy and results in the cooling of the tool face. Following this study, Obikawa, et al. [79] studied steel cutting with three types of flank textured tool namely parallel, perpendicular and crosshatch grooves with low-pressure jet coolant. They found that the jet coolant and flank texture on the cutting

tool increases the tool life by more than 100% in comparison with the non-texture tool. Gajrani et al. [80] studied flank texture on uncoated carbide tool in cutting of cast alloy 718. In comparison to a non-textured tool, they found that the flank wear is reduced by 20–35%, tool-chip area and flank wear area by 12–17%.

Texture geometry and its distribution have a key role in the performance of the textured cutting tools, together with material, geometry and cutting conditions. Table 2.3 gives an extensive summary of the previously reported work on the effect of micro/nano-textures on cutting tools with the view to increase the performance of the cutting tools. The table summarizes the materials used, geometry, cutting conditions, fabrication method, texture dimensions and their orientations as reported by the authors. The table also gives the significance and contribution of the work done in chronological order. The following sections will discuss the results of the reported studies factor by factor.

2.3.1 Tool and workpiece

Research on the tested tools so far were made of HSS tools [38], Al₂O₃/TiC ceramic tools [62] and tungsten carbide tools [55]. Researchers have tested positive [58], negative [46] and zero [66] rake angle tools for texture effect. Though positive rake angled tools were effective in terms of material removal mechanism, a trade-off between material removal mechanism and tool strength or tool life for hard to cut materials means that these materials were usually cut with negative rake angle tools. The workpiece materials studied by the researchers for the texture effect ranged from soft to very hard materials, including aluminium [46], magnesium [82], steel [71] and titanium alloys [30]. It can be stated that the main objectives of these studies were to reduce the adhesion in aluminium, wear in steel and both wear and heat (spark [30]) in

the case of titanium, together with the common aim to shift to more sustainable manufacturing processes by reducing or eliminating the use of cutting fluids.

2.3.2 Micro/ nano-texturing

Laser micromachining is used by many researchers [8, 25, 26, 55, 56, 58] for producing the textures on the cutting tools, but other methods such as EDM [38, 40], photolithography [24], micro-grooving [29, 30] are also used to produce the textures. Researchers have conducted cutting experiments for both nano-textured tool and micro-textured tools and their combinations. Micro-texture dimensions range from 10 to 300 μm in lateral dimension and from 5 to 200 μm in depth. The nano-texture dimensions depend on the wavelength of the laser utilised and range from 100 to 200 μm in lateral dimension and 150–200 μm in depth. Kawasegi et al. [26] showed that the workpiece material adhered to the tool surface of a micro-textured tool more than a nano-textured tool. On the contrary, Sugihara et al. [55], observed that micro-stripe textured tools have better adhesive resistance than the nano-textured tool, particularly in the dry cutting of aluminium [55]. Deng et al. [49] and Ze et al. [54] reported that rake textured tools are more effective than flank textured tools when both are filled with solid lubricants in machining hardened steel. Xie et al. [29] stated that the micro-groove should have a smaller width than the cutting chip and large groove depth to maintain the air space between chip back surface and tool rake surface.

2.3.3 Texture shape and orientation

A variety of shapes have been proposed for texturing: circular dimples [46, 47], stripes [55] (of various depth, concave and convex regions width, parallel, perpendicular, oblique), ellipse [53], square pits [24], rectangular pits [46], square dots [24], cross [26], V grooves [30],

(parallel, perpendicular, oblique), areal [38, 62], wavy stripes [63] and snake scale-shaped [67]. The texture could be formed on the tool surface either by digging or by protruding structures on the surface. The textures produced may have height, as in the case of micro bumps [24, 65], or depth, as in the case of dimples and stripes [46, 55] (i.e., textures with depth or height) in the tool surface.

The textures orientation plays a major role in the performance of the cutting tool. In this report, the orientation of the main cutting tool edge is used as a reference. Parallel, orthogonal, cross, pits and dots textures are shown in Figure 2.20. Parallel textures are those for which stripes are parallel to the cutting edge. Likewise, perpendicular textures are those for which stripes are perpendicular to the cutting edge. It is to be noted that some researchers such as Kawasegi et al. [26] used the chip flow direction as a reference for naming the orientation, which is opposite to the adopted nomenclature here.

Figure 2.20: Textures differ by orientation (a) perpendicular[63], (b) parallel [63], (c) oblique [30], (d) pits [24], (e) dots [24] (f) ellipse[53]

Obikawa et al. [24] reported that micro-textures with parallel groove pattern performed better than a non-texture tool and other tested textured tools while machining aluminium. It

was also stated that smaller and deeper micro-texture patterns displayed most effective lubrication. Sugihara et al. [55] tested various tools in both dry and wet conditions of varying pitch and size of the valley and flat, as shown Figure 2.21. They found that micro stripe textures with grooves of 5 μm depth, 20 μm width and 50 μm convex and concave performed very efficiently in terms of anti-adhesive properties. On the contrary, Koshy and Tovey [38] concluded that areal texture was more effective than groove texture. Similarly, Xing et al. [62] said that areal textures were more effective than that of banded textures, except that in Xing et al., the textures were nanoscale and WS_2/Zr coated.

Figure 2.21: Change in adhesion due to change in texture size and [55]

Sugihara et al. [55] found that parallel textures are more effective than perpendicular textures in improving the cutting tool performance. Deng et al. [53] stated that elliptical textures were more effective than parallel textures. Xing et al. [63] in their study found that wavy microscale textures on the rake face are more effective than parallel and perpendicular textured tools in improving the performance of the cutting tool. Xing et al. [46] in their latest

study stated that tools with the rectangular type of textures are the most efficient in terms of cutting forces and friction coefficient, anti-adhesivity and surface quality of the newly formed surface. Sugihara et al. [47] in their latest study stated that discontinuous textures or close shape textures are more effective than continuous textures or open type textures, particularly in the case of dry cutting. They demonstrated that textures in the form of dimples (discontinuous/closed shape textures) performed better than open type groove textures.

2.3.4 Rake/flank face texture

Researchers have been studying the effect of surface textures in the cutting tool, either on the rake surface [29], flank surface [71] or on both rake and flank surface [58, 66]. The main objective or the effect expected from the rake textures is that the change in friction between chip and tool rake surface could result in a change in shear angle, chip morphology, reduction in crater wear; these might then lead to an improvement in performance of the tool. The flank texture effect was studied with the main objective to reduce the flank wear, thereby increasing the tool life. Ze et al. [54] reported that rake textured tool showed the lowest cutting forces, temperatures, friction coefficient and chip thickness ratio. The flank textured tool showed the highest improved tool life of 10 to 30%.

2.3.5 Cutting conditions

Researchers have reported cutting tests conducted for a textured cutting tool with cutting speeds ranging from 2 to 840 mm/min and depth of cut ranging from 0.025 to 0.3 mm. Deng et al. [40] demonstrated the dependency of the textured tool effect on the cutting speed. They stated that the texture effect is more effective only at low-speed cutting, that the effect is almost negligible at high speed cutting in terms of cutting forces and friction coefficient, and that the

textured tool behaved very similarly to a non-textured tool at higher cutting speeds. Wu Ze et al. [54] reported that the cutting forces and temperature reduction for the rake textured tool is more apparent at a low cutting speed. Koshy et al. [38], Deng et al. [56] and Ze et al. [54] found that the effectiveness of textures decreased with an increase in cutting speed. The reason could be the decrease in the lubrication effectiveness with an increase in cutting speed, as the cutting speed is inversely proportional to the distance to which lubricant can penetrate [38]. Xing et al. [46] also showed that at low cutting speeds, the performance of the textured tool is improved, and that the lubricity at the tool-chip interface is effective. When increasing the cutting speed above 219.6 m/min, lubricity was found to decrease and had the possibility of even becoming counteractive.

2.3.6 Dry cutting

Though the manufacturing industries aim for dry cutting, there should be an alternative to the functions that cutting fluids are employed to do. The cutting fluids help in increasing lubricity, reducing the cutting temperature, carry away the debris and the chips. Texturing was proposed as a good alternative to the flood coolant lubrication of cutting fluid, either under MQL or dry cutting. Researchers reported the effective use of texture in wet cutting and dry cutting with the idea that in wet cutting, textures acted as a reservoir for lubricants and in dry cutting, textures acted as air pockets. In both cases, these textures are inside the contact zones where the cutting fluid in a conventional cutting tool has no access. In both cases, the textures will result in a reduced actual contact area. The friction is expected to reduce as a final effect. Some researchers also stated that textures could act as entrapments to collect the debris produced thereby reducing third body friction.

Chen et al. [83] reported that for dry cutting, the effect of micro-texture diminishes with continuing cutting because of the decrease of the real contact area between tool and chip. This leads to a faster change of friction than that of positive pressure in addition to the failure of the dynamic pressure oil film formation.

The use of texture does not always result in a reduction of friction, which is an adverse effect that can take place and may result in the cutting force being larger than for the non-textured tool. Enomoto et al. [52] reported the negative effect of textured tool in dry cutting in terms of severe adhesion of aluminium chip material to the rake face of the tool. Xie et al. [30] reported the positive effect of textured tool in dry cutting of titanium alloy in terms of increase in stability of the cutting process. In their subsequent study [29], they reasoned that the textures in the form of micro-grooves applied over the tool rake face produced the air spaces between and tool rake surface and cutting chip back surfaces and that these air spaces helped in rapid chip removal and cooling.

Table 2.3: Overview of reported texture effect on cutting tool performance

Year	Author	Material		Tool geometry	Texture					Orientation/ Array type	Study parameters	Conclusions
					V_c	t_o	f_c	Fabrication method	Dimensions			
		Tool	Work-piece		m/min	mm	mm/rev		μm			
2009	Deng et al. [49]	WC-Co textured filled with MoS ₂	Steel	Rake: 10° Flank: 5°		0.2	0.1	Micro EDM	Diameter 200-250 Depth 250	Single micro Hole Rake Flank Non-textured	Cutting force Friction coefficient Wear	Rake textured -lowest friction. Flank textured -lowest wear. The attributed reason is solid lubricant in micro-hole released during cutting forming a lubricating film.
2009	Kawasegi et al. [26]	WC-Co	Al A5052	Rake: 5°	600	0.2	0.1	Femto-second laser	Micro-texture Width :2.2 μm Depth:1.3 μm Nano-texture Depth: 150 nm Pitch: 800 nm	Orthogonal Parallel Cross Non-textured Orthogonal Parallel Non-textured	Force vs type of texture. Speed, Pitch, Depth, Direction of waviness and Nano-texture Friction, Shear angle	Both micro and nano textures reduce μ and F_c . F_c decrement much observed at high cutting speeds.
2009	Lei, Devarajan, & Chang [48]	Tool: WC-uncoated	Work: 1045 steel, cold rolled	Rake: 5° Side: 15°	2.0	1	0.3	Micro EDM	Diameter 70 μm and 200 μm Depth few times diameter	Micro holes	Cutting force Chip morphology Contact area	Compared dry, flood, micro pool (oil and solid lubricant). Micro pool lubrication reduces cutting force. Chip curl for the textured lubricated tool. Shown that micro-holes are not affecting the strength of the tool with the help of FEM model

2009	Sugihara & Enomoto [25]	Tool: WC-Co	Work: Al - A5052 W	Rake: 12.4 °	380	3	0.12	Femto-second laser.	Micro grooves Depth 5 µm Width: 20,50,100 µm Nano/micro textures Depth: 100-150 nm Pitch: 700 nm	Parallel Convex & Concave width (20,50,100 µm) Orthogonal Banded Non-textured.	Concentration of atom vs Texture types Adhesion vs Cutting distance Shear angle Friction coefficient Dry cutting Evaluation texture dimension.	Micro stripe shows anti-adhesiveness in both wet and dry cutting. Parallel grooves 5 µm deep, 20 µm convex and 50 µm concave width is best among tested.
2010	Enomoto & Sugihara [51]	Tool: WC-Co	Work: Al - A5052 W	Rake: 12.4 °	380	3	0.12	Plasma-enhanced CVD with W mask DLC film Femto-second laser.	Micro-texture Depth 0.8 µm Width: 150µm x 150µm Nano/micro-groove texture Depth: 100-150 nm Pitch: 700 nm DLC coated.	Square Parallel Perpendicular Polished	Concentration of Al atom Adhesion area Shear angle Friction coefficient	Chips get clogged in the texture grooves. Parallel- nano/micro-groove textured tool displays improved anti-adhesivity.
2011	Deng et al. [50]			Rake: 8° Flank: 8°	60-220	0.2	0.1	Femto-second laser.	Diameter: 150 µm Depth: 200 µm	Rake textured-one hole, 4 holes Flank textured-one hole		Friction reduction demonstrated by reciprocating sliding and dry cutting tests. The textured effect is observed very much at low cutting speeds.
2011	Enomoto & Sugihara. [52]	Tool: WC-Co	Work: Al - A5052 W	Rake: 12.4 °	3 8 0	3	0.12	Femto-second laser.	Nano/micro textures Depth: 100-150 nm Pitch: 700 nm DLC coated.	Parallel Convex & Concave width (20,50,100 µm) Orthogonal Banded Non-Textured.	Concentration of Al atom Conventional vs Textured tool for Wet and Dry cutting	In wet cutting -chip adhesion is very much reduced for nano/micro texture, but chip adheres severely in case of dry cutting.

2011	Koshy & Tovey. [38]	Tool: HSS	Work: Al steel	Rake: 0°	2-75 2	0.0 25-0.1 0.1	3	Thin shim stock tooling-EDM Die sink EDM	Width :100 µm Depth:100 µm Areal texture	Parallel stripes Random	Force vs Textured and Non-textured tool, Speed, Area textured Cutting force, Thrust force and Friction vs Textures	Textured tool reduces Fc (wet). The areal texture is found to be more effective. Texture performance is high at low speeds.
2011	Obikawa, Kamio, Takaoka, & Osada. [24]	Tool: WC-Co - Ni coated	Work: A6061-T6	Rake: 6 °-6 °	240 420 840	0.1	1	Nickel coating textured Selective etching photo-resist. DLC coated	Width: 25&50 µm Depth: 0.5,1.0 & 1.2 µm Distance from cutting edge: 100 & 150 µm	Parallel Perpendicular Pits Dots	Wet vs Dry Force vs Speed	Parallel, dot type-effective and textures are effective With texture depth ↑ and size ↓.
2011	Wenlong et al. [50]			Rake: -8 ° Flank: 5 °	60-140	0.2	0.1	Femto-second laser	Dia:150 µm Depth: 300 µm	Rake textured-4 holes filled with different solid lubricants		For cutting speed of below 100 m/min - MoS ₂ has good self-lubricating effect, - CaF ₂ shows much-reduced force - graphite shows the steady lubricating effect
2012	Deng, Ze, Yunsong, Ting, & Jie. [53]	Tool: WC-Co	Work: A5052 W	Rake: -5 ° Flank: 5 °	60-300	0.5	0.1	Femto-second laser	Width: 50 µm Depth: 200 µm Filled with MoS ₂	Rake Elliptical, Parallel & Linear	Temperature, Force and Friction at the tool-chip interface for parallel elliptical and non-textured tool.	Rake face elliptical groove textured tool displays best performance in terms of cutting forces, friction coefficient and cutting temperature. Two mechanisms: Reduced contact length at the tool-chip interface. A low shear strength lubricating film is formed in the tool-chip contact zone.

2012	Sugihara & Enomoto. [55]	Tool: WC-Co	Al - A5052 W	Rake: 12.4 °	380	3	0.12	Femto-second laser.	Micro-grooves Depth 5 µm Width: 20,50,100 µm - Convex Concave	Parallel Orthogonal	Evaluation of adhesion Evaluation of cutting forces chip shapes	Micro stripe shows anti-adhesiveness in both wet and dry cutting. Nano/micro-textured tool not effective in anti-adhesive properties for the dry condition. Parallel grooves with 5 µm deep, 20 µm convex, 50 µm concave wide are best among tested.
2012	Toshiyuki Enomoto, Sugihara, Yukinaga, Hirose, & Satake. [8]	Tool: WC-Co	carbon steel S53C	Rake: 12.4	200	2	0.2	Femto-second laser	Polished Coated TiAlN Micro-grooved Depth 1,5 µm Width :20,50 µm Pitch: 20,50 µm Nanotextured 100–150 nm deep and 700 nm apart	Parallel orthogonal	Concentration of Fe atom Conventional vs Textured tool for wear influence of groove depth and direction; width and spacing	In steel cutting, micro-grooves show significant wear resistance and lubricity whereas nano/micro-grooves are not effective.
2012	Xie, Luo, He, Liu, & Tan. [30]	Tool: Carbide tool	Work: Ti–6Al–4V	Rake: 7 ° Flank: 7 °	φ26 150 mm 2000 rpm	1	0.1440 mm	Micro-grooving	Depth 155.1 µm. Micro-groove angle α of 80.25° Micro-groove interval δ of 400 µm Micro-groove tip radius of 45.6 µm	Orthogonal Diagonal	Tool wear Surface roughness Chip topography Shear angle Chip length Chip thickness	Micro-grooved tools may reduce cutting Sparks, tool-chip contact length and tool wear. Although micro-grooved tools cause large surface roughness, they produce more uniform surface quality without chattering strong chip breaking ability and decrease shear angle by about 24.3%
2012	Wu, Deng, Chen, Xing, & Zhao. [54]	Tool: WC-Co	Work: Ti–6Al–4V	Rake: -5 ° Flank: 5 °	60–180	0.2	0.05–0.3	Femto-second laser	Width: 50 µm Depth: 150 µm	Rake elliptical flank linear MoS ₂ filled	Cutting force Friction coefficient Temperature, Chip thickness ratio Tool wear	The rake and flank textured tools exhibit excellent anti-wear property. Tool life is improved by 10–15% and 10–30%, respectively at v=120 m/min.

2013	Fatima & Mativenga . [59]	Tool: cemented carbide - uncoated and flat	AISI 1045 hardened steel	Rake: 0 ° Flank: 7 °	283 m/min	2.5 mm	0.1 mm/rev	Femto-second laser	Width 50 100 150 µm Pitch 50 100 150 µm Depth 10 15 20 µm Distance (de) 100 150 200 µm	Rake textured with stripes parallel to cutting edge	Cutting forces Friction coefficient Compression ratio Contact length Temperature Fe concentration	Distance of the texture from cutting-edge plays a significant role. Texture reduces sticking zone length and adhesion of chip material to rake face of the cutting tool. Texture also shifts the sticking zone further up the rake face.
2013	Deng, Yunsong, Ze, & Youqiang. [56]	Tool: WC-Co Work: Steel		Rake: -5 ° Flank: 5 °	50-250	0.3	0.1	Femto-second laser WS ₂ lubricant	Width: 300 nm Depth: 200 nm Pitch: 700 nm	Rake textured WS ₂ soft coated Uncoated	Cutting force Friction coefficient Temperature Wear track	The rake textured tool with nanoscale surface texturing and WS ₂ coatings display very effective performance in terms of cutting forces, friction coefficient and cutting temperature.
2013	Lian, Deng, Yan, Cheng, & Zhao. [57]	Tool: WC-Co	Steel	Rake: -5 ° Flank: 5 °	50-250	0.3	0.1	Femto-second laser WS ₂ lubricant	Width: 300 nm Depth: 200 nm Pitch: 700 nm	Rake textured WS ₂ soft coated Uncoated	Cutting force Friction - coefficient Temperature Wear	Development of WS ₂ lubricating film with low shear strength from the solid lubricant. Reduces contact length, adhesive wear Improves oxidation resistance.
2013	Sugihara & Enomoto. [58]	Tool: WC-Co with 100 µm wide chamfer.	Steel S53C	Rake: 12.4	200	2	0.2	Femto-second laser	Micro-grooves Depth 5 µm Width :20 µm Pitch: 20 µm	Rake: Parallel & Orthogonal micro stripe grooves Flank: Parallel micro stripe grooves	Cater and flank Wear resistance textures Evaluation of effective texture dimension	Texture suppresses the crater wear even under dry cutting. Wear resistance depends on the geometry of the textures. Flank textures also show wear resistivity.

2013	Xie, Luo, Wu, Yang, & Li. [29]	Tool: Carbi de tool	Ti–6Al–4V	Rake: 0 ° Flank: 0 °	36, 39, 47, 49 m/min	0.1, 0.5	0.1, 0.3 mm	Micro-grooving		Orthogonal Diagonal	Cutting force Temperature Tool wear Chip topography Shear angle	The decrease in the depth of micro-groove from 149 µm to 25 µm results in shearing angle increase and cutting temperature decrease. Texture groove depth should be large enough to maintain the air space between the underside of chip and rake face. Groove width should be smaller than depth of cut
2014	Fatima, Whitehead & Mativenga . [64]	Tool: cemented carbide - uncoated and flat	AISI/SAE 4140 steel	Rake: 0 ° Flank: 7 °	100, 198, 283, 394 m/min	2.5 m	0.3 mm/rev	Femto-second laser	Width 50 µm Pitch 140 µm Distance (de) 300 µm	Rake textured with stripes parallel to cutting edge	Cutting forces Feed force	This study analyses femtosecond laser machining conditions to create micro-textures on carbide tools. The texture can act as a pocket to retain cutting fluid and will reduce real contact area.
2014	Wu, Deng, Chen, Xing, & Zhao.[61]	Tool:	Work: Ti-6Al-4V	Rake: -5 ° Flank: 5 °	60-180	0.5	0.3	Femto-second laser		Triangular grooves Width: 50 µm Depth: 100 µm	Rake elliptical MoS ₂ filled	In addition to the reduction in cutting force and friction coefficient, the textures will accelerate heat dissipation of the cutting insert and reduces the cutting temperature in the machining process.

2014	Xing, Deng, Feng, & Yu [62]	Tool: Al ₂ O ₃ /TiC ceramic tools	AISI 1045 hardened steel	Rake: -5 ° Flank: 5 °	80-260 m/min	0.2	0.2	Femto-second laser	Nano-grooves Width 350–400 nm, Depth 120–150 nm, Period 700–800 nm. Band of 50 µm and 50 µm spacing for parallel and perpendicular textures	Perpendicular Parallel Areal textures Coated perpendicular Coated parallel Coated areal textures WS ₂ /Zr coating	Friction coefficient Cutting force Wear Temperature	The composite coatings of WS ₂ /Zr are effective in terms of reduction of force, temperature and tool wear. The solid lubricant will form a low shear strength WS ₂ lubricating film in the tool-chip interface which results in a reduction of friction, contact length and wear.
2014	Xing et al. [63]	Tool: Al ₂ O ₃ /TiC ceramic tools	AISI 1045 hardened steel	Rake: -5 ° Flank: 5 °	80-260 m/min	0.2	0.2	Laser (10 nS) for Micro-texture Femto-second laser-nano-texture	Micro-grooves Depth: 40-50 µm Width: 40-50 µm Pitch: 150 µm Chamfer : nano-grooves width 350–400 nm, Depth 120–150 nm, Period 750 nm.	Perpendicular Parallel Wavy grooves WS ₂ /Zr coating	Cutting force Chip morphology Friction coefficient Cutting temperature Surface roughness wear	Developed tools increase the surface roughness while reducing the vibration and produce more uniform surface quality. Promote chip curl. Tool wear is significantly reduced due to lubricated film.

2015	Fatima & Mativenga . [66]	Tool: Al ₂ O ₃ /TiC ceramic tools	AISI 1045 hardened steel	Rake: 0 ° Flank: 7 °	100 , 198 , 394 m/min	2.5 m	0.1 mm/rev	Femto-second laser	Width 50 µm Pitch 100 µm Depth 20 µm Distance (de) 150 µm	Rake and Flank textured with stripes parallel to cutting edge	Cutting forces Friction coefficient Compression ratio Contact length Temperature Flank wear	Textured tools show improved performance in comparison to non-textured tool and are measured in terms of reduction in cutting force, feed force, compression ratio, Friction coefficient reduced by 10%, 23%, 17% and 18 % respectively. Further, calculations showed that sticking contact was reduced from 52 to 43 %, cutting temperature and flank wear reduced by 12% and 13% on average respectively.
2015	Fatima & Mativenga , 2015b. [67]	Tool: cemented carbide - uncoated and flat	AISI/SAE 4140 steel	Rake: 0 ° Flank: 7 °	283 , 628 m/min	2.5 m	0.1 mm/rev	Femto-second laser	Width 50 µm Pitch 100 µm Depth 20 µm Distance (de) 150 µm	Non-texture Flank parallel Stripe textured Snake scale inspired structure	Cutting forces Compression ratio Contact length Temperature Flank wear Fe concentration Power consumption	Nature-inspired design structures significantly reduced forces, temperature, compression ratio, contact length and power consumption.
2016	Fatima & Mativenga . [71]	Tool: cemented carbide - uncoated and flat	AISI/SAE 4140 steel	Rake: 0 ° Flank: 7 °	100 , 198 , 394 , 628 m/min	2.5 m	0.1 mm/rev	Femto-second laser	Width 50 µm Pitch 100 µm Depth 20 µm Distance (de) 100,150,200 µm	Conventional Flank parallel Stripe textured Snake scale inspired structure	Cutting forces Compression ratio Shear angle Contact length Temperature Rate of flank wear Fe concentration Surface roughness Power consumption	The developed flank texture tool displays 16% reduction in the sticking 12% decrease in tool temperature 18% increase in tool life 37% reduction in cutting power requirement

2016	Xing, Deng, Wang, Ehmann, & Cao. [46]	Tool: Al ₂ O ₃ /TiC ceramic tools	6061 Aluminium	Rake: -5 ° Flank: 5 °	54.9 to 439.2 m/min	2	0.05	Laser (10 nS) for Micro-texture Femto-second laser-nano-texture	Micro-grooves Depth: 10 µm Width: 20µm for linear, 50 µm for rectangular Diameter 50 µm Pitch: 100,150µm	Linear Circular Rectangular	Cutting force, Chip morphology Friction Shear angle Adhesion Surface roughness	Rectangular discontinuous texture displays very effective cutting tool performance in terms of force friction, anti-adhesion and quality of surface machined.
2017	Sugihara & Enomoto [47]	Tool: Cemented carbide P10, Non-coated tool	Medium carbon steel	Rake: 12.4	200 m/min	2	0.2	Femto-second laser	Micro dimple Depth 5 µm Diameter 30,50,70 µm Pitch: 55,75,95 µm Micro-grooves Depth 5 µm Width :20 µm Pitch: 100 µm	Micro dimple Linear array Zigzag array Micro-grooves	Dry and wet cutting Crater wear Cutting force Friction coefficient	Micro-dimple texture suppresses the crater wear even under dry cutting. Texture acts as micro-reservoir for lubricant and micro-trap for wear debris. Under severe lubricating condition, closed shape textures such as micro dimples perform better than open type textured such as microgrooves.
2017	Fang et al.[78]	CNM G120 408 and S05	Inconel 718	Rake: 6 ° Flank: -6 °	120 m/min	0.5	0.1	Laser	Width 50 µm Depth 10-20 µm Height 10-20 µm	Flank texture 3 types of texture High-pressure jet coolant	Tool life	The flow patterns of the coolant are analysed by CFD. The results show that micro-textures increase the turbulent kinetic energy and result in cooling of tool face.
2018	Obikawa, et al. [79]	CNM G120 408	SUS304 steel	Rake: 6 ° Flank: -6 °	120 m/min	0.5	0.1	Laser	Pin fins Plate fins Pits 0.3 mm away from cutting edge	Flank-microtextured tools- 3 types Jet coolant Low pressure High Reynolds no.	Flank wear evolution Jet coolant + Texture compared with non-texture	Tool life increased more than 100 % microtextured tools and jet coolant compared to machining using flood coolant and a tool without microtexture.

2018	Gajrani et al. [80]	Uncoated Carbide	Cast Alloy 718	Rake: 0° Flank: 7°	30–105 m/min	1 m	0.1–0.3 mm/rev	Laser	Square pyramid Cone Cylinder	Rake and Flank texture	Flank wear Profile measurement Flank wear area calculations Contact area	Reduction in Flank wear by 20–35% Tool-chip contact and flank wear area by 12–17%
2018	Jesudass et al. [39]	HSS	Steel Al	Rake: 4° Flank: 6°	30–110 m/min	0.5 m	0.143 mm/rev	Rockwell Vickers hardness tester Diamond dresser scratch	Micro texture	Lathe dry machining Varying cutting speed	Cutting force, Temperature Surface roughness	Reduction in cutting forces and cutting temperature. Difference in chip formation reported.

2.4 Discussion in terms of response parameters

This section details the results presented by researchers in terms of various response parameters and discusses the agreements, disagreements and attributions made by the researchers in explaining the texture effect. The general trends for each parameter concerning micro-texture effect are also discussed in this section.

2.4.1 Cutting force

Lei et al. [48] reported that textured cutting tools with micro pool lubrication reduce the mean cutting forces by 10 to 30%. Kawasegi et al. [26] also reported the reduction in cutting forces for textured tools and concluded that the texture effect depended largely on the orientation of textures and on the cutting speed. Deng et al. [49] demonstrated that one micro-hole [49] and multiple micro-holes [40] filled with solid lubricants greatly reduced the cutting forces compared to a non-textured tool. In addition, they demonstrated that rake textured tools with elliptical grooves showed smaller cutting forces than parallel textures [53]. Wu et al. [61] showed that the developed tool with textures reduced the cutting forces F_c , F_t and F_f by 10–15%, 15–25% and 10–20%, respectively. Deng et al. [56] and Xing et al. [62] showed that nano-texture tools with solid lubricant coatings on its rake face reduced the cutting forces when compared to non-textured and textured non-coated tools.

Koshy and Tovey [38] demonstrated that micro-texturing of cutting tools not only reduced the machining force but also decreased the variability of cutting forces during the machining of hardened steel. They also reasoned that giving texture to a tool maintains a consistent tool-chip contact length in comparison to non-textured tools. They further mentioned that kurtosis and skewness of the texture heights are good indicators of the extent of force reduction. Xie et

al. [29] showed that their developed tool with 25 μm depth micro-grooved texture reduced the cutting forces by 32.7% to 56.1% (based on the material removal rate) in comparison to the non-textured tool while machining titanium. Zhang et al. [76] reported that for the developed textured tool, the cutting forces were reduced by 21.2 to 34.7% under full lubrication condition, whereas for starved lubrication, it was only 2 to 8% reduction. With this, they concluded that the beneficial effect of surface textures was primarily because of the textures serving as a micro-reservoir for constant lubricant replenishment and the secondary actions of textures, including trapping the wear debris, contributing much less to the cutting force reduction.

Fatima et al. [64] showed that surface texturing on the flank face of a cutting tool led to a decrease in both cutting forces by 12% on average compared to the non-textured tool. They further reported that a rake-flank textured tool reduced the cutting force and thrust force by 10% and 23%, respectively [66]. They asserted that reduced friction coefficient and compression ratio were responsible for such reduction. Xing et al. in their latest study [46] showed that a rectangular textured tool had the smallest cutting force.

2.4.2 Coefficient of friction

Liquid and solid lubricants were found to be equally effective [48]. Sugihara [25] stated that banded groove textured tools resulted in smaller friction coefficient than parallel groove textured tools due to enhanced surface lubricity of banded grooves. Deng et al. [40, 49] showed that a rake self-lubricated tool with micro-holes of diameter 150 μm and depth 200 μm filled with solid lubricants on its rake face possessed the lower coefficient of friction compared with that of a non-textured carbide tool. Wu et al. in their subsequent study [61] showed that the developed tools with textures could decrease the coefficient of friction by 5 to 20%. Fatima et

al. [66] demonstrated that surface texturing on rake and flank surfaces of a cutting tool reduced the coefficient of friction up to 18 % in comparison with that of a non-textured tool.

2.4.3 Shear angle and chip morphology

Lei et al. [48] reported that a textured tool produced coiled chip [48]. Wu et al. [61] showed that the developed tools with texture and cooling system increased chip curling and reduced the chip thickness ratio in comparison with a non-textured tool. From their results, it could be observed that the coiling of the chip was caused by micro-texture effect as a self-cooling tool (without texture) only resulted in non-curved chips. It was found that textured tools increased the shear angle in comparison to a non-textured tool in the turning of aluminium [25], steel [53] and titanium [29] alloys for a range of cutting speeds. The increase in shear angle resulted in thinner chips and stable cutting process. Xie et al. [30] showed that a diagonal micro-grooved tool increased the shear angle by 24.3% against an orthogonal micro-groove textured tool in the cutting of Ti workpiece. They reported that 25 mm depth groove texture resulted in the largest shear angle and decreased with an increase in groove depth. It is to be noted that a larger shear angle would result in less specific cutting energy and hence, more efficient cutting process. Fatima et al. [66] showed that surface texturing on both rake, and flank faces of a cutting tool effectively reduced the chip compression ratio of the chip to 17% as compared to a non-textured tool. The decrease in the chip thickness ratio was observed with an increase in cutting speed while machining with a textured tool for titanium [54] and steel [59] alloys at a lower cutting speed range. This decrease in chip thickness ratio is due to a reduction in energy spent on plastic deformation of work material which is a desirable condition. The texture of the tool can also behave as chip breaker, and thereby help in decreasing the tool-chip contact length

and in promoting earlier removal of the chip from a tool surface. The early removal of chips facilitates the decrease in cutting temperature through a quicker dissipation of heat.

Xie et al. [29] observed the formation of finer saw-tooth on the external chip surface from the SEM images of the chips formed by textured tools in machining Ti alloys. They stated that the saw tool formation and thinner chips produced by a textured tool is an indication of an increase in shear angle in comparison with a non-textured tool. They further reported that comparing with a conventional tool, a textured tool promoted chip curl [63]. They also observed that extremely rough areas occurred on the back surface of the chip for the perpendicular textured self-lubricated tool due to the fact that the textures were patterned on the surface of the chip; for the parallel and wavy textured self-lubricated tools, the surfaces of the chips were smooth and uniform. They observed that shear angle increased with a decrease in groove depth from 149 μm to 25 μm , but the trend was reversed at a depth of 7 μm and an aspect ratio of 0.14. This might be due to the much-reduced airspace for heat dissipation and aerodynamic lubrication.

2.4.4 Contact area and Contact length

The contact area is measured on the tool surface from the periphery of traces of workpiece smeared on the tool surface to the cutting edge. This can be seen from the measurements made by Lei et al. [48], Obikawa et al.[24], Wu et al.[61] and Fatima et al.[64] in Figure 2.23, Figure 2.24 and Figure 2.25 respectively. It should be noted that contact length is measured from the cutting edge to the end of traces of smeared workpiece material based on the researcher's judgment and that no systematic method was used. The measurement is justified as they use the same method for a comparative study of non-textured tools.

Figure 2.22: Tool-chip contact length measurement (a) Dry cutting (b) flood cooling (c) oil lubrication (d) solid lubrication. [48]

Figure 2.23: Tool-chip contact length measurement (a) flat; (b) perpendicular; (c) parallel and (d) pit. [24]

Figure 2.24: Tool-chip contact length measurement (a) non-textured, (b) Textured with solid lubricant, (c) non-textured with internal cooling and (d) textured with solid lubricant and internal cooling [61]

Figure 2.25: (a) Textured tool and (b) contact area for the textured tool [64]

Lei et al. [48] stated that micro pool lubricated cutting tools reduced contact length by 30% in comparison to non-textured dry cutting in mild steel alloy machining. Kawasegi et al. related

the force reduction in metal cutting to a reduction in chip-tool contact length [26]. Deng et al. [53], Ze et al. [54] and Xing et al. [63] attributed the reduction in contact length to the formation of a thin lubricating film by the solid lubricant embossed in textured tools. Fatima et al. [64] demonstrated that the sticking contact of flank face textured tools is reduced by 16% in comparison to non-textured tools. They further reported that the contact length of the cutting tool is a function of the cross-sectional shape of the texture units [66].

2.4.5 Anti-adhesivity

Sugihara et al. [25] found that texturing of the cutting tool was an effective way to achieve anti-adhesion. They reported that good anti-adhesive effect was achieved by improving lubricant retention on the cutting tool textured for machining of aluminium. They demonstrated that the nano/micro-texture significantly improved anti-adhesivity and lubricity of the rake surface of the cutting tool in wet cutting; in contrast, for dry cutting, the adhesion increased. They further found that anti-adhesivity of the tool rake surface had a strong relationship with the width of the valleys/convex area of the texture units [55]. They demonstrated that tools developed with micro-groove texture improved the anti-adhesivity property even in dry machining conditions. Among the tools they have developed and tested, the tools with micro groove texture of 5 μm depth, 20 μm convex width and 50 μm concave width displayed superior anti-adhesive property. In steel cutting, Fatima et al. [66] reported that a rake and flank textured tool reduced adhesion of Fe by 21% on the rake face and reduced the sticking contact by 9%. Kümmel et al. [68] attributed the decrement in cutting temperature to the improved anti-adhesion property of the textured tool in the dry turning of steel. On the contrary, Xing et al. [62, 63] reported that the increased tool-chip contact area in non-textured tool cutting produced more heat, which softened the chip material and caused less adhesion on the rake

surface, whereas for a textured cutting tool, the sliding of the chip over the more irregular rake surface due to textures might result in more chip adhesion.

2.4.6 Resistivity to wear

Deng et al. [49] showed that a micro-hole in the flank face filled with solid lubricant MoS_2 had more resistance to flank wear than a non-textured tool. Enomoto et al.'s [8] experimental results showed that textured tools with nano/micro-grooves did not improve wear resistance, whereas parallel textured tools with micro-stripe grooves, coated with TiAlN and with dimensions of $20 \times 5 \mu\text{m}$, $20 \mu\text{m}$ pitch, showed significant improvement in wear resistance and lubricity of the cutting tool surface. Sugihara et al. [58] stated that the textures, serving as a micro-reservoir for lubricant and a microtrap for wear debris, improved crater and flank wear resistance. They reported the existence of a strong correlation between wear resistance and concave/convex area ratio of the texture. In their recent study [47], they demonstrated an effective reduction in crater wear by dimple textured tool in the dry cutting of medium carbon steels. Song et al. [50] showed that the rake face of self-lubricated tools had reduced rake wear even at very high temperatures and high cutting speeds and that the wear rate depended on the chemical inertness of the solid lubricant at such conditions. Ze et al. [54] showed that both rake and flank face texturing exhibited anti-wear property against both crater and flank wear respectively. From their experiments, it was clear that flank face with stripes texture showed superior anti-wear ability with up to 30% improvement in the tool life and rake face with the ellipse texture resulted in tool life improvement by 10 to 15%. Xie et al. in their study of turning titanium alloy [30] found that grooved textured tools could account for rapid heat removal and resulted in reduced wear. It was observed that diagonal micro-grooved tools might decrease tool wear 6.7% more than orthogonal micro-grooved tools, as the grooving direction was

identical to the chip flow on the tool rake surface, providing less resistance to the flow and rapid heat removal due to the groove spacing. However, wider grooves (123 μm) resulted in more friction in the tool-chip contact region. They further demonstrated that micro-groove textured tools with a groove depth of 25 μm produced less tool tip wear than the rest of the tools tested [29]. Xing et al. [62] stated that areal nano-textured tools with WS_2/Zr coating displayed the most effective anti-wear property. Kümmel et al. [68] in their studies found that dimple texture decreased wear due to mechanical interlocking between the built-up layer and the dimple edges (wear protecting property), in contrast to channel textures found to increase the wear. Zhang et al. [76] reported that in textured tool wear, depth is reduced regardless of the lubrication condition. In their experiments, they achieved a wear depth reduction for textured coated tools of 0.5 μm in full lubrication and 0.9 μm in starved lubrication in comparison with non-textured coated tools, which had a wear depth of 2.1 μm in full lubrication and 2.2 μm in starved lubrication. Fatima et al. [64] showed that textures on the flank face increased the tool life by 18%, i.e. increased the tool life from 44 to 52 min.

2.4.7 Temperature

Deng et al. [53] stated that rake textured tools filled with solid lubricant reduced the cutting temperature by 5 to 15% in comparison with the non-textured tool at high speed cutting (>120 m/min). The lubrication regime formed by the filled solid lubricant between the contacting surfaces during cutting helped not only in reducing friction but also the temperature, which resulted in better tool edge integrity and less chip adhesion and tool wear. They also found that elliptical groove textured tool had the smallest cutting temperature than the parallel and perpendicular groove textured tools. Similarly, Xing et al. [62] stated that wavy patterns exhibited more temperature reduction than linear groove textured tools. Sharma et al. [84] in

their review paper explained that wavy grooves [62] and elliptical groove textures [53, 54] had more surface area for heat dissipation on the rake surface of the tool. Wu et al. [61] further reduced the cutting temperature by 15 to 20% using their specially developed cutting tool, which in addition to surface textures had a pulsating cooling system. Fatima et al. [64] showed that groove textures decreased the tool temperature by 12% at lower cutting speeds in comparison with the non-textured tool.

Xie et al. [29, 30] stated that reduction in cutting temperature was not only due to reduced tool-chip contact area but also to airspace introduced by textures in the contact zone between the chip backside and the textured rake surface. These air spaces helped in rapid sliding and heat dissipation of the cutting chip in the dry turning of titanium alloy. They stated that micro-grooved textures decreased the cutting tool temperature by 103 °C in comparison with the non-textured tool. They reported that the textures reduced the cutting tip temperature below 500 °C, which was predicted as 1322 °C for a non-textured tool. The cutting temperature decreased with a decrease in groove depth from 149 µm to 25 µm, but the reverse happened at 7 µm depth with 0.14 aspect ratio. This reversal could be due to poor airspace for heat dissipation. They pointed out that the texture grooves should have a width less than the uncut chip thickness for the chip to flow over the rake face of the tool. They also demonstrated that a micro-grooved tool with 25 µm depth decreased the cutting temperature between 20.0% to 27.2% (based on material removal rate) in the dry turning of titanium alloy.

2.4.8 Surface roughness

Deng et al. [40] showed that textured tools filled with solid lubricant slightly increased the surface roughness of the machined workpiece in comparison with a non-textured tool, which is not a desirable effect of textures. Xie et al. [30] showed that though the textured tools

increased the roughness of the newly formed workpiece, the variation in surface roughness was considerably reduced in comparison with the surface produced by a non-textured tool. They also found that the diagonally micro-grooved tool decreased the surface roughness of the machined surface of a titanium workpiece by 37.3% against the orthogonally micro-grooved tool. Kümmel et al. [68] found that dimple textured tools led to a slightly higher surface roughness of the machined workpiece due to stabilised BUE while the channel textures resulted in better surface quality BUE formation, which is destabilised by the presence of texture.

In contradiction to the above mentioned textured tools, Jiang [81] developed a bio-inspired cutting tool (which has a surface finish similar to that of shark teeth) and improved the surface finish of the machined workpiece compared to the highly polished non-textured conventional tool. The improvement in surface finish could be attributed to the better anti-wear ability of the textured tool.

2.5 Contradictory findings and disagreements in literature

Research papers on texture of cutting tools are abundant. Although an attempt is made here to classify the effects reported and to summarize the observed trends in the previous sections, some contradictory findings were also found in the literature. It is to be noted that the conditions of the experiments were different and therefore the results are not directly comparable, which can explain the difference in findings. Examples of contradictory findings are listed here.

Koshy and Tovey [38] stated that for effective force reduction, the texture has to be fabricated farther from the cutting edge at a distance depending on the feed value. A similar observation was reported by Fatima et al. [71] on the distance of flank texture on the flank face, which does not follow a monotonous trend. In fact, they reported that texture at a distance of

150 μm led to a lower cutting force than a texture at 100 μm and 200 μm . However, Obikawa et al. [24] and Lei et al. [48] stated that texture should be placed as close as possible to the cutting edge to obtain maximum reduction in cutting force. The only factor that restricts the texture location from the cutting edge is the strength or integrity of the cutting tool. As such, the texture should be placed at a sufficient distance to cause no harm to the strength of the cutting edge. Lei et al. [48] have performed a FEM analysis to show that the texture location does not affect the strength of the cutting tool.

Obikawa et al. [24] reported that the effect of lubrication for textured tools increased with the depth of texture units in the machining of aluminium alloys. This contradicts the findings of Xie et al. [29], who reported that texture effect decreased with an increase in depth of texture units. They mentioned that large groove depth would have more tool-chip contact area and will result in higher machining forces. They also stated that shallow depth texture would clog easily by the debris, as chip flows over the rake face of a textured tool. The larger depth of texture units not only accounted for more space for debris entrapment but also for larger lubricant storage capacity. Thus, unlike deeper texture units, shallow textures will clog with chip material and would lead to more friction in tool-chip and high cutting forces. This is supported by Xie et al. [29] who use a different argument; i.e. to decrease friction in the tool-chip interface and to reduce the cutting temperature, the texture depth needs to be large enough to sustain the air gap between the tool rake surface and the chip underside.

Fatima et al. [64] stated that the flank textures reduced the flank wear growth rate and would contribute to improving the surface finish of a workpiece, while textured tools produced by other researchers resulted in higher surface roughness of the machined parts [30, 40, 63] and [68]. Xing et al. [63] reported that the developed self-lubricating textured tool increased the

surface roughness of a machined workpiece, while it reduced vibration for stable cutting and produced more uniform surface quality.

Kawasegi et al. [26] stated that the texture effect was only observed at high cutting speeds over 420 m/min whereas Deng et al. [40] found that the textured effect is predominant only at a low-speed cutting (<140 m/min). It was also reported that the effectiveness of textures decreased with an increase in cutting speed [38, 54, 56]. For example, Xing et al. [46] stated that above 219.6 m/min, lubricity is decreased and the texture effect is negative.

2.6 Mechanisms leading to texture effect in cutting tools

From the previous sections, it is clear that the texture effect was observed with respect to various parameters by several researchers. The mechanisms behind such a texture effect have been explained for wet cutting and dry cutting, and with and without solid lubricants as follows.

In wet cutting, Lei et al. [48] stated that micro pool lubrication would help the lubricants to reach the tool-chip interface and enhance the lubrication conditions in the contact zone, thereby reducing the friction and frictional energy loss. Kawasegi et al. [26] stated that a textured tool reduced friction due to a reduction in contact length and led to a reduction in cutting force at high speeds due to the difference in material adhesivity. Sugihara et al. [25] stated that fluid retention on the tool rake face was important to achieve good anti-adhesive properties and suggested texturing the rake face to help in lubricant retention. Enomoto et al. [52] explained that for wet cutting, the cutting fluid in the texture maintained the lubricant film on the tool-chip interface from being broken, whereas in a non-textured cutting tool the lubricant film on the tool surface was getting depleted easily due to non-accessibility of lubricant in the tool-chip interface. The chip underside, which is a chemically active nascent surface, caused

diffusion and adhesion on the tool surface when it came in direct contact with the tool rake face. The direct contact caused a severe sliding condition for the chip on the non-textured tool rake face. Additionally, they stated that the texturing on the tool surface also decreased the actual tool-chip contact area.

For the dry cutting process, (1) the reduction in the tool-chip contact area, (2) the increase in lubricity and dissipation of heat due to air packets between the chip underside and tool texture and (3) the act of texture as wear trap for debris [47] might be the three reasons for the beneficial texture effect. It is possible to generate surfaces that have naturally lower friction than that of polished surfaces.

In the dry cutting process with textured filed with solid lubricants, Deng et al. [49] explained that the solid lubricant got smeared and formed a self-lubricating film between the tool-chip interface, which lubrication enhancement in the cutting process. Their further study demonstrated that in addition to the self-lubricating effect, the reduced contact length at the tool-chip interface decreased the actual contact area at the tool-chip interface [40]. This was acknowledged by Wu et al. [54] and Xing et al. [62]. Lian et al. [57] listed two other mechanisms in addition to the mechanisms mentioned above, which are responsible for the texture effect. They are the anti-adhesive effects of the solid lubricant that reduced the adhesive wear and anti-oxidation effect of the solid lubricants even at high cutting speed and high cutting temperature. Wu et al. [61] demonstrated that accelerated heat dissipation would also help in performance improvement of the cutting insert. Xing et al. [63] demonstrated that tool wear was significantly reduced due to the formation of a lubricating film at the cutting tool-chip interface.

2.7 Computational modelling of the cutting process

In the cutting process, process parameters are selected through experience, experimental tests and machines and equipment availability. Sometimes, due to practical limitations, it may not be possible to experiment with certain required parameters. In many cases, there is a limitation to experiment extensively due to cost consideration. More importantly, an experimental solution is not necessarily the best solution due to various environmental and physical limitations. With these limitations, difficulties and lack of robustness in quantitative method, finite element method (FEM) can be considered as an effective approach to study the cutting process. From a FEM study, one can evaluate parameters that are difficult to measure (such as temperature, energy, and stress) in actual processes, in addition to the reduction in cost.

Researchers have also conducted simulation studies on the textured tool effect to analyse the fundamentals behind the texture effect. The machining process, in general, has been widely investigated via computational simulations to study forces, temperatures, contact and stresses distributions. Table 2.4 gives a summary of the work conducted on texture effect using FEM. Ma et al. used the AdvantEdge 2D software to study the effect of micro-grooves [60, 85] and micro-bumps [65] on the cutting tool in AISI 1045 steel dry machining. In their subsequent studies, they used the AdvantEdge 3D to model micro holes and micro-grooves tools and studied the three-dimensional machining of Ti-6Al-4V [69, 72]. They presented a study on the texture effect variation with a change in texture parameters, which included the edge distance, textures width and height. The output data were cutting forces, temperature and stress distribution. Qiu et al. [73] used the same model and studied the residual stress generated by the textured tool. Arulkirubakaran et al. [74, 75] carried out experiments for three types of

textured tools and compared that with the Deform-3D simulation for the Ti-6Al-4V alloy and stated that perpendicular textures were more efficient in terms of reduction in cutting force and cutting temperature. Wu et al. [86] studied the cutting of Al6061-T6 by WC/Co using Abaqus software for different groove width of 20, 40, 100 μm and different convex width of 20, 50, 100 μm and compared with a non-textured tool. They developed a dislocation density model and studied the cutting force, chip thickness and dislocation density. They found that microgroove width can effectively change the grain size profile and dislocation density along the depth from tool-chip/workpiece interfaces.

Table 2.4: FEM simulation of textured tool reported by researchers

Year	Author	Software	Material		Tool geometry	Texture				Validated	Study parameters		
						V _c	t ₀	f	Dimensions		Orientation/ Array type		
			Tool	Work-piece		m/min		mm/rev	μm				
2013	Ma et al. [85]	AdvantEdge -2D	WC	AISI 1045 Steel	Rake 5 Clearance 6 Edge radius 20μm	120	1	0.3	Texture edge distance 200, 100, 5 Width 200, 100, 5 Distance 200, 100, 5 Depth Ratio 1, 2, 3		Microgroove	Cutting forces	Force and stress vs groove parameter effect for different Texture edge distance, Width, and Depth ratio.
2014	Ma et al.[60]	AdvantEdge -2D	(WC/Co)	AISI 1045 Steel	Rake 5 Clearance 6 Edge radius 20μm	120	1	0.3	Edge distance (50,100,200) Groove width (200,250,300,400 μm) Width to Hight ratio (1,2,3,6,8)		Microgroove	Cutting forces	Temperature distribution (tex vs non tex) Stress distribution (tex vs non tex)
2015	Ma et al. [65]	AdvantEdge -3D	(WC/Co)	AISI 1045 Steel	Rake 5 Clearance 6 Edge radius 20μm	120	1	0.3	Edge distance (620, 550, 480, 420, 370, 320, 200, 100, 50, 20) Bump width (700, 600, 500, 400, 300,) Distance Di 200, 100, 50, 20 Width to Hight ratio (2, 3, 4, 6, 8,10, 12, 14, 16)		Microbump	Force Only with non-texture	(Force vs time) for Texture edge distance, Width and Height ratio Force & Stress vs Texture edge distance, Width and Height ratio

2015	Ma et al. [69]	Deform 3D	WC/Co	Ti-6Al-4V	Rake 5 Clearance 10 Edge radius 20μm	100	2	0.1	Edge distance (120, 100, 90, 80, 70, 60, 40) Groove width 120, 110, 100, 90, 80, 70, 60, 50, 40 Width to depth ratio (1,2,3,4, 6,8,12, 16)	Microgroove	Force [87]	3D forces groove parameter effect on forces and stress for different texture edge distance, width, and depth ratio.
2016	Ma et al. [72]	Deform 3D	WC/Co	Ti-6Al-4V	Rake 5 Clearance 10 Edge radius 20μm				Distance 100, 80, 60, 40, 20 Diameter 40, 60, 80, 100, 120 Position pattern 0, 20, 40 Diameter- Depth ratio 1, 2, 4, 8, 10, 12, 14, 16	Microhole	Force [87] [54]	Force, contact length & stress vs texture diameter distance from cutting edge Diameter -depth ratio Microhole distribution
2016	Qiu et al. [73]	Deform 3D	WC/Co	Ti-6Al-4V	Rake 5 Clearance 10 Edge radius 20μm	100	2	0.1	Edge distance (120, 100, 90, 80, 70, 60, 40) Groove width 120, 110, 100, 90, 80, 70, 60, 50, 40 Width to depth ratio (1,2,3,4, 6,8,12, 16)	Microgroove	Force [87]	Residual stress Microgrooves reduce tensile residual stress and induce compressive residual improve the fatigue life
2015	Kim et al. [70]	Deform 3D		AISI52100	Rake 5 Edge radius 800μm	182	0.203	0.152	Edge distance (150, 100, 50) Pitch (150, 100, 50) Height 50/100		Force	Force, vs Shape Edge distance Pitch Height Friction factor 0.2/0.6/0.8

2016	Arulkirubakaran et al. [75]	Deform 2D		Ti-6Al-4V alloy		60,90 and 120	0.5	0.1	Non-texture Cross texture Parallel texture Perpendicular texture Textured tool used in simulation is not shown	Parallel Perpendicular Dross	Cutting forces	Texture (3 types) vs non-texture for both experimental and simulation. (Cutting speed 60,90,120 m/min) Cutting force Thrust force Friction coefficient Temperature Shear angle Thermal imaging camera image SEM image
2016	Arulkirubakaran et al. [74]	Deform 3D	uncoated tool	Ti-6Al-4V alloy		60,90 and 120	0.5	0.1	Non-texture Cross texture Parallel texture Perpendicular texture	Parallel Perpendicular Cross	Cutting force	3D forces Temperature Chip formation Tool wear Optical images of tool wear and chip surface study.
2016	Yu et al.	Deform 3D		Stainless steel	Rake angle 0 Flank angle 7	rpm 6000 9000 12000 15000 Diameter 6mm	0.04	10		Parallel Perpendicular Oblique Dimples		Tool wear Temperature Cutting force
2017	Wu et al. [86]	Abaqus	WC/Co	Al6061-T6	Rake angle 6 Flank angle 8	124.8 m/min	0.059	1	Edge distance 20 μm Groove width 20, 40, 100 μm Convex width 20, 50, 100 μm Microgroove depth 5 μm	Regular Convex 20 Convex 50 Convex 100	Cutting force Chip thickness Dislocation density model	The microgroove width can effectively change grain size profile and dislocation density along depth from tool-chip/workpiece interfaces.

2.8 Summary

This chapter reports the contributions by researchers in the field of micro-texture utilisation in improving the performance of cutting tools and thus making the machining process more sustainable. The methods available for texturing the cutting tool were first summarized, then followed by a description of the state of the art in the application of textures on cutting tools. A detailed comparative analysis in the form of tables and discussions is presented in this chapter to highlight the effect of textures on the performance of cutting tools. The reported effects of various input parameters, including material, texture size, shape, orientation and cutting conditions on textured compared with non-textured tools were discussed extensively. Texturing of the rake surface was found to be more effective, and the orientation of textures was found to have more influence on the cutting tool performance. It was shown that stripes textures oriented in the direction parallel to the cutting edge were more effective than textures oriented in other directions. Though a texture with wet cutting conditions is found to be more efficient in most of the studies, researchers have shown that textures are also effective in the absence of lubrication. Textured tools are reported to reduce friction, cutting forces, adhesion, contact area, temperature and tool wear in comparison with conventional tools. The reported results and contributions by the researchers were first tabulated in chronological order to have an overall picture before being analysed topic by topic. This chapter also discussed the arguments, contradictions and mechanisms responsible for the texture effect on cutting tools in the literature. Computational studies reported on the texture effect on cutting tools were also discussed and tabulated for overall assessment.

2.9 Outcome of the literature review and research gaps

Most of the micro-texture applications for cutting tools were made in machining of hard to cut materials like steel or titanium with the aim to reduce cutting forces or to reduce the wear of a cutting tool. There will only a few studies on aluminium, mostly because aluminium is considered as an easy to cut material and it has not received much attention for a reduction of the cutting forces. However, the biggest challenge of cutting aluminium is related to adhesion in machining. In this thesis, micro-texture effect on the machining of aluminium is extensively studied in terms of cutting force for various cutting speeds and depths of cut. In addition to cutting forces, shear angle, contact area, chip morphology and adhesion are also studied experimentally in the following chapters. Though some preliminary studies were made on studying the texture effect using FEM, there is a need for more rigorous study particularly in analysing the change in cutting mechanisms due to the introduction of texture. In addition, the parameters which are difficult to study experimentally are studied with the help of FEM. Almost all studies reported attributed the reason for the texture effect in a cutting process to a change of friction behaviour due to textures on the contact zone. However, metal cutting is a complex process and it is not easy to study the texture effect in terms of friction in the contact zone. Therefore, the contact zone with and without texture is studied in simulated experimental and FEM setup. The studies reported here followed an established and accepted approach in discovering and estimating the texture effect during machining. This involved the conduction of experimental work followed by the examination of chips, tool surface and analysis. A new method of estimating the texture effect with the help of acoustic emission (AE) is proposed here, and it can be developed to analyse the texture effect in process analysis and for monitoring purposes.

Chapter 3: Effect of micro-textures on cutting tools performance

A preliminary study on the effect of micro textures on the performance of cutting tools is presented in this chapter. The objective is to verify the positive effects of the introduction of textures on the performance of cutting tools and to evaluate the changes in performance parameters due to the texture effect for different cutting conditions. The results obtained from the experimental investigations are presented in comparison with a non-textured tool. The results are discussed on a case by case basis and are used to verify and demonstrate the functionality of micro-textures for improving the performance of cutting tools. This preliminary study will help the understanding of the fundamentals of surface textures behaviour for cutting tools.

3.1 Cutting tool

Two types of cutting tools were examined, one is a customised tool (see Figure 3.1), which is used in low cutting speed experiments and is made of high speed steel (HSS), and the other is a commercial tungsten carbide tool GY1B0220D020N, supplied by Mitsubishi, used in high cutting speed experiments.

Figure 3.1: Customised HSS tool

Both types of tools are non-coated, have no chip breaker and have flat rake face to facilitate the texturing of the tool surface to study only the effect of texture parameters. The cutting tool is made of cemented carbide with Co as the binder. The tool is conductive because of the cobalt binder and it is machinable using EDM. The geometric details and the placement of the tool in the tool holder are shown in Figure 3.2.

Figure 3.2: Commercial tungsten carbide tool

3.2 Texturing by EDM

Electric discharge machining (EDM) is a non-conventional machining process in which electric sparks are used to achieve the desired features. When a voltage is applied to a workpiece and a tool electrode, which are separated by a dielectric fluid, repetitive sparks occur that can be utilised to remove materials from the workpiece. When the electrode is brought close to the workpiece, the electric field intensity between the nearest points of the tool electrode and the workpiece can exceed the dielectric strength. At this point, the dielectric strength breaks and allows current to flow between the electrodes, producing a spark, which results in the removal of material from both the workpiece and the electrode. In this work,

micro-texturing on customised cutting tool faces is achieved through a Panasonic Micro EDM MG-ED72W machine, which is shown in Figure 3.3.

Figure 3.3: (a) Panasonic Micro EDM MG-ED72W machine (b) Wire Electric Discharge Grinding-WEDG set-up for making electrode tools and (c) Micro Electrical-discharge machining set-up for producing textures on the tool surfaces

The cutting tool was clamped in the working tank filled with an oil-based dielectric as shown in Figure 3.4 (a). The tool electrode is a tungsten wire, which underwent machined wire-electrical discharged grinding (WEDG) to reduce the tool electrode diameter from $300\ \mu\text{m}$ down to $15 \pm 2\ \mu\text{m}$. The machined electrode was subsequently used to generate the micro-textures on the rake and flank surfaces of the cutting tools.

Figure 3.4: (a) μ -EDM set-up for producing textures with tungsten electrode

The μ -EDM texturing method is able to produce micro texture dimensions as small as $15\ \mu\text{m}$ and able to produce the texture features with high repeatability. Two types of micro-textures, namely the dimple textures and stripes textures, were produced on the tool surfaces. The dimple texture was made in the form of circular blind holes arrays. Such dimples are axisymmetrical and independent of the flow direction of the chip as compared to the groove textures. A smooth edge throughout would yield more consistent results, unlike stripes textures. The stripes textures were made by series of stripes parallel to the cutting edge which could act as secondary cutting edges.

A series of dimples is produced by varying the EDM machining parameters to achieve the target depth and diameter of the dimples of $17\ \mu\text{m}$ and $15\ \mu\text{m}$ respectively with high repeatability. Such dimples are made with machining parameters set at 70 V or 100 V, and capacitance of (1) 20 pF, (2) 80 pF, (3) 220 pF or (4) 3300 pF. The depth and diameter of the eight produced dimples for each condition were measured and their average values were plotted with error plots in Figure 3.5 and Figure 3.6.

Figure 3.5 : Average depth of dimples with error plot

Figure 3.6: Average diameter of dimples with error plot

Figure 3.5 shows the depth of textures produced on the tool surface. The significant dimple variations shown in Figure 3.5 could well be due to the distribution of WC in the Co binder and the stability of the EDM machine parameters. Figure 3.6 shows the hole diameter of the textures produced on the tool surface. To achieve a result close to the targeted depth and hole diameter, the condition of 100 volt and capacitance 3 is selected, which has the minimum deviation and variation from the targeted values.

Thus, the conditions 100 V and 220 pF (cap 3) are selected to produce the dimples of the required depth and diameter in terms of target values and error values. The dimple array was made on the cutting tool and was inspected using infinite focus optical 3D surface metrology system (Alicona). Figure 3.7 shows the scanned image and depth profile of one of the dimples.

Figure 3.7: (a) Textured tool surface and (b) scanned profile

In addition to an array of dimples, a stripes texture (rectangular micro-slots) was also generated by orienting the stripes parallel to the cutting edge.

Figure 3.8 shows the comparison of dimple and stripes type textured tool. The stripes are $15 \pm 2 \mu\text{m}$ in width and $18 \pm 2 \mu\text{m}$ in depth with a pitch of $60 \mu\text{m}$. The distance of the first row of texture from the cutting edge is $50\text{--}80 \mu\text{m}$. It should be highlighted here that the dimple texture is used extensively in the experimental study and is referred as a textured tool throughout the section unless otherwise stated.

(a) Stripe textured tool

(b) Dimple textured tool

Figure 3.8: Single tool with textured and non-textured region

To reduce the tool related variability, which can be caused by a change in tool for non-textured and textured comparison, a single tool was textured for half the surface (2 mm wide), and the other half surface was non-textured (2 mm wide), Figure 3.8. The width of cut was only 1 mm wide, and so the experiments can be conducted sequentially on the textured or non-textured region of the cutting tool without overlap and without changing the tool. The difference in result for the experiments conducted for the non-textured and textured regions of the tool without changing the tool is assured to be free of any variability due to tool and tool setting changes. However, on repeating the experiments, the tool must be changed and the variability in tool setting might take place. However, this developed method would be useful for the case to case comparison with non-textured and textured regions on the same tool.

3.3 Texturing by Laser

Laser processing has been used to fabricate microscale textures through conventional ablation for cutting tool surface [24-26]. Most of the reported study on micro-texture effect on cutting tool uses femtosecond laser to produce the micro-texture, see Figure 2.3. In this study, the rake face of the cutting tools was textured using two different types of laser machines, namely Quantronix femtosecond laser machine and Time-Bandwidth Picosecond Laser (Duetto) laser machine. The laser parameters are varied to obtain a suitable combination that produces dimple and stripes textures with dimensions ranging from 50-150 μm in diameter and 50 μm width respectively. Textures were generated with different depth ranging from 10-50 μm . The width or diameter of the texture produced by the laser machine was limited to the spot size of the laser scanner; thus, textures only above 100 μm diameter could be produced by the Quantronix femtosecond laser, see Figure 3.9 for experimental set-up. On the other hand, Duetto Time-Bandwidth Picosecond Laser has a smaller spot size of less than 20 μm and was used to produce textures of diameter 50 μm , 100 μm , 150 μm , as described in Chapter 4. Figure 3.11 explains the texture formation using the laser and the parameters for defining the texture type. The laser power was varied between 1.3 and 1.5 W at a frequency of 100 kHz and 300 kHz to produce textures.

Figure 3.9: Quantronix femtosecond laser-texturing machining setup.

The laser velocity, pass and frequency are varied in the range of 1–100, 1–10 and 1–300 kHz, respectively to achieve required dimensions. A series of texture units is made by varying the pass speed and frequency, and the results are shown in Figure 3.10, in terms of texture depth. It was found that the pass follows a linear trend; beyond 5 mm/s, the texture would have negligible depth; with an increase in frequency, depth increases, but the rate of increase is much less. The laser marking speed of 1 mm/s, 4 passes and 100 kHz was selected for texturing the tool surface. The textured tools produced by laser are polished to remove any recast layer or deposit on the surface using the same methodology explained in section 3.2.

Figure 3.10: Laser parameter influence in texture depth.

Figure 3.11: Laser textured tool

When using laser and EDM, the texturing produces dimples with recast and deposition layers, therefore the surface is polished after laser texturing by manual polishing. The textured tools are handheld and polished in Struers polishing machine with MD-Mol and MD-Chem surfaces with diamond suspension ($3\mu\text{m}$) and colloidal silica suspension ($0.04\mu\text{m}$) as abrasives respectively. Since the abrasive type used is less than $3\mu\text{m}$, the removal depth will be less than $3\mu\text{m}$. As such, the recast and re-deposition near the dimple edges can be removed. The polished

tools are then cleaned in an ultrasonic bath. The polished dimple and stripes textured tools are shown in Figure 3.12.

Figure 3.12: Dimple vs Stripes textured tool

3.4 Workpiece

The workpiece selected for this experimental study is made of aluminium alloy. Aluminium alloys are widely used for their high strength to mass ratio and machinability characteristics. The mechanical property of pure aluminium is very low and is improved by alloying with other metals. Among the Al-alloys, Al 6061, which is formed by alloying with Mg and Si, exhibits excellent mechanical properties, corrosion resistance and weldability. Though aluminium is an easy-to-cut material, it is associated with high adhesivity, which would lead to BUE and tool failure. Texturing on the cutting tool surface near to the cutting edge was expected to solve this difficulty, and Al 6061 was selected for this study.

Two types of Al workpieces were used in this study, namely Al workpiece with stripes, and Al tubular cylindrical workpiece of 30 mm diameter or 60 mm diameter. The Al workpiece with fabricated stripes is shown in Figure 3.13; such workpieces were limited for cutting speed, which is limited by the travel velocity of the machine. The workpiece with parallel stripes were machined to have stripe thickness of 1 mm in order to facilitate orthogonal cutting. In order to

test the texture effect at high cutting speeds, workpieces were fabricated in the form of thin-walled tubes as shown in Figure 3.14.

Figure 3.13: Workpiece for low-speed cutting –Al stripes (a) Top view (b) Isometric view

The tubular cylindrical workpiece of outer diameter 30 mm, which is fabricated with a tube thickness of 1 mm, is used in the Mikrotol machining setup. A larger cylindrical workpiece with an outer diameter of 61 mm and tube thickness of 1mm and length of 70 mm is fabricated for the Mazak lathe machining setup. This workpiece has a base thickness of 25mm to avoid deformation of the tube due to holding by the chuck. The workpiece details are given in Figure 3.16 and Figure 3.16. In addition to Al6061-T6 workpieces, Cu workpieces are also fabricated. Cu workpieces are used for testing the texture effect on other less adhesive material.

Figure 3.14: Workpiece for high speed cutting – Al tubes (a) Ø 30 mm and (b) Ø 60 mm

Figure 3.15: Details of 30 mm diameter workpiece -Al tube

Figure 3.16: Details of 61 mm diameter workpiece for high speed cutting – Al tube

3.5 Experimental setup for orthogonal cutting

The experiments were carried out in two machines (i) Mikrotol DT-110 Machine and (ii) Mazak Lathe Machine due to the limitations of the former machine in terms of speed and torque. Both stripes cutting (low cutting speed) and tube cutting (high cutting speed) experiments were conducted. The low-speed cutting experiments were carried out on a

numerically controlled ultra-precision machine-tool (Mikrotool DT-110), and the experimental setup is shown in Figure 3.17. This setup is used to study the rake texture effect in the cutting of Al, Steel and Cu in orthogonal cutting by the WC tool. The experimental results of the textured tool were compared with the non-textured tool. The cutting speed used for the experiments were 1 and 2 m/min, which was limited by the feed motion of the machine. Figure 3.18 shows the orthogonal cutting arrangement of rib and tool.

Figure 3.17: MiKrotool experimental setup for orthogonal cutting of ribs

The effect of texture on the rake and flank face of the tool are studied for Aluminium in an orthogonal tube cutting by the HSS tool. The experimental setup is shown in Figure 3.18. The tubular aluminium workpiece used in this experimental setup is attached to the spindle by means of a collet. The experiments were conducted using both non-textured tool and textured tool (separately done on the flank and on the rake), and the results were compared. This setup has limitations of small collet attachment and spindle torque, which limits the diameter, depth of cut and workpiece material.

Figure 3.18: Mikrotol machine setup for orthogonal tube cutting

The experimental study for different depth of cutting at various speeds was conducted on the Mazak 6T lathe machining centre (3-Axis numerically controlled machine). The experimental setup is shown in Figure 3.19. This setup has a maximum spindle speed of 6000 rpm with no limitation in diameter and torque. Experiments were conducted for 60, 120, 240 and 360 m/min for 10, 50 and 100 depths of cut. The workpiece used in this set had an outer diameter of 61 mm with a tube thickness of 1 mm. The details of the experiments conducted on three experimental setups are given in Table 3.1.

The lubricant used for the mist condition is Ondina oil, which is a highly refined mineral oil lubricant. It is selected because of its low volatility, high viscosity and high thermal stability. The kinematic viscosity of the lubricant is $19 \text{ mm}^2/\text{s}$ at 20°C and $9.8 \text{ mm}^2/\text{s}$ at 40°C . The supply rate of the lubricant in the form of mist is maintained at 2.6 L/min at a pressure of 0.6 MPa by external air mixture equipment with a flow rate controller.

Figure 3.19: Mazak experimental setup for orthogonal tube cutting

Table 3.1: Cutting conditions

Parameters	Low-speed cutting Mikrotool	High-speed cutting Mikrotool	High-speed cutting Mazak lathe
Cutting tool	WC	HSS	WC
Tool geometry	Customized Rake 5°, Flank 2° Edge radius ~7.5μm	Customized Rake 5°, Flank 2° Edge radius ~7.5μm	GY1B0220D020N Rake 0° Flank 7° Edge radius 200μm
Texture region	Rake	Rake, Flank	Rake
Workpiece	Al, Cu, Steel	Al	Al, Cu
Cutting speed (m/min)	1,2	283	60,120,240,360
Width of cut (μm)	1	1	1
Depth of cut (μm)	10, 25, 50	10,50	10, 25, 50
Cutting length (m)	0.025, 0.5	7.5	7.5
Environment	Mist /Dry	Mist	Flood coolant

3.6 Parameters considered and their assessment methodology

3.6.1 Cutting forces and coefficient of friction

Cutting forces are a direct measure of the performance of the cutting tool. The effort made in reducing the cutting force will directly reflect an increase in the performance of the tool life as well as a reduction in the carbon footprints. It is demonstrated that cutting forces could be

reduced with the application of texture on the cutting tool surface. Cutting force is one such parameter that almost all the researchers [24, 26, 38, 53, 55] used as a measure to prove the performance improvement of cutting tool by textures. The reduction percentage might vary with the texture size and shape cutting conditions (Cutting velocity V , depth of cut d and feed rate f), material, tool geometry, lubricant conditions and so on. Cutting forces for orthogonal cutting comprises of the main cutting force F_c and thrust force F_t , and feed force F_f which is zero as it is cutting only a thin wall orthogonally. The cutting forces are sensed by the Kistler MiniDyne Type 9256C1 Dynamometer. The signals are amplified and processed with the help of a data acquisition system using the DEWESoft software. The schematic of the force measuring system is shown in Figure 3.20.

Figure 3.20: Schematic illustration of experimental setup for force measurement

The specific cutting energy is often used to address the efficiency of the cutting process and is given by:

$$\text{Specific energy} = \frac{F_c V}{\eta} \quad (3.1)$$

where F_c is the cutting force, V is the cutting speed and η is the material removal rate. The textured tool is expected to have a reduced cutting force and thus, a reduced specific cutting energy is required to machine the workpiece.

Coefficient of friction is the ratio of cutting force (F_c) with thrust force (F_t), and this would quantitatively characterise the frictional behaviour of the surface in the interface. This is used by many researchers as a performance parameter of the textured tool [25, 26, 53, 88]. Friction coefficient is measured with the help of dynamometer. However, this ratio of forces, called the apparent coefficient of friction, is the result of interaction not only between the rake face of the tool and the chip underside but also the tool edge, the flank face and the newly formed surface of the workpiece. The interactions zones are shown in Figure 3.21. Thus, the actual friction between the tool textured surface and the workpiece/chip might be different from the apparent friction coefficient. The actual friction can be obtained by simulating the cutting conditions in a tribometer setup.

*Figure 3.21: Interaction zones in cutting process***3.6.2 Shear angle/Chip thickness ratio**

The shear angle increases with a decrease in friction on the rake face [89], which implies that the increase in shear angle is facilitated by the ease of chip flow over the rake face due to the reduced friction. The relationship between the friction coefficient and the shear angle can be realised from equations (3.2) and (3.3) below [90]:

$$\phi + \frac{\beta}{2} - \frac{\alpha}{2} = \frac{\pi}{4} \quad (3.2)$$

$$\beta = \tan^{-1} \mu \quad (3.3)$$

where ϕ is the shear angle, β is the friction angle, α is the rake angle and μ is the coefficient of friction. The increase in shear angle reduces the coefficient of friction and vice versa for a constant rake angle. Thus, texturing of tool either decreases the friction or increases the shear angle, which is beneficial as they are interdependent. In addition to a reduction in friction coefficient, the shear angle increment has other classical benefits including a reduction in shear plane area, reduced cutting force and less energy spent on cutting process.

Equation (3.4) gives the shear angle value that is valid for orthogonal cutting [91]. The texture on the rake face affects the chip thickness ratio and thereby the shear angle, as the formation of chips involves the shearing of the workpiece material in a plane extending from the tool edge to the position where the chip leaves the work surface [92].

$$\Phi = \tan^{-1} \left(\frac{r_c \cos \alpha}{1 - r_c \sin \alpha} \right) \quad (3.4)$$

where, α = rake angle and r_c is the chip thickness ratio and is given by Equation (3.5)

$$r_c = \frac{\text{Undeformed Chip Thickness}}{\text{Deformed Chip Thickness}} \quad (3.5)$$

The undeformed chip thickness is the feed or depth of cut in orthogonal cutting. The deformed chip thickness can be measured by using a micrometre; however, as the chip is very soft, a micrometre may not give the correct reading. Thus, the chip is placed on clips and by using a hot mould, sample of the moulded chips are produced. The samples are polished to measure the chip thickness under a microscope as shown in Figure 3.22. Thus, the shear angle can be measured from the chip thickness ratio. Additionally, it is possible to measure the shear angle by the quick stop [2] method or by using a highspeed camera image. Quick stop method is an attempt to study the chip formation characteristics by suddenly bringing the spindle to rest with the idea to freeze the cutting process in the middle of cutting. However, due to the inertial effect of the spindle, it is not possible to bring it to rest all of a sudden. To address this inertial effect, Subbiah [2] devised a method in which the tool is supported on a very brittle material. When cutting is in progress, a manual hand blow is used to break the brittle material to take the tool out of contact from the workpiece instantly. In such a case, the steady state cutting chip attached to the workpiece is used for chip formation analysis and chip root analysis. In this thesis, high speed camera is used instead to study the chip forming process, and the process can be digitally frozen at any instant of time.

Figure 3.22: Chip measurement from polished hot moulded sample

3.6.3 Tool–chip contact length/area

The contact length/area reduction in addition to friction reduction is considered as a reason for the performance improvement of a textured tool. The contact area is the area on the cutting tool that is in contact with the chip during cutting. This parameter has a direct influence on the performance of the cutting tool. Greater the contact area, greater the friction or the restriction on the flow of chip. This relationship can be written as [90].

$$F_{fr} = A_w \tau_c \quad (3.6)$$

where, F_{fr} is the frictional force, A_w is the contact area between the chip and the tool rake face and τ_c is the shear strength at the tool-chip interface.

It should be noted that the tool-chip contact zone is not purely a sliding contact region. It consists of both sliding and sticking regions. The sliding region may be independent of friction in terms of the true contact area, but a change in sticking region affects the friction and the cutting forces [93]. Thus, the contact area has a direct influence on the performance of the cutting tool. The greater the contact area, the larger the restriction to the chip flow and therefore, higher the friction. The contact area is mapped for the tool specimen from the images taken with the help of SEM. The boundary of the contact region in the image obtained is traced

by using a Web Plot Digitizer software by a series of data points. The data points were plotted, and a polynomial curve is fitted using the software Graph. The area under the polynomial represents the overall contact area between the rake face of the cutting tool and the chip. The actual contact area is the area obtained by subtracting the dimple areas from the overall contact area. The protocol adopted to measure the contact area is shown in Figure 3.23. This measurement protocol gives an assured contact measurement, and a small difference in contact between the specimens can be traced. To measure the contact area in a more systematic way, the following procedure is followed.

1. SEM image is captured for the tool surface which has the traces of workpiece material particles deposited during the cutting process.
2. The image is processed by a software called 'Web Plot Digitizer' to trace the boundary of the contact region by a series of points. A minimum of 50 data points is marked on the boundary line and are exported as excel files.
3. These data points are plotted using the software 'Graph' to fit the polynomial curve with the boundary points.
4. The area under the polynomial which represents the contact area is calculated by integration using the same software.
5. The actual contact area is calculated by subtracting the area of the enclosed texture units and is illustrated in Figure 3.24. The textures can be fully or partially enclosed in the contact zone. The partially enclosed textures are categorised into four stages namely 25%, 50%, 75% and 100% enclosed textures and the intermittent enclosures are rounded to the next nearest stage.
6. Contact area divided by the width of contact gives the equivalent contact length.

Figure 3.23: Contact area measurement

Figure 3.24: Contact area measurement for partly covered dimple textured tool

3.6.4 Chip morphology

The chip morphology affects the dynamics of the machining process. Chip formation analysis is important to reduce the tool wear and increase the tool life. This analysis will help in understanding the stress distribution and behaviour of the material under a severe deformation process [84]. Any attempt made to modify the chip morphology will have an effect on the cutting forces and the machinability of the workpiece material. By controlling the chip morphology, the machinability of the material can be controlled.

The textured cutting tool results in the formation of more curled chips and thinner chips, and hence, in thinner chip, which will result in an increase in shear angle. The change in chip formation is shown in Figure 3.25. The chip morphology is studied from the curvature of the chip formed and the underside of the chip formed. Additionally, the length of the chip without breakage is considered for the assessment of texture effect. A high-speed camera and chip examination under the microscope were used to assess the texture effect in terms of chip morphology.

Figure 3.25: Schematic of change in chip morphology due to texture on rake face of the tool

3.6.5 Anti-adhesivity

In metal cutting, particularly in the cutting of ductile materials, the workpiece material adhesion with the tool would affect the repeatability of the machined part and would increase wear on the tool surface. Adhesion is one of the biggest problems in machining aluminium alloys. In aluminium cutting, friction and high temperature at the interface regions will cause aluminium to melt and stick to the cutting tool surfaces. This will lead to the adhesion of aluminium on the tool surface. Additionally, the adhesion is facilitated by the chemical affinity of aluminium atoms at high temperature. Higher adhesion of aluminium atoms implies lower efficiency of cutting. Furthermore, the higher adhesion will result in an increase in build-up

edge. Aluminium chips readily and severely adhere to the surface of the cutting tool, often leading to tool failure [55]. The application of texture on the cutting tool will reduce the adhesion of aluminium on the cutting tool surface [89]. The concentration of aluminium material on the rake face of the cutting tools after cutting gives a measure of the texture effect on anti-adhesivity. This measurement was done by using a SEM and an Energy Dispersive Spectroscopy (EDS) (INCA EDS apparatus, Oxford Instruments Pte Ltd). The EDS apparatus coupled with the SEM can decipher the material composition of a sample for subsequent analysis.

For aluminium cutting by a tungsten carbide tool, three-materials Al, W and C are taken into consideration in the EDS analysis. The change in percentage concentration of the workpiece material for the textured and the non-textured tools gives a measure of the texture effect on the adhesivity of the material elements.

3.7 Experimental results and discussion

All results discussed in this chapter were taken from aluminium workpiece cutting process unless otherwise stated.

3.7.1 Cutting forces

Figure 3.26 shows the texture effect on cutting forces for experimental cutting tests conducted on the Mikrotool machine for Al ribs cut by WC tool. The tests were conducted for 1 mm width, 10 μm depth of cut, and 25 passes. Data were plotted with maximum and minimum error bars calculated from two repeated experiments. In this thesis, all the plots with error bars are for values averaged from two repeated tests unless otherwise stated. It was found that for the rake textured tool, the cutting force is lower than for the non-textured tool in both

mist and dry conditions. The thrust force follows the same trend as the cutting force, but the reduction in force is extremely small. It is to be noted that the tool used in these experiments were textured only on the rake face, and thus, the effect due to the texture will reflect more on the cutting force. However, the tool has a rake angle of 5° , and hence, the texture will also have some influence on the thrust force.

Figure 3.26: Texture effect on cutting forces in mist and dry conditions

Figure 3.27 shows the comparison of cutting force and trust force obtained for non-textured, flank textured, flank and rake textured and rake textured tool. The results were taken from the tube cutting experiments conducted on the Mikrotol machine in mist condition. The cutting width was 1 mm, depth of cut was $10\text{ }\mu\text{m}$, and the cutting speed was 282 mm/min. From the results, it can be observed that the flank texture either had negative or nil effect on the test conducted. There is not much difference between the ‘rake’ textured tool and ‘flank and rake’ texture tool, which implies that the flank texture has a negligible effect. The flank face texture is studied in detail in Section 3.8.

Figure 3.27: Comparison of non-textured with flank, flank and rake and rake textured too for the cutting speed of 282 mm/min under mist condition

Furthermore, in comparison to the non-textured tool flank, the textured tool has slightly higher cutting forces, which might be due to the adverse effect of the flank textured tool. The ‘rake’ textured and the ‘flank and rake’ textured tool shows a decrement in both cutting force and thrust force in comparison with the non-textured tool. It is observed that the rake textured tool encounters lower cutting force and thrust force as compared to the non-textured tool by 17% and 29%, respectively.

Figure 3.28: Texture effect on cutting force for different cutting speeds

Figure 3.28 and Figure 3.29 show the results obtained from experiments conducted in the Mazak lathe machine in orthogonal tube cutting of Al workpiece with WC tool. The textured tool used in the experiments was laser textured and is shown in Figure 3.11. The results shown in Figure 3.28 were obtained from the experiments conducted for 1 mm width of cut, 25 μm depth of cut for a cutting speeds of 60 m/min, 120 m/min, 240 m/min or 360 m/min. The figure shows the variation in texture effect on cutting force for an increase in cutting speed; it can be observed that the texture effect increases with speed from 1% at 60 m/min to 9% at 360 m/min.

Figure 3.28 is the result of 6 iterations. The much larger variation for non-textured tool for cutting speed 240m/min is caused by a single outlier data point; it was not eliminated from the result for completeness. If this data point is eliminated, the variation will be small and similar to the rest of the non-textured tool.

Figure 3.29: Texture effect for Al and Cu at various depth of cut

Figure 3.29 shows the effect of the depth of cut on a textured and a non-textured tool for Al and Cu workpiece material for a cutting speed of 240 mm/min. It can be observed that a textured tool performs better in the cutting of both Al and Cu in terms of both cutting forces.

It is to be noted that the error bars for copper at 50 μm depth of cut is overlapping for both cutting forces and thrust force. Excluding the overlapping results, it can be noticed that the texture effect increases with the depth of cut for aluminium and for copper; the texture effect is more for 25 μm depth of cut. The geometric parameters of the texture have their own influences in reducing the cutting forces of the textured cutting tool. More detailed study on geometric and distribution parameter on texture units is presented in Chapter 4.

3.7.2 Chip forming characteristics

The chips created by the rake textured tool are seen to be more curled and break into smaller pieces, whereas the chips from the non-textured tool are long and continuous. This is due to the chip losing its contact with the tool at the texture, and it starts to curl; as the chip is very thin and made of Al soft material, it breaks into smaller pieces. Non-texture tool chips have more contact with the tool; thus, the chips are relatively long and straight, which can be observed from Figure 3.30. These chips are obtained from the tube cutting experiment in the Mikrotool machine.

Figure 3.30: Aluminium chips produced by the non-textured and rake textured tool.

Figure 3.31 shows the chips produced at various cutting speed by the non-textured and the textured tool for the cutting experiments conducted in the Mazak Lathe machine. It can be observed that for the non-textured tool, the curling of the chip decreases with an increase in

speed and becomes a straight chip. For the textured tool, the chip is comparatively more curled at all cutting speeds, and the chip curl diameter increases with speed.

Figure 3.31: Chips produced by the non-textured and rake textured tool at various cutting speeds.

The change in chip formation can be better understood by capturing the chip formation using the high-speed camera. The images from high-speed camera videos are taken at various speeds for both the non-textured and the textured tool; the experiments conducted on the Mazak Lathe machine are shown in Figure 3.32.

Figure 3.32: Change in chip morphology for textured tool for various speed

These observations provide an idea of how much curl the chip has, the change in angle and length at which the chip leaves the tool. It can be observed that the chip generated from the textured tool tends to separate from the tool rake face earlier and becomes shorter in tool-chip contact length as compared to that generated from the non-textured tools discussed in Section 3.6.4. Thus, the reduction of chip contact length at the tool rake surface is attributed to the presence of the microtexture and hence, it reduces the friction and thereby, the cutting forces.

It is reported [25, 26, 38] that friction is reduced due to texture. These may result in an increase in chip velocity and thus, in more curl of the chip, i.e., the curl diameter decreases. In contradiction, friction could also increase in the presence of surface texture, i.e., textures cause significant resistance to the chip flow. Thus, chips prefer to curl rather than continuously flow over the tool rake face; in other words, the chip will take the path that requires less energy. This consequently results in lower tool-chip contact length and forces. Thus, the reason behind the curl of the chip or decrease in the contact length of the chip is not clear. To understand this friction on the interface, it has to be studied locally.

3.7.3 Shear angle

Figure 3.33 shows the change in chip thickness ratio and the shear angle due to the introduction of texture on the cutting tool rake surface. The results were obtained from the measurement taken from the chips obtained from the machining of the Al tube cutting in the Mikrotool machine for the non-textured and the textured tool. The test was conducted for 1mm width and 50 μm depth of cut for a cutting speed of 3000 rpm. It can be observed that the textured tool produces thinner chips and results in a decrement of the shear angle by 22.57%.

Figure 3.33: Chip thickness measurement for non-textured and textured tool

Figure 3.34 shows the decrease in chip thickness and the corresponding increase in shear angle of the textured tool for various cutting speeds. The chip thickness is measured from the chips obtained from the cutting experiments conducted on the Mazak Lathe machine. The chip thickness decreases with an increase in the cutting speed from 120 m/min to 360 m/min.

Figure 3.34: Chip thickness and shear angle for non-textured and textured tool

3.7.4 Tool-chip contact length

The trace of aluminium on the rake surface can be used to measure the contact length of the tool-chip contact. This can be used to identify the location and to measure the tool-chip contact length. The tool-chip contact length for the non-textured tool is longer than that of the dimple and stripe textured tool. Figure 3.35 shows the photomicrograph of the rake face of the tool,

which is taken after the experiment conducted with a cutting speed of 240 mm/min and a depth of cut 50 μm under dry conditions. The method measuring the contact area and the contact length has already been outlined in Section 3.6.3 and is more systematic than that reported in the literature, which was discussed in Section 2.5.4. From Figure 3.35, it can be observed that the traces of aluminium deposits were traced by a series of points and the area under the locus of traced points gives the contact area; the area divided by the width of cut gives the equivalent tool-chip contact length as explained in Section 3.6.3. The equivalent contact length measured for the non-textured, dimple textured, and stripe textured tool were found to be 450 μm , 360 μm and 370 μm respectively and are represented in Figure 3.35. This confirms that the contact lengths are affected by the texture, and the contact length (tool with chip) for the non-textured tool is more than that of the textured tools. For the textured tool, the contact between the tool and the chip is less, and this might be one of the reasons for the decrease in cutting forces. The corresponding decrease in cutting force and thrust force for the same cutting condition can be seen from Figure 3.29 (50 μm depth of cut column in plot for aluminium).

Figure 3.35: Contact difference for (a) Dimple and (b) Stripe textured tool with the non-textured tool

The trace of aluminium on the rake surface can be used to measure the contact length of the tool-chip contact. This can be used to identify the location and to measure the tool-chip contact

area. The tool-chip contact length for the non-textured tool is longer than that of the dimple and stripe textured tool

The chip curl early in the presence of texture. It is to be noted that the texture effect is different from the chip breaker phenomenon. In tools with a chip breaker, the chip will be separated immediately on the onset of the chip breaker groove or at the change in the face angle of the breaker. In contrast, in the rake textured tool, the chip will flow over four to five rows of texture before getting separated from the tool. Additionally, the size of the chip breaker is macro size whereas the texture is of micro size. Dimple textured tool gets clogged more than the stripes textured tool by the workpiece material as can be seen from Figure 3.35. In stripes textured tool, the stripes act as secondary cutting edges, and so traces of aluminium intermittently deposited on the textured region can be observed and traces of aluminium can be seen further from the cutting edge than that for the dimple textured tool. Thus, the contact area for the stripes textured tool is more than that of the dimple textured tool.

It is clear from both literature and the experimental results that contact length decreases in the presence of textures on the rake face. Reports in the literature [24-26] calculated the friction coefficient from the cutting forces obtained from the experiments and hence, cited frictional decrease as the tribological phenomenon triggered by the presence of the texture. However, there were no direct evidence presented for a reduction of friction by the introduction of texture on the cutting tool surface in that textures have indeed reduced friction. Forces might be simply lower because of reduced contact.

3.7.5 Adhesivity of aluminium atom

The following section highlights a comparative EDS spectra analysis of tool rake surfaces of HSS tool, which is examined after cutting aluminium workpiece between non-textured and textured cutting inserts. Figure 3.36 gives the EDS spectra for the non-textured tool with lines showing the amount of Al, Fe and C present on the rake surface of the used cutting tool along the scan line. Figure 3.37 and Figure 3.38 show the EDS spectra for dimple textured tool and stripe textured tool respectively.

Figure 3.36: EDS spectra for non-textured tool

It can be noted that in textured tools, the textured depths are filled with the workpiece material and is observed as wavy deposition of Al due to the discontinuous surface of the textured and non-textured space on the rake face.

Figure 3.37: EDS spectra for dimple textured tool

It can also be observed from the EDS spectra that the distance to which aluminium is deposited on the non-textured tool is relatively higher than that of the textured tools. In the flat region of the textured tool, the amount of Al deposited is almost the same in the textured and non-textured tool, whereas the textured regions of the textured tools were clogged with Al deposition.

Figure 3.38: EDS spectra for stripe textured tool

3.8 Influence of flank textures

The influence of flank texture on the cutting tool is exclusively studied in this section. From Figure 3.27 it can be noticed that the presence of texture on the flank face of the tool did not show much difference from the non-textured tool in cutting forces. This implies that micro-texturing the flank face does not influence the cutting forces. This might be because the contact length on the flank face is smaller than the distance of the first row of dimples from the cutting edge (50 µm). The ineffectiveness of the flank texture could be linked to the clearance angle design of the cutting tool. Therefore, 0° clearance angle (or the so-called flat flank surface) tool is used for this investigation in an attempt to increase the contact length/area. In addition, texturing on the flank face is to be made closer to the cutting edge on the flank side of the tool without damaging the cutting edge.

Figure 3.39 shows the comparison between 2° and 0° clearance angle tool. For 0° clearance, a flat distance of $200\text{ }\mu\text{m}$ is textured, and in the flank region, the contact will not be more than $200\text{ }\mu\text{m}$ from the cutting edge. EDM is used to texture the flat region that varies from 150 to $200\text{ }\mu\text{m}$ from the cutting edge. The parallel stripes are approximately $40\text{ }\mu\text{m}$ from the cutting edge with a pitch of $60\text{ }\mu\text{m}$. The stripes are approximately $18\text{ }\mu\text{m}$ in width and $20\text{ }\mu\text{m}$ in depth. The orthogonal tube cutting experiments are conducted at a cutting speed of 1 m/min and for different depths of cut $10, 50, 100\text{ }\mu\text{m}$ in the Mikrotool machine. For both the textured and the non-textured tools, the experiments were conducted in mist and dry conditions. The different depth of cut is attempted to study the effect due to elastic recovery of the newly formed material surface and the texture on the flank face for the increased depth of cut. The proposed design is to make the flank contact with the workpiece so that the flank texture effect can be studied. This is justified by the fact that a flat surface on the flank surface will be generated after prolonged cutting due to normal flank wear, and thus, pre-generating such flat will be akin to simulating flank wear progression.

Figure 3.39: Schematic diagram of flat flank tool

For the cutting forces obtained from the experiments for different depths of cut, it is seen that the flank textures do not have much effect on the performance of the cutting process of

aluminium as the workpiece. The results shown in Figure 3.40 were obtained from the average value of two repeated tests for each case. The flank textured tool in dry condition performs worse than both the non-textured and textured tool in wet conditions. Excluding the dry cutting results, there is just a difference of 1 N between the flank textured and non-textured tools for both cutting and thrust forces. An exception is for the 50 μm depth of cut when the difference is 3N. Thus, overall the flank textures did not show any significant improvement in terms of cutting or thrust forces both in mist and dry conditions. It should be noted that the results obtained are for a particular cutting speed and a particular type of texture. Both these factors have their own individual effect on the performance of the tool.

Figure 3.40: Flat flank tool results

3.9 Summary

This chapter explains the details of the experiments, cutting tool, workpiece, experimental setup, instruments and equipment used, texturing methods and methodology for measuring various performance parameters to assess the cutting tool performance. Two micro-texturing methods namely, EDM and laser texturing, were used to texture the tool surface. These

methods were explained with setup and working conditions. The advantages and disadvantages of both methods were discussed.

The cutting parameters investigated are the cutting force, thrust force, chip thickness ratio, shear angle, contact length, chip morphology and anti-adhesivity. The cutting forces for the textured tool are less than the non-textured tool, and the effect is more in the presence of a lubricant. The rake textured tool is found to have more influence on the cutting forces among the tested tools. The texture effect on a cutting tool is found to increase with an increase in the cutting speed. Texture effect is not found to be influenced by the increase in depth of cut for both aluminium and copper workpieces.

For textured tools, the chip curled more than the non-textured tool, and the curvature of curl is more for low cutting speeds. The textured tool produces thinner chips due to an increase in shear angle. The difference in tool-chip contact area for the non-textured tool with the textured tool is observed. With the help of EDS, the adhesion of workpiece material on the tool rake is measured, and it is observed that the textured tool reduces the adhesion considerably, and the texture units are getting clogged with workpiece material during the cutting process.

The results obtained from the experimental study were presented in comparison with the non-textured tool for all the parameters investigated and were discussed on the basis of improvement in performance of the cutting tool. It is found that the experimental investigation contained in this chapter confirms the positive effect of textured tool in improving the performance of a cutting tool. Based on this preliminary study, further investigations are conducted and presented in the following Chapters.

Chapter 4: Assessment of geometry and distribution parameters of micro-texture on cutting tool

Micro-textures on cutting tool surfaces have been reported for their benefits in terms of reduction of adhesion, wear, force and friction during the cutting process. However, these benefits are dependent on the micro-texture parameters. In this chapter, the influence of texture geometry parameters such as texture shape and size, depth and distribution parameters such as pitch and distance of texture from the cutting edge, will be studied using statistical analysis. Micro-textures were fabricated on the rake face of the tungsten carbide (WC) cutting tools by a picosecond laser. Circular dimples were selected as the texture unit cell, and the parameters included diameter, depth, pitch and distance from the cutting edge.

4.1 Texture parameters selected for study

The geometry selected for the experiments were circular patterns (dimples) due to their symmetrical pattern on all sides. An even edge throughout will yield more consistent results, and that is the reason why dimples were selected over other patterns. For example, star-shaped patterns imprinted may be an issue when the cutting tool comes into contact with the workpiece through their edges. Kümmel et al. reported that dimple textures were more efficient regarding wear reduction in contrast to continuous / channel (stripes) micro-textures, where wear was increased [68]. Sugihara et al. [94] from their experimental studies concluded that micro-dimple textures exhibit better performance even under severe lubricating conditions than micro-groove textures. The improved performance of dimple textured cutting tool is demonstrated in section 3.7.1 for various cutting speed and depth of cut; from section 3.7.4, it

is observed that the contact area for the stripes textured tool is more and stripes texture edges act as secondary cutting edges. The above-mentioned reasons lead to the selection of dimple textures over stripes textures for this study. Distribution of the patterns on the cutting tool is very important as having the right parameter level will result in utmost utilisation of the texture effect in the cutting process. As such, four texture parameters are identified, which are diameter of the circular patterns, depth of the patterns, pitch between each dimple and distance from the edge of the cutting tool. The details of the parameters are shown in Figure 4.1.

Figure 4.1: Details of texture parameters including depth, diameter, pitch and distance

Pitch is the distance between the centres of two adjacent dimples that should not be too near or too far from one another. Distance of the first row of dimples from the cutting edge has to be optimum as being too near may interfere with the cutting process or may decrease the

strength of the cutting tool near the cutting edge. Being too far from the cutting edge may reduce the effectiveness of the texture. The dimple can serve as a reservoir for lubricants, and thus, the depth may play a role in retaining the lubricants. Lastly, the diameter of each dimple is also considered in the study to find the effective size of the textures.

4.2 Methodology

These four textured parameters are studied in three levels, and the range of each parameter is selected based on the previous studies conducted by Deng et al. [53, 56], Xing et al. [46], Lian et al. [57], Sugihara et al. [25, 55] and Enomoto et al. [8, 89]. In traditional experimental design, with the increase in process parameters, parameter levels and repeated trials, the procedure becomes too complex and requires a large number of experiments. To reduce the number of experiments required and to find the significance and contribution of the parameters, the Taguchi method was adopted. This method consists of a plan of experiments with the objective of acquiring data in a controlled way. Its advantage is reducing the number of experiments, thereby, saving experimental time, cost, material and yet the significance of each parameter considered can be discovered [95]. In this study, the Taguchi L9 orthogonal design (four-factor, three-level) model was selected to evaluate the effects of texture parameters on the performance of the cutting tool. The experiments were performed based on this model, which requires nine kinds of texture parameter combination. The levels of each parameter chosen for the experiment are shown in Table 4.1. The levels were taken to cover the entire range that was used by researchers for each parameter. Table 4.2 indicates nine texture combinations that were textured on the experiment tool specimens. Figure 4.2 shows the fabricated textured tools. The schematic of the distance of the first row of texture from the cutting edge is shown in Figure 4.3.

Table 4.1: Levels of the four texture parameters

Parameter (μm)	Level		
	L1	L2	L3
Texture diameter	50	100	150
Depth	10	25	50
Pitch	50	100	150
Distance from edge	75	125	175

Table 4.2: Taguchi L9 orthogonal design with nine texture combinations

Experiment tool specimen	Factors			
	Diameter μm	Depth μm	Pitch μm	Distance μm
1	50	10	50	75
2	50	25	100	125
3	50	50	150	175
4	100	10	100	175
5	100	25	150	75
6	100	50	50	125
7	150	10	150	125
8	150	25	50	175
9	150	50	100	75

Figure 4.2: Nine types of textured tool specimens used in the experiment

Figure 4.3: Schematic of distance of the first row of texture from cutting edge for 1-9 specimen

The Al6061 alloy workpiece was fabricated as a tubular cylinder with 61 mm outer diameter, 1 mm tube thickness and 70 mm length, and produced with 25 mm base thickness to avoid deformation of the tube by holding it on the chuck. Orthogonal tube cutting experiment was conducted on a lathe machine (Mazak 6T Quickturn CNC Turning Centre, Yamazaki Mazak Singapore Pte Ltd). The experimental setup is shown in Figure 3.19. The experiments were carried out under the cutting conditions shown in Table 4.3. These cutting parameters were selected based on the cutting tool manufacturer's recommendation and industrial applications.

Table 4.3: Cutting conditions

Parameters	Values
Cutting velocity (m/min)	300
Depth of cut (μm)	50
Cutting length (m)	7.5
Coolant supply (L/hr) at 0.6 MPa	2.6

The experiments were conducted for all the nine types of textured tools and the non-textured tool. The four responses studied were cutting force, shear angle, contact area and percentage concentration of workpiece material on the rake surface. Based on the Taguchi method, signal-to-noise (S/N) ratio was calculated for all the responses. Signal represents the desirable value (mean), and noise represents the undesirable value (standard deviation) for the output response. Equation 4.1 calculates the S/N ratio for 'smaller is better' consideration and is employed for finding the S/N ratio for cutting forces, contact area and adhesion of aluminium on the tool. Equation 4.2 calculates the S/N ratio for 'larger is better' consideration, which is used for shear angle response.

$$\frac{S}{N} = -10 * \log \left(\frac{\sum Y^2}{n} \right) \quad (4.1)$$

$$\frac{S}{N} = -10 * \log \left(\frac{\sum (1/Y^2)}{n} \right) \quad (4.2)$$

where Y is the measured data and n is the number of data.

Irrespective of the category combination of texture parameters, better performance is given by the higher value of S/N ratio. Regardless of the ‘smaller the better’ or ‘larger the better’ consideration, the highest absolute value on the effect-plot for the S/N ratio gives the most significant effect.

4.3 Results and Discussions

The responses were measured based on the experiments conducted for the nine types of tool specimens and the non-textured tool. All experiments were repeated for two times. The responses included cutting force, thrust force, shear angle, contact area and percentage concentration of aluminium atoms. In addition to the nine specimen values, the non-textured tool specimen value was also recorded for comparison purpose but was not used in the Taguchi analysis.

4.3.1 Cutting forces

The cutting forces (both cutting force and thrust force) measured experimentally for the different combinations of textured tools are shown in Figure 4.4. The results indicated that specimen 9 with the combination of 150 μm diameter, 50 μm depth, 100 μm pitch and 75 μm distance had the least cutting force and thrust force with respect to other combinations tested. It can be observed that the change in texture parameters has an impact on the cutting forces. Cutting force and thrust force are reduced by 7.3% and 16.5%, respectively by specimen 9.

Figure 4.4: Comparison of the forces for non-textured and textured tool

The individual effect of texture parameters on the cutting and thrust forces are shown in Figure 4.5. The cutting forces decreased with an increase of diameter and depth of the texture units, whereas they increased with an increase of pitch and distance from the cutting edge. Based on the analysis of the S/N ratio, the minimum cutting force would be for the texture parameters that are 150 μm in diameter, 50 μm in depth, 50 μm in pitch and 75 μm in distance from the cutting edge.

Figure 4.5: Effect of texture parameters on cutting force

The delta for each parameter, namely the difference between maximum and minimum S/N ratio values, is calculated. The parameter corresponding to the biggest value of delta is the most significant parameter. From Figure 4.5, the diameter of the texture that has the largest delta value, has the most significant effect on the cutting force. This is followed by distance, depth and pitch.

Figure 4.6 gives the effect of texture parameters on the thrust force. For thrust force as output response, except the pitch of textures, all the other parameters have the same kind of impact as the cutting force. For thrust force, the parameters of texture follow the same order of significance as the cutting force. From the analysis of S/N ratio, the minimum thrust force was obtained from the combination of 150 μm in diameter, 50 μm in depth, 100 μm in pitch and 75 μm in distance from the cutting edge.

Figure 4.6: Effect of texture parameters on thrust force

The results (ANOVA - with at least 90% confidence) for the texture parameters considered for the cutting force are presented in Table 4.4. Based on the F-test, the most significant parameter in terms of percentage contribution is the diameter of the texture units with almost 50% of contribution followed by the distance of texture from the cutting edge and depth. The least significant is the pitch parameter with 3.4% contribution.

Table 4.4: ANOVA results for cutting force

Parameters	SS	DOF	V	F	Contribution
Diameter	8.5398	2	4.2699	14.628	49.65 %
Depth	2.5998	2	1.2999	4.453	15.12 %
Pitch	Pooled	-	-	-	-
Distance	5.4726	2	2.7363	9.374	31.82 %
Error	0.5838	2	0.2919	-	3.39 %
Total	17	8	-	-	100 %

(At least 90% confidence level. Where SS - Summation of squares, DOF - Degree of freedom, V - Variance and F - F test value)

Figure 4.7: Percentage contribution of texture parameters on texture effect

Increasing the diameter of texture units will result in a higher reduction in the contact area and a larger area for lubricant entrapment. This could be the reason why a tool with larger texture diameter showed the highest reduction in the cutting forces. This is reflected in the S/N ratio and the ANOVA result for the texture with the largest diameter (150 μm). The second

influential parameter is the distance from the cutting edge. Figure 4.5 and Figure 4.6 show that a smaller distance of texture from the cutting edge will have a greater reduction in the cutting force, but this is limited to a distance that should not degrade the strength of the cutting edge. The depth of the texture shows no significant effect when increasing from 10 μm to 25 μm , but the effect of depth increases when further increasing the depth to 50 μm . The effect of texture depth is to be examined further for the influence of the capillary effect of the texture units with an increase in depth. The least significant parameter is the pitch of the texture distribution. Additionally, it is evident from the texture that it is efficient when the pitch of the texture units is within 50 to 100 μm . The texture effect reduces when the pitch distance increases.

The experimental confirmation test was conducted for the Taguchi analysis to verify the predicted value based on the equation for the optimal parameters. The predicted optimal S/N ratio is calculated from Equation 4.3.

$$S/N_{opt} = S/N_m + \sum_{i=1}^n [S/N_i - S/N_m] \quad (4.3)$$

where S/N_{opt} is the predicted value, S/N_m is the total mean, S/N_i is the mean at optimal levels, and i is the number of main design parameter. The experimental confirmation and the predicted values are given in Table 4.5, and the error is found to be within reasonable accuracy.

Table 4.5: Comparison of experimental confirmation and predicted values

Experiment parameters	Cutting force (N)	S/N ratio (dB)		
		Experimental	Predicted	Error
150 μm diameter, 50 μm depth, 50 μm pitch and 75 μm distance	56.70	-35.07	-35.51	1.23%

The confirmation experiment gives the least cutting force of 56.70 N, the corresponding thrust force is 51.10 N which is larger than the thrust force of specimen 9. Thus specimen 9

(with 100 μm pitch) corresponds to higher cutting force by 1% and a smaller thrust force by 4.9% in comparison to the experimental confirmation test. The 1% difference in cutting force might not be very significant, but the reduction of thrust force by 4.9% is very significant. Therefore, considering both the response of cutting force and thrust force, specimen 9 is the efficient textured tool within the studied range of parameters.

4.3.2 Shear angle

Six measurements of chip thickness were taken in different parts of each chip collected from the experiments conducted for each combination of texture parameters. The measurement of every reading was not taken at the starting and ending of the chip. This is to ensure cutting feed was steady on the part of the chip where the reading was taken. The average values of chip thickness and their corresponding ratio and shear angle are given in Figure 4.6. This table illustrates the shear angle change with a different combination of texture parameters and the shear angle for the non-textured tool. The chip thickness for the non-textured tool was the highest among all the tools.

The S/N ratio is calculated for shear angle as a response, and the effect of texture parameters on shear angle is shown in

Figure 4.8. It shows that the pitch and distance of texture from the cutting edge are less significant on the shear angle, whereas the texture diameter and the depth of dimples are very significant. It is also observed that the most effective texture parameters on shear angle are given by 100 μm in diameter, 10 μm in depth and 125 μm in distance from the cutting edge. This setting gives the maximum shear angle. The trends on the effect plot are not clear for diameter, pitch and distance as they show the mid-level as the best level.

Table 4.6: Experimental chip thickness ratio and shear angle

Exp. No.	Chip thickness (mm)	Chip Thickness Ratio (r_c)	Shear angle (Φ)	S/N ratio (dB)
1	0.286	0.1748	9.916	19.9267
2	0.291	0.1718	9.749	19.7792
3	0.291	0.1718	9.749	19.7792
4	0.281	0.1779	10.089	20.0770
5	0.287	0.1742	9.882	19.8969
6	0.278	0.1798	10.196	20.1686
7	0.280	0.1785	10.125	20.1079
8	0.295	0.1694	9.619	19.6626
9	0.302	0.1655	9.401	19.4635
Non-textured	0.304	0.1644	9.340	-

Figure 4.8: Texture parameters effect on shear angle

4.3.3 Actual contact area

The same methodology explained in Section 3.6.3 is used to measure the actual contact area of tool-chip contact region. The difference in the contact area for different types of texture

combination is shown in Figure 4.9. After calculation, it is found that specimen 9 shows the least actual contact area, which is 61% less in comparison with that of the non-textured tool.

Figure 4.9: Contact area images for nine specimens

The dependency of the cutting force on actual contact area can be observed from Figure 4.10. The deviation of the specimen is attributed to the effects of other factors such as distance from the cutting edge and depth of the textures.

Figure 4.10: Dependency of the cutting force on actual contact area

It is clear that the non-textured tool has the largest contact area with 0.44 mm^2 in comparison with all the textured tools regardless of their pattern. The largest contact area among the textured tools is specimen 3 with a contact area of 0.35 mm^2 . It means that there is at least 20% less contact area for a textured tool when compared to a non-textured tool. Thus, it is clear evidence that texture has a significant effect on the tool-chip actual contact area.

The Taguchi analysis was done for the contact area as a response, and the details are given in Figure 4.11. The best combination to get a minimum contact area ('smaller is better') among the tested levels is provided by $150 \mu\text{m}$ diameter, $50 \mu\text{m}$ depth, $50 \mu\text{m}$ pitch and $75 \mu\text{m}$ distance from the cutting edge. Additionally, it indicates that distance is the most significant factor followed by diameter.

Figure 4.11: Texture parameters effect on actual contact area

4.3.4 Concentration of aluminium atom on the rake face of cutting tool

With the help of EDS, the concentration of Al atoms on the tool surface was measured in terms of percentage with respect to tungsten and carbon as the cutting tool was made of tungsten carbide. The EDS spectra of the specimens are given in Figure 4.12. The percentage concentration and the S/N ratio were listed in Table 4.7. The reduction in percentage concentration of Al atoms is an indication of reduction in adhesion in the tool-chip interface.

Figure 4.12: EDS spectra for the non-textured and textured tool specimen 1-9

Table 4.7: Concentration of atoms on the rake face of the used tool

Specimen	Aluminium (%)	S/N ratio (dB)
1	10.63	-20.53
2	21.16	-26.51
3	19.98	-26.01
4	23.73	-27.50
5	25.62	-28.17
6	19.39	-25.75
7	23.59	-27.45
8	27.90	-28.91
9	23.64	-27.47
Non-textured	25.09	-

The Taguchi analysis was applied with concentration of Al atoms as the response and texture parameters as variants. The S/N ratio plot is shown in Figure 4.13 with ‘smaller is better’ consideration. The amount of aluminium sticking decreases with an increase of diameter, depth, pitch and distance from the cutting edge. Except for the depth, the trend is the same for other parameters. The efficient texture parameters among the tested levels obtained were 50

μm in diameter, $10\ \mu\text{m}$ in depth, $50\ \mu\text{m}$ in pitch and $75\ \mu\text{m}$ in distance from the cutting edge. This setting causes the least sticking of aluminium on the rake face.

Aluminium is very adhesive to the cutting tool surface at high temperature and pressure which prevail in the contact zone of the cutting process. The non-textured tool surface provides a flat surface which facilitates adhesion. In the textured tool, the rake face is interrupted by dimples, which facilitate heat diffusion and reduce the temperature. In addition, the dimples interrupted the textured tool rake face and will not allow the workpiece material to build up and to prevail for the longer cutting time. Thus, texturing will facilitate the reduction of adhesion of aluminium on the rake face of the cutting tool. However, it is to be noted that clogging of aluminium is also taken place in the texture dimples. It can be observed that the percentage concentration of Al sticking on the rake face is more for the tool with larger texture diameters. The larger texture diameter will allow more Al material to get clogged in the texture. As a result, more concentration of Al is found on the rake face. It is to be noted that though the texture dimples might get clogged with Al material, it will still facilitate quick heat dissipation than the non-textured tool as aluminium has higher thermal conductivity than the tool material.

However, the desired effect is minimum adhesion of Al, which is given by minimum texture diameter. The sticking should be less for larger depth for two reasons. One reason is that the debris gets entrapped in the dimples and so reduces the third body abrasion and reduces the sticking of aluminium. The other reason is that, as the depth increases, the internal surface area of the texture increases which will facilitate more heat transfer and thereby lesser sticking of aluminium. As expected, the sticking increased with increment in depth from $10\ \mu\text{m}$ to $25\ \mu\text{m}$, but after that, increment to $50\ \mu\text{m}$ decreases the sticking. Similar behaviour is observed by Xie et al. [59] on decreasing the microgroove depth from $148\ \mu\text{m}$ to $25\ \mu\text{m}$, the cutting shear angle

increases. On further reduction to the texture depth to 7 μm , the cutting shear angle decreases. They attributed this to too small an aspect ratio for forming the air spaces between the cutting chip back and tool rake face. The same could be true for such behaviour in sticking as shear angle decrement is the result of a reduction in friction with a reduction in sticking. The relationship between shear angle and friction is explained in detail in Section 6.1.

The increase in pitch of the dimples in texture causes more aluminium sticking, which is shown in the pitch column of Figure 4.13. However, the effect of pitch was higher only in the range of 50 μm to 100 μm and became less significant on further increment. The effect of texture distance from the cutting edge is monotonous. The smaller the distance from the edge the more reduction is the sticking of aluminium. However, it should be noted that placing the texture very near to the cutting edge might weaken the strength of the cutting tool. Thus, the diameter is the most significant parameter, followed by the depth, pitch and distance with respect to aluminium concentration on the cutting tool.

Figure 4.13: Texture parameters effect on concentration of Al

4.3.5 Texture parameter effects on various responses - Comparison

In this study, textured cutting tool performance was analysed in terms of four responses which are cutting and thrust forces, shear angle, contact area and the percentage concentration of aluminium atom. The texture parameters have different effects, and the amount of influence on each response varies. Figure 4.14 shows the overall comparison of all the responses for the non-textured and textured tool. The textured tool data show the best result in the analysis of each response.

Figure 4.14: Comparison of responses for non-textured and textured tools

Table 4.8 summaries the relative significance level of each parameter for all the response factors considered in the experiments. It is observed that there is a difference in the ranking of the parameter for their effects. Diameter and distance are more significant in most of the cases while pitch has the least effect.

Table 4.8: Comparison of effect of texture parameters on various responses

Parameters response rank	Diameter	Depth	Pitch	Distance
Cutting force	1	3	4	2
Thrust Force	1	3	4	2
Shear Angle	1	2	4	3
Contact Area	2	4	3	1
% Con. Al	1	2	3	4

Table 4.9: Best tool specimen for individual responses

Responses	Best tool specimen	2nd best tool specimen	% change of best specimen from non-textured tool	% change of 2 nd best specimen from non-textured tool
Cutting force	9	6	7.39	7.31
Thrust force	9	6	16.56	11.93
Share angle	6	7	9.16	8.40
Contact area	9	6	61.36	4.55
% Aluminium	1	6	57.63	22.71

In the overall comparison of all the responses, specimen 9 and specimen 6 performed better than the other specimens, see Table 4.9. Specimen 9 shows the best performance in terms of cutting force, thrust force and contact area. In terms of shear angle and percentage of Al on the tool surface, specimen 9 shows the least improvement in comparison to other specimens. Since the trend of effect plot for shear angle does not give a trend, shear angle parameter is given less weight in terms of overall comparison. Though contact area and adhesion are related phenomena yet their result is contradictory. As contact area is concerned, specimen 9 performs better, whereas in terms of adhesion specimen 9 is not showing very good performance. The reason is attributed to the larger size of dimples in specimen 9 which leads to more clogging of Al resulting in an increase in adhesivity in the EDS adhesivity calculation. Though the texture dimples might get clogged with Al material, it will still facilitate quick heat dissipation than the non-textured tool as aluminium has higher thermal conductivity than the tool material. Specimen 9 shows the best performance, and specimen 6 shows the second-best performance in terms of cutting forces, contact area and percentage concentration of Al. Therefore,

considering all the responses, texture parameters corresponding to specimen 9 and specimen 6 are identified as the suitable combinations in the considered range.

4.4 Summary

This chapter studied the texture parameter effects on the performance of cutting tool in orthogonal cutting of Al6061-T6 alloy. Experiments were conducted by varying these parameters using the Taguchi method. Signal-to-noise (S/N) ratio and analysis of variance (ANOVA) were used to find the optimal levels of the selected parameters and to study the effect of the micro-textures on cutting forces, shear angle, contact area as well as adhesion of aluminium. A confirmation test using the derived levels of texture parameters was carried out to demonstrate the effectiveness of the micro-texture. The best combination of texture parameters was identified considering all the responses and the range of parameters. The effect on all the responses is finally compared for the texture parameters. The observed behaviour of the parameters will be very useful for effective utilization of dimples micro-textures, and the followings can be concluded from the study:

- The diameter of the texture is the most influential process parameter. It is the most significant texture parameter with respect to the responses including cutting force, thrust force, shear angle, percentage of aluminium adhesion and is the second most influential parameter in terms of contact area.
- Smearing or adhesion of aluminium is less in the textured tool in comparison with the non-textured tool. The lowest percentage of aluminium on the textured cutting tool after being used is 15% less than that of the non-textured tool.

- The suitable combinations of texture parameters are identified to be specimen 9 and specimen 6 with respect to all the responses and within the range of parameters considered.
- For all the response parameters, the textured tool shows better performance than the non-textured tool. The difference between the non-textured and the textured tool is quite significant in actual contact area. The actual contact area for the textured tool with the best combination of texture parameters is reduced by 61%.

The significance of the texture parameters on the different response parameters varies and may be contrasted with each other. For example, distance from the cutting edge is the most significant parameter for the contact area, whereas it is the least significant parameter in terms of percentage concentration of Al atoms on the tool surface. Therefore, for future work, the overall significance of each texture parameter should be determined by estimating the weightage of each response on the total performance of the cutting tool. Besides, the dependency of texture effect on a workpiece material and the cutting conditions are to be considered.

Chapter 5: FEM modelling of micro-textured tool cutting process and study of texture effects

Micro-textured cutting tool improves chip-tool tribological interactions. The mechanism by which this improvement occurs is far from clear. Some parameters cannot be studied experimentally on the tool-workpiece contact, which include stress distribution, contact pressure and temperature distribution. FEM allows us to simulate and study these parameters. Numerical simulation of textured tool cutting process is done to focus on the change in chip formation due to texture effect, which has the direct inference of a change in cutting mechanism. In this Chapter, the FEM model is validated for cutting force, contact stress and contact pressure. The validated model is then used to study the texture effect for different textured tools. Such simulation-based studies pave the way for effective micro-texture design for advanced cutting tools.

In addition to the experimental study, a simulation study has also been conducted to analyse the fundamentals behind the texture effect. The machining process, in general, has been widely investigated via the use of numerical simulations to study forces, temperatures, contact, stresses and strains distributions in great detail. In this chapter, FEM simulations are used to study the effect of textures on the tool. Though previous researchers show the reduction in cutting forces due to texture, the science behind the texture effect is not well explained with evidence. This chapter attempts to study the change in the mechanism of chip formation, stress distribution and temperature distribution due to texture effect. The salient features of the study may be summarised as:

- This study focuses on the change in chip morphology due to the introduction of texture on the rake face. All the studies conducted so far simulate the cutting length not exceeding 20 times the depth of cut and show the stabilisation of the cutting force within the cutting length. However, the shape of the chip formed, and the stabilisation of chip formation have not yet been reported in any numerical studies. In all the numerical studies on micro-textured cutting tool machining [60, 65, 70, 72, 74, 75], the chip is not allowed to form freely beyond the influence of the initial impact from the cutting tool. As such, the chip formation shown in these studies were not out of the influence of the impact of the initial contact by the tool. The simulation in this investigation allows for sufficient cutting length until stable chip formation is obtained.
- In this study, an explicit solver is used as the machining process is highly complex and dynamic. As such, this model is different from the model used by other researchers who use implicit solver [60, 65, 70, 72, 74, 75]. Though implicit solver is extremely stable, the drawback of this method is the requirement of update and construction of stiffness matrix for each iteration for the Newton-Raphson iterations. This can incur more computational cost.
- The Abaqus simulation model used in this study has a high level of control by the user over the material property, their elastic and plastic behaviour, damage, damage evolution and deletion of elements. Additionally, the user has very fine control over the meshing and the element types to be used in the model.
- Aluminium has extremely vast applications in automobiles and aerospace. Though it is very easy to machine, material adhesion is a major problem in machining. It

leads to build-up edge further to tool breakage. Sugihara and Enomoto [55] experimentally showed that micro-textures reduce the adhesion of aluminium. They presented that texture on the cutting tool rake surface improves the performance of cutting tool in terms of cutting force, friction and anti-adhesion. This chapter is an attempt to understand the texture behaviour in the cutting of aluminium.

The FEM model is used to investigate how micro-textures make a difference in cutting mechanism and how these texture effects contribute to the improvement in dry orthogonal machining of Al 6061. Though aluminium alloys are easy to cut materials, adhesion at the tool-chip interface causes an adverse effect in machining, particularly in dry cutting. Usually, to avoid adhesion, more cutting fluids are used. However, in most cases, cutting fluids may be harmful to the environment, are difficult to dispose of and recycle [46] and are adding additional cost to manufacturing. Regulations concerning the environment have forced the development of machining methods without using cutting fluids [95, 96]. Therefore, there is a need for the cutting of aluminium alloys without lubrication, which is associated with high friction and adhesion at the tool-chip interface. This will result in increased tool wear and reduced tool life. Introduction of texture on the tool surface might help in reducing friction and adhesion. The simulation results are validated with experimental results. Subsequently, the validated model is used in a comprehensive investigation of micro-texture effects on the changes in the cutting process.

5.1 Simulation model

A FEM model of orthogonal machining is developed with the Abaqus software. Machining is simulated using the explicit dynamic solution procedure using the Lagrangian algorithm [97],

as it can handle dynamics and complex contacts involved in machining, including the coupling of material damage and its fracture energy [98].

Table 5.1 gives an idea of input parameters to be considered in modelling the cutting process.

Figure 5.1: Factors considered in modelling of cutting process

The cutting tool is modelled to have a rake angle of 5° , flank (clearance) angle of 2° and edge radius of $20\ \mu\text{m}$. The upper part of the workpiece is partitioned, and the boundary condition applied is shown in Figure 5.2. For the 3D model, C3D8RT elements (an 8-node thermally coupled brick, trilinear displacement and temperature, reduced integration, hourglass control) were used to model the workpiece and the non-textured tool; C3D4T elements (a 4-node thermally coupled tetrahedron, linear displacement and temperature) were used to model the tool. For the 2D model, CPE4RT elements (A 4-node plane strain thermally coupled quadrilateral, bilinear displacement and temperature, reduced integration, hourglass control)

were used to model the tool and workpiece. The workpiece is held fixed, and the tool is given a cutting velocity of 1000 to 4000 mm/min in relative to the fixed workpiece, and the depth of cut is 10-200 μm . Element/mesh size in the cutting region of the workpiece is 1 μm in length. Arbitrary Lagrangian-Eulerian (ALE) adaptive meshing with Lagrangian formulation is enforced to the chip mesh region to enhance the chip formation process and to avoid abortion of the simulation process due to the extreme distortion of the elements. The physical parameters of both the workpiece and the tool insert used in the model are given in Table 5.1.

Figure 5.2: Simulation model

Table 5.1: Material properties used in the model [99]

Property	Workpiece	Cutting tool
Material	Al6061-T6	WC
Density (kg/m^3)	2770	15000
Specific Heat (J/kg K)	875.0	203
Thermal Conductivity (λ)	121	46
Co. of Thermal Expansion ($^{\circ}\text{C}^{-1}$)	24.7×10^{-6}	4.7×10^{-6}
Young's Modulus (GPa)	73	800
Poisson's Ratio	0.33	0.2
Melting Temperature ($^{\circ}\text{C}$)	502	-

5.1.1 2D vs 3D Finite element model

Generally, orthogonal cutting is assumed as a 2D problem; thus, the cutting process is investigated as a plane contact problem, i.e., like a slice of 3D model in the thickness direction. 2D problems can be solved at a relatively low computational cost. In this investigation, both 2D and 3D model are used. 3D model is required mainly for two reasons. First, the 2D plane model is not able to distinguish between dimple and stripes texture. Second, in Abaqus, the general contact formulation cannot be applied to the 2D elements, and the selection of internal surface of mesh structure which might come in contact with the tool is difficult in the 2D model. In the 3D model, the failure of elements is arbitrary, and damage can happen actually at any plane of the element. The material in the simulation is allowed to fracture anywhere in the vicinity of the cutting tool, and fracture combined with the removed elements dictates where material fails and how the chip forms. To reduce the model size, a thin one element thickness (1 μm) model is developed with plane strain conditions enforced on either side of the model surfaces. This contact is defined as the ‘General’ contact (explicit) with mechanical constraint formulation of penalty contact method with contact friction coefficient ($\mu = 0.5$).

Texture geometries (cylindrical blind holes) are modelled on the rake surface of the cutting tool; they are similar to that generated on the actual face of the tool used for the experiments. The simulation models of cutting tools and cutting process are shown in Figure 5.3 and Figure 5.4.

Figure 5.3: FEM model (a) non-texture (b) texture tool

Figure 5.4: 3D-model of tool-workpiece used in simulation model

5.1.2 Constitutive model for plasticity

Johnson-Cook's (J-C) material constitutive model is used to define the plastic behaviour of the workpiece material Al6061-T6. This model is capable of providing a reasonable description for ductile material plastic behaviour since it considers strains, strain rates and temperature dependent visco-plasticity properties [100]. This model provides yield strength for the material in terms of strain rate to depict the material behaviour accurately. The flow stress of the material is given as the product of the strain effect, strain rate effect and temperature effect as given in Equation (5.1).

$$\bar{\sigma} = [A + B(\bar{\epsilon})^n] \left[C \ln \left(\frac{\dot{\bar{\epsilon}}}{\dot{\bar{\epsilon}}_0} \right) \right] \left[1 - \left(\frac{T - T_{room}}{T_{melt} - T_{room}} \right)^m \right] \quad (5.1)$$

where, $\bar{\sigma}$ is the equivalent flow stress, A is the initial yield strength [MPa], B is the hardening modulus [MPa], $\bar{\epsilon}$ is the equivalent plastic strain, n is the work-hardening exponent, C is the coefficient dependent on the strain rate, $\dot{\bar{\epsilon}}$ is the equivalent plastic strain rate, $\dot{\bar{\epsilon}}_0$ is the reference strain rate and m is the thermal softening coefficient. T_{room} and T_{melt} represent the room temperature and melting temperature. The parameters of J-C plasticity model for Al6061-T6 workpiece are given in Table 5.2.

Table 5.2: Johnson-Cook plasticity model [101]

	A	B	n	m	C
Johnson-Cook Strength Model	MPa	MPa	-	-	-
	324	114	0.42	1.34	0.002

5.1.3 Damage initiation model

In this investigation, chip separation was modelled using the Johnson-Cook damage model and the element deletion technique. In this model, there are no predetermined separation lines or sacrificial layers to facilitate the chip formation. The damage initiation in the J-C material model is derived from the strain cumulative damage law given in Equation (5.2).

$$w = \sum \frac{\Delta \bar{\epsilon}}{\bar{\epsilon}^f} \quad (5.2)$$

where, $\Delta \bar{\epsilon}$ is the accumulated increment of equivalent plastic strain during an integration step, $\bar{\epsilon}^f$ is the equivalent strain to fracture, w is the damage parameter and failure initiates when w reaches the value of 1. The J-C plasticity model is used in combination with the damage model, which is appropriate for high strain rate deformation, such as high-speed machining [102]. Equation (5.3) gives the expression for the fracture strain. A J-C damage criterion and its values for Al6061-T6 are given in Table 5.3.[86]

$$\bar{\epsilon}^f = \left(D_1 + D_2 \exp D_3 \frac{\sigma_m}{\bar{\sigma}} \right) \left(1 + D_4 \ln \frac{\dot{\bar{\epsilon}}}{\dot{\bar{\epsilon}}_0} \right) \left(1 + D_5 \left(\frac{T - T_{\text{room}}}{T_{\text{melt}} - T_{\text{room}}} \right) \right) \quad (5.3)$$

where, $\bar{\epsilon}^f$ is the equivalent strain to fracture, D_1 the initial failure strain, D_2 the exponential factor, D_3 the triaxiality factor, D_4 the strain rate factor, and D_5 the temperature factor, σ_m and $\bar{\sigma}$ are the average of the three normal stresses and the von Mises equivalent stress respectively.

Table 5.3: Johnson-Cook damage model [101]

	D1	D2	D3	D4	D5
Johnson-Cook Damage Model	-0.77	1.45	0.47	0.011	0

5.1.4 Damage evolution model

Once the damage initiated in the elements, the stress-strain relationship defined for the elastic-plastic material cannot represent the material behaviour properly. Hillerborg proposed a stress-displacement response instead of the stress-strain response to mitigate the problem of strain localisation due to mesh dependency. This model is a damage evolution model that causes linear softening of the element material based on the fracture energy which governs the stress-displacement response. The use of damage initiation followed by damage evolution results in a progressive damage until an ultimate failure of the element happens. Then, the fracture energy is given by Equation (5.4).

$$G_f = \int_{\bar{\epsilon}_0^{pl}}^{\bar{\epsilon}_f^{pl}} L \sigma_y d\bar{\epsilon}^{pl} = \int_0^{\bar{u}_f^{pl}} \sigma_y d\bar{u}^{pl} \quad (5.4)$$

where, L is the characteristic length of the element used. For the solid element, it is given by the cubic root of its volume. It is recommended to have elements with aspect ratios close to unity, as the direction in which the fracture occurs is unknown and large aspect ratio elements might show different behaviour based on the direction in which the crack occurs. $\bar{u}^{pl}$ is the equivalent plastic displacement after damage initiation; before damage initiation, it is equal to zero. It can be defined as $\dot{\bar{u}}^{pl} = L \dot{\bar{\epsilon}}^{pl}$. Thus, the evolution of damage is stated in terms of equivalent plastic displacement $\bar{u}^{pl}$ and the characteristic length of the element to eliminate mesh dependency.

The effective plastic displacement at failure $\bar{u}_f^{pl}$ can be specified for the element at which full degradation occurs, which is called the point of failure. Assuming linear evolution of damage with the relative plastic displacement, the damage variable increment is given by Equation (5.5).

$$D = \frac{L\bar{\epsilon}^{pl}}{\bar{u}_f^{pl}} = \frac{\bar{u}^{pl}}{\bar{u}_f^{pl}} \quad (5.5)$$

Thus, when D is equal to 1, i.e., the effective plastic displacement of the damaged element reaches the specified failure value, the material stiffness will be completely degraded. Then, the particular element is removed from the rest of the computation, by availing the element deletion in Abaqus. The effective plastic displacement at failure for the model is fixed as 0.005 based on the trial and error method. The degradation variable SDEG in this study is set as the default value of 0.99 in Abaqus for ease of element deletion.

5.1.5 Heat generation

In metal cutting, there are two sources of heat generation. One is due to inelastic plastic deformation in the shear zone, and another is due to friction between the sliding surfaces. In a high-speed metal cutting process, there is only a little time to diffuse the heat generated due to local energy dissipation. This will cause local heating to take place in the active plastic regions. Thus, the temperature rise is considered as an adiabatic heat effect by inelastic deformation. The default value of 0.9 is assumed for the inelastic heat fraction in Abaqus. The fraction of dissipated energy caused by friction between the sliding surfaces is assumed to be 0.9.

5.1.6 Friction model

The friction model considered for FEA simulation is the default friction model in Abaqus simulation, namely the Coulomb friction model:

$$\tau = \sigma_n \cdot \mu \quad (5.6)$$

The Coulomb friction model is not always applicable. This is because the value of stress τ cannot exceed the shear strength of the material, which is exceeded at high stress levels as defined by the Coulomb friction model. The shear strength k of the material may be written as:

$$k = \sigma_0 / \sqrt{3} \quad (5.7)$$

In this situation the Schley friction model (the shear model) may be employed instead:

$$\tau = \frac{m}{\sqrt{3}} \sigma_0 = m \cdot k \quad (5.8)$$

where

τ - frictional shear stress

σ_0 - normal stress at the interface

μ - coefficient of friction

m - shear or frictional factor ($m=0$ for frictionless interface, $m=1$ for sticking condition)

σ_0 – yield strength of the deforming material

These two models can be implemented into the analysis directly by noting the existence of the two regions observed on the rake face during cutting, namely the sliding and the sticking regions. The Coulomb model with constant coefficient of friction can be utilized in the sliding region; the Schley friction model with a constant frictional stress equal to the shear flow stress τ_f of the chip material can be applied in the sticking zone.

In cutting, the normal stress on the tool rake face decreases with distance from the tool tip. As such, there can be a transition from Schley to Coulomb friction behaviours. This transition can be modelled by the following transition equations:

$$\tau(\sigma_n) = \mu\sigma_n, \text{ when } \tau < \tau_f \quad (5.9)$$

$$\tau = \tau_f, \text{ when } \tau \geq \tau_f \quad (5.10)$$

5.2 Model validation

The developed model is validated with published experimental results and simulation results in terms of cutting force, contact pressure and normal stress. For the model validation, the cutting velocity is 2053 mm/sec, the uncut chip thickness is 122 μm , the width of cut is 2mm, the rake angle is 6° , the clearance angle is 8° and the edge radius is 20 μm , i.e. the same experimental conditions used by Ding et al. [64]. Mesh convergence were conducted, and the optimal mesh size is selected as 1 μm . The model has 15058 elements for the 2D model, likewise 5 μm element size and 24724 elements for the 3D model. It is to be noted that the experiment's data used for validation were conducted under dry cutting condition. As such, the effect of lubricant or coolant is not necessary to be considered.

Figure 5.5 shows the comparison of cutting force F_c and thrust force F_t for the developed simulation model data and experimental data [64]. The forces mentioned here is the average value of forces and were taken only after the cutting process reaches the steady state condition and the error percentages are calculated to be 9.8% and 8.6% for cutting force and thrust force respectively. Figure 5.6 shows the simulation results of cutting force getting into the steady state after a dip in the initial stage.

Figure 5.5 Validated result of simulation

Figure 5.6 Simulation result of non- textured tool

Figure 5.7 and Figure 5.8 show that the normal stress and contact pressure obtained from the FEA model following the same trend as the experimental values obtained for the same cutting conditions with the magnitude of maximum stress slightly varying.

(a) Normal stress-reported result [103]

(b) Normal stress-simulation result

Figure 5.7: Normal stress validation along the contact length

(c) Contact pressure -reported result [103]

(d) Contact pressure -Simulation result

Figure 5.8: Contact pressure validation along the contact length

5.3 Results and discussion

Series of simulations are conducted with different texture parameters and cutting conditions to study the effect of each parameter on the texture effect on cutting tool performance. For this study, the cutting conditions used are 2053 mm/ cutting speed and 122 mm depth of cut and forces are calculated for 1 mm width of cut unless otherwise stated. Table 5.4 shows the list of parameters that are studied using FEM model, which will be discussed in the following session.

Table 5.4: Parameters selected for study by FEM

S. No	Type	Parameter	Values	Units
1	Study on texture parameter	Width of texture	20, 40, 60, 80	μm
2		Pitch of texture	30, 45, 60, 75, 90	μm
3		Distance of texture from cutting edge	20, 30, 50, 70, 100	μm
4		Depth of texture	20, 40, 60	μm
5	Study of cutting conditions on textured tool performance	velocity	1000, 2000, 2053, 3000, 4000	mm/s
6		Depth of cut	50, 100, 122, 150, 200	μm

5.3.1 Effects of geometry of micro textured cutting tool performance

This section presents a study on the effects of microtexture geometry parameters on cutting forces, stress distribution and chip formation in the cutting of Al workpiece by textured cutting tool by FEM simulations. The parameters considered for this study are the distance of texture from the cutting edge, texture width, pitch and depth of texture. The effect of each parameter is compared with the non-texture tool results. Figure 5.9 shows the effect of texture in comparison to non-textured tool for different texture widths (20, 40, 60 and 80 μm). It is found that the texture with 50x20x60 (which represents 50 μm distance from the cutting edge, 20 μm width of the texture and 60 μm pitch of the texture units) shows better performance in terms of cutting force. In terms of thrust force, the non-texture tool shows better performance. Figure 5.10 shows the chip formation and stress distribution on the workpiece for various width of textured tool in comparison to the non-textured tool.

Figure 5.9 Effect of texture width on cutting forces for different texture widths -(50x20-80x60 represents Distance x width x pitch)

Width = 20 μm

Width = 40 μm

Figure 5.10 Effect of texture pitch on Stress distribution for different texture width thickness (MPa)-
(50x20-80 x60 represents Distance x width x pitch)

Figure 5.11 shows the effect of pitch on cutting forces and thrust forces of the cutting tool. The texture pitch is varied from 30 to 90 μm in five intervals. Examining the performance of all the tools investigated, including the non-textured tool, the textured tool with 60 μm pitch shows the lowest cutting force, and the textured tool with 75 μm pitch shows the lowest thrust force. Figure 5.112 shows the chip formation and stress distribution for textured tool which different pitch. It is observed that the workpiece element gets entangles with the texture with a smaller pitch and gets deleted causing the difference in chip formation. However, the chip formation on tools with a larger pitch is much similar to that of the non-textured tool. The stress distribution on the shear zone is found to be affected by the presence of texture. It is noted that the magnitude of the stress is the same as a non-textured tool, but the shear band is thinner in tools with higher pitch values.

Figure 5.11 Effect of texture pitch on cutting forces for different texture pitch-(50x20x30-90 represents Distance $\times$ width $\times$ pitch)

Figure 5.12: Effect of texture pitch on Stress distribution for different texture pitch (MPa)- (50x20x30-90 represents Distance x width x pitch)

Figure 5.13 shows the effect of texture distance from the cutting edge of the tool. It is clear from the results that the nearer the texture to the cutting edge, the more effective the tool will be. It is observed that the tool with 20 μm has the least cutting force and thrust force, but the effect is very much observed on the cutting force. It should be noted that the texture cannot be made too close to the cutting edge practically as the texture may affect the strength and integrity of the tool. Figure 5.14 and Figure 5.14 shows the effect of distance of texture from the cutting edge of the tools in terms of cutting forces, stress distribution and chip formation.

Figure 5.13 Effect of texture distance from the cutting edge on cutting forces- (20-100x20x60 represents Distance x width x pitch)

Figure 5.14 Effect of texture distance from centre on stress distribution (MPa)- (20-70x20x60 represents Distance x width x pitch)

Figure 5.15 shows that the texture unit depth has no effect on the cutting tool performance and the difference is very small for the variation of texture depth. It should be noted that the simulation model developed is a depiction of dry cutting process; it does not take into consideration that the texture depth might serve as a reservoir for lubricant in the actual wet cutting process which would have some effect on cutting performance. Figure 5.16 shows the chip formation and stress distribution do not change much with texture depth.

Figure 5.15 Effect of microtexture depth on cutting forces- (50x20x60 represents Distance x width x pitch)

Figure 5.16 Effect of microtexture depth on Stress distribution (MPa)- (50x20x60 represents Distance x width x pitch)

5.3.2 Effects of cutting conditions on micro textured cutting performance

Figure 5.17 shows the drop in cutting force and thrust force with an increase in speed, and Figure 5.18 shows the increase in forces with an increase in depth of cut for the textured tool. The rate of change of cutting force is larger than that of thrust force and this indicates that the cutting force is much influenced by the textured tool. It should be noted that the textures were made only on the rake face of the tool.

Figure 5.17 Effect of texture on cutting forces at different cutting speed-(50x20x60 represents Distance $\times$ width $\times$ pitch)

Figure 5.18 Effect of texture on cutting forces at different depth of cut (50x20x60 represents Distance $\times$ width $\times$ pitch)

Figure 5.19 and Figure 5.20 show the effect of texture for varying cutting speed and depth of cut respectively. For a change in cutting speed, it has very little effect on chip morphology and stress distribution. For an increase in depth of cut, in terms of tool-chip contact length and stress distribution, more significant effect of texture is observed as the number of texture in between the tool-chip increases.

Figure 5.19: Effect of texture on stress distribution (MPa) at different cutting speed (50x20x60 represents Distance x width x pitch) - Stress in MPa

Figure 5.20 Effect of texture on stress distribution (MPa) at different depth of cut (50x20x60 represents Distance x width x pitch)- Stress in MPa

5.3.3 Texture effect on chip formation

The chip created by the rake textured tool experimentally is seen to be more curled and breaks into smaller pieces, whereas the chip from the non-textured tool is long and continuous, as shown in Figure 5.21. This same effect is reproduced in the simulation of the textured and non-textured tool.

Figure 5.21: Chips observed during experiments and simulation

Figure 5.22 shows the difference in chip formation for textured tool and non-textured tool. It also shows the stress values during the cutting process in the 3D model. It can be observed that the textured tool has a smaller Von Mises stress than the non-textured tool. In addition, it can be noticed that the distribution of shear zone is relatively smaller for the textured zone in comparison with the non-textured tool from Figure 5.23.

Figure 5.22: Stress distribution (MPa) for non-textured and texture tool-isometric view-(50x20x60 represents Distance x width x pitch)

Figure 5.23: Stress distribution (MPa) for non-textured and texture tool-sectional view(70x20x50 represents Distance x width x pitch)

It is also observed that due to the presence of texture, there are changes in the distribution of stress both in the primary and the secondary zones. Additionally, the chip formation also changes due to the presence of texture. Both simulations are conducted with the same parameters and for the same time interval. From Figure 5.22, it is clear that the edges of the microtexture can act as a micro cutting edge and disturbs the chip flow. These micro cutting edges result in highly localised pressure and temperature, which may lead to microchip curling into the dimples. Consequently, this may cause high localised wear, and thus can affect the tool life. Microtextures on the rake face of a cutting tool are effective in reducing cutting forces, which means that the frictional behaviour at the chip-tool interface is improved despite the undesirable micro cutting phenomena taking place at the interface. The chip generated from the textured tool tends to separate earlier, which results in smaller contact length; the reason can be attributed to the micro-texture, which reduces friction and the cutting forces.

5.3.4 Effect of speed texture filled with workpiece material

In actual textured tool cutting of workpiece materials, over a period of cut the textures were be filled with workpiece material. To study the workpiece material filled textured on continuous cutting, a simulation model is constructed with the textures filled with Al material as shown in Figure 5.24. The textured tool filled with workpiece material (Al) depicts the clogged tool over a period of cut, and tool texture filled with tool material (WC) depicts the non-textured tool; this is done to avoid any differences in meshing and geometry between these two tools in the comparison study.

Figure 5.24: Textured tool filled with workpiece and tool material for study(70x20x50 represents Distance x width x pitch)

Figure 5.25 shows the temperature distribution of textured tool filled with workpiece material (Al) is lower at all cutting speeds tested than that of non-textured tool equivalent. This indicates that even in dry cutting conditions and a clogged tool, heat dissipation of the textured

tool is more than the non-textured tool. Similarly, Figure 5.26 shows the stress distribution for the non-texture equivalent and clogged textured tool. It can be observed that the shear deformation region for textured tool filled with Al is thinner than the non-textured tool equivalent.

Figure 5.25: Effect of texture on temperature ($^{\circ}\text{C}$) for non-textured tool and clogged tool for different cutting speeds-(50x20x60 represents Distance x width x pitch)

Figure 5.26 Effect of texture on stress distribution (Mpa) for non-textured tool and clogged tool for different cutting speeds

5.4 Summary

In this study, Abaqus is used to model the orthogonal machining of Al6061-T6 alloy to investigate the effects of microtextures in cutting tools in terms of cutting force chip formation and Von Mises stress. The key findings can be summarized as:

- The simulation model is developed by incorporating the J C damage model and a plasticity model to facilitate the formation of the chip without any sacrificial layer. The developed model is validated by comparison with experimental results available in the literature.

- Micro textures show improvement in the performance of the tool in terms of cutting forces, chip morphology and stress distribution. The micro texture width and pitch is found to have more influence on the performance of the cutting tool.
- The texture effect is small with an increase in the cutting speed. The texture effect is much more significant on a change in the depth of cut; this is because as the depth of cut increases, the textures in the tool-chip contact increases.
- The micro-texture makes the chip to curl early, resulting in smaller tool-chip contact length and thereby smaller friction. This will improve the performance of the tool as the sliding distance over the tool rake reduces and less amount of energy would be spent.
- The textured tool filled with Al to depict the clogged / used textured tool still shows improved thermal and stress behaviour. Thus, even if the texture is clogged in a real cutting process, the textured tool still can perform better as there is a difference in specific heat conductivity for tool and workpiece material which will help in quicker dissipation of heat.

Chapter 6: Analysis of improvement in tribological contact by surface micro-texturing

Only 30–50% of the energy required by the cutting system is spent in useful work, i.e. for the separation of the layer being removed from the workpiece; the rest is spent at the tool-chip and tool-workpiece interfaces [103]. The introduction of micro-texture on these interfaces can help in the reduction of energy loss at the interfaces. Surface textures have been extensively used in sliding contact in mixed lubrication conditions. Recently, surface textures are used in a metal cutting process for the storage of lubrication to reduce friction, to reduce the excessive rise in temperature and to reduce the actual contact area. The performance improvement due to texture introduction is reported in terms of cutting forces, shear angle, anti-adhesion, wear resistance [8, 10, 24-26, 38, 55, 58], but the phenomena behind the texture effect are attributed to a reduction in friction and contact area by the researchers. The texture effect could be due to tribological changes in the interface, wear entrapment, enhancement of lubrication or actual contact area reduction in the interface region.

In general, the coefficient of friction cannot exceed 1.0, with sticking friction having the maximum coefficient of friction of 1.0. Thus, if the coefficient of friction remains constant for a given cutting conditions, the reduction of contact area will result in a reduction of frictional force, as the force is the product of area and coefficient of friction. Indeed, the coefficient of friction may change with cutting conditions.

This chapter investigates the change in frictional property due to the introduction of texture on the rake face of the tool in terms of simple tribology test, developed in-situ tribometer test

and FEM study. This chapter attempts to produce the direct evidence for the reduction of friction by the introduction of texture on the cutting tool surface.

6.1 Effect of tool-chip interface friction on cutting mechanism

By definition, tribology is the study of contact between two metals in relative motion. From Figure 6.1(a), it can be noted that the chip and tool are in relative motion. Therefore, the tool-chip contact area is referred to as a tribological contact. The schematic of the texture introduction in the tool-chip interface and its effect on the shear angle and the chip thickness is shown in Figure 6.1 (b). It shows the shear angle for the non-textured tool when there is no friction, which is an ideal case where the shear angle is 45° . In an actual case, there will be friction between the interfaces, and thus, the shear angle will be smaller than that of the ideal case. With the introduction of the texture, if the friction is reduced between the interfaces, the shear angle will increase towards the ideal case. However, the question here is whether the friction is really decreasing with the introduction of the texture.

The texture on the rake face affects the chip thickness ratio and thereby the shear angle, as the formation of chips involves the shearing of the workpiece material in a plane extending from the tool edge to the position where the chip leaves the work surface. The effect of texture on the change in the chip thickness and the shear angle was explained in Section 2.4.3.

Figure 6.1: Effect of texture on chip thickness and shear angle

In an ideal case when there is no friction between the tool and the chip, t_0 is equal to t_c . However, in a real case, there will be friction. Due to the frictional effect, the chip thickness increases and the shear angle decreases. With the introduction of texture, it is reported that the chip thickness is decreased and hence, an increase in the shear angle is observed. Thus, the introduction of texture in the rake face has a direct influence on the chip forming mechanism.

6.2 Reduction of friction in the tool-chip interface

Cutting fluid helps to reduce the friction between the tool-chip interface by its lubrication effect and reduces the cutting temperature by its cooling effect. The cutting fluid reduces the contact area between chip and tool, and its effectiveness depends on the ability to penetrate in the chip-tool interface and create a lubricating layer in the interface. Sales et al. [104] reported that it is neither completely clear how cutting fluid reaches this interface in the cutting zone nor how deep it can go. Trent stated that it is difficult for the lubricants to access the seizure

zone on the tool rake face [105]. Postnikov [106] suggested that the lubricant penetrates against the metal flow, reaching the tool nose through a capillary action. Horne et al. [107] used transparent sapphire tools and confirmed that the cutting fluid flow reaches the interface by the lateral parts of the contact, instead of moving against the chip flow.

Figure 6.2 shows a schematic diagram to explain the contact nature of tool chip interface in the sticking and sliding region. It shows the contact nature of tool-chip interface with the sticking region and sliding region with perfect surface contact and contact with gaps respectively.

Figure 6.2: Schematic of tool-chip contact surface condition

Cutting fluid lubrication occurs mainly by penetration of lubricants through microscopic passages existing between the tool-chip interface [108]. Godlevski et al. [109] explained the liquid lubricant penetration through a network of internal capillaries in the contact zone on the basis of micro-droplet expansion model. In their model, they considered a single interface capillary, with an open end at the exterior and a closed end inside the contact zone. The capillary action of the lubricant is explained by three stages: 1. Liquid phase penetration, 2.

Micro-droplet explosion and 3. Filling the capillary with gas phase lubrication; these stages are shown in Figure 6.3.

Figure 6.3: Three stages of cutting lubricant penetration into a single interface capillary [Modified from [108]]

Extending this concept of lubrication enhancement to the textured cutting tool, in addition to the microscopic gap between the tool-chip interface, there exist the microscopic textures that can act as a lubricant reservoir, which is reached through capillary action. The pressure within the texture cavity and the microscopic gaps is less as lubricant is supplied with pressure. This facilitates the capillary action and enhances penetration of lubricant and is expected to be collected in the texture cavities. The temperature in the contact zone is very high, and it can

expand and vaporize the lubricant in the interface; moreover, cavities give rise to the formation of vapour film in the tool-chip interface. Godlevski et al. [108] have shown that the capillary's filling of lubricants might be a periodic process. Considering a number of such capillaries are situated in the contact zone, the evaporating lubricants fill up the capillary and the gas pressure inside the texture, and the capillary reaches an equilibrium state. Thus, a vapour film is expected to be generated throughout the cutting process by the continuous capillary action in the contact zone. Additionally, it is to be noted that the texture filled with a lubricant or empty texture in the sticking zone will help in more heat dissipation due to the increased surface area and high heat conductivity of lubricant and air gap. In case the texture in the sticking zone is clogged with the workpiece material, the heat conduction in the workpiece will be comparatively higher than in the tool material. Thus, it is expected that texturing of tool rake face of the cutting tool enhances the lubrication condition and increases the performance of the cutting tool. Figure 6.4 illustrates the lubricant vapour film formation in the textured tool cutting process.

Figure 6.4: Lubricant vapour film formation enhanced by surface texture

6.3 Friction measurement for textured surfaces

To find the friction condition between the two interface surfaces, a tribology test is conducted for tool material samples with and without texture and for dry and lubricated conditions. The texture in the form of dimples and stripes are produced on the HSS flat samples by using the same technique explained in Section 3.2 with the help of the same μ -EDM machine. The types of textured produced are dimple, parallel stripes and perpendicular stripes textures and are shown in Figure 6.5. The textures were made with 150 μm pitch and dimple diameter of 100 μm or stripes width of 50 μm . A CETR-UMT2 tribometer is used to find the frictional properties of the four types of samples (three textured samples and one non-textured) by using a reciprocating drive and a steel ball of 6 mm diameter. Tests were conducted for 2N load and at 2 Hz frequency for 20 minutes for each test, and the test setup is shown in Figure 6.6. The texture area of each texture is made to cover 8 x 5 mm x mm area on the flat HSS sample so that 4 mm stroke length of the tribometer contact with the workpiece will be within the textured region.

Figure 6.5: Type of textures produced for tribometer test (a) dimple (b) parallel stripes and (c) perpendicular stripes

Figure 6.6: Tribometer test setup

Figure 6.7 shows that friction is reduced by the introduction of texture and the texture effect is further enhanced by the presence of lubrication in the textured surface. The perpendicular textured surface shows the lowest friction both in dry and wet conditions. It can also be observed that the dimple textured surface shows a significant reduction in friction from dry to wet conditions. This method of utilising frictional laboratory tests has its own limitation of not being able to have the actual cutting conditions in terms of pressure (1-2 GPa), temperature (350-450 °C) and velocity (240 mm/min); in addition, the pin runs over the same track, not on the newly generated surface [110]. In a lab tribometer setup, the contact is between the ball and

the workpiece, the load applied is 2 N, and the contact is only at the tip of the 6 mm ball, with the maximum contact pressure less than 0.5 GPa. In a tribometer setup the contact is between the spherical ball and the flat region, in contrast, in an actual cutting process, the chip slides over the tool's flat region. In the reciprocating tribometer setup, the ball will be moving in a reciprocating motion at 2 Hz on the flat region made of tool material; in contrast, in a cutting process the portion of chip flows over the tool surface only once and new region of chip is formed at a cutting velocity of 240 mm/min. Thus, there is a need for a special tribometer for studying the tribological effect at actual cutting conditions.

Figure 6.7: Friction coefficient measured from pin on plate test for HSS plate (for 2 Hz, 2 N load)

6.4 Actual friction measurement using in-process tribometer

To understand the tribological phenomena at the interfaces at actual cutting conditions in terms of pressure, temperature, velocity, and to have the pin run over the newly generated surface, an in-process tribometer is designed and used. A similar in-process tribometer was used by other researchers; Olsson's modified pin on disc setup [111] was able to produce the

relevant sliding velocity and temperature, but only to a maximum contact pressure of 15 MPa, which is much smaller than the pressure at the actual cutting process in the range of some GPa [112]. Hedenqvist [113] and Bonnet et al. [114] modified the pin on ring test in which the pin rubs over the workpiece cylinder in a helical fashion. Zemzemi et al. [115], who used pneumatic loading for the pin and Smolenski et al., who used spring loaded system [112], were both able to achieve the required pressure of 1–2 GPa. Here, a similar kind of model is designed and is used for the friction coefficient measurement. The limitation of the modified system is distance controlled; thus, the force or pressure cannot be maintained at a constant value as the material gets deformed or removed. The schematic of the in-process tribometer designed to measure friction during the orthogonal cutting process is shown in Figure 6.9.

The pin with 6 mm diametrical circular tip is mounted behind the cutting edge and rubs on the freshly generated workpiece surface. The distance between the cutting edge and pin must be kept as low as possible in order to ensure that the freshly prepared surface is in contact with the pin without any chemical reactivity with the atmosphere. The pin is textured by the Quantronis Integra c-10 femtosecond laser ($\lambda = 527$ nm). The texture is made as an array of dimples with a pitch of 0.5 mm and dimple dimension of 0.15 mm diameter and 0.025 mm depth. The contact face of non-textured and texture pin is shown in Figure 6.8. The pin is pushed over the workpiece by means of a pneumatic loading system. The pin is mounted over the dynamometer to measure the forces. This setup simulates the actual cutting condition for the tribometer in terms of contact pressure and velocity. The contact pressure of 1 GPa is applied to the pin by means of the pneumatic system. The workpiece is rotating at the actual cutting speed and the pin will come in contact to the workpiece immediately after the newly formed surface is produced by the preceding cutting tool.

Figure 6.8: contact face of the pin (a) non-textured (b) textured

Figure 6.9: In-process Tribometer

This set-up is designed such that the tool preceding the tribometer-pin will constantly generate a newly formed metal surface, which is going to be in contact with the preloaded pin. The normal and frictional forces acting between the pin and the newly formed surface are measured by means of the 3D-Dynamometer Kistler 9256C1. Previous cutting force measurements are used to set the pin preload F_n by a pneumatic system, which corresponds to the feed force at the same cutting conditions. The experimental setup is shown in Figure 6.10.

Figure 6.10: In-Process tribometer Experimental Setup

Figure 6.11: In-Process tribometer Force measurement

Figure 6.11 shows the pin at 60° from the cutter. Hence, directional force cannot be neglected. Therefore, the resultant tangential force is calculated from $\sqrt{F_x^2 + F_y^2}$. The friction coefficient is the ratio of the resultant force to the normal force.

All three-directional reaction forces between the pin and the newly formed workpiece are measured by the dynamometer, including the thrust force, which is the preloaded force on the

pin. The experiment was repeated two times and Figure 6.12 gives the average friction coefficient values for the non-textured and the textured pins for different speeds. It is observed that the friction coefficient decreases with speed regardless of a non-textured or textured pin. When comparing with the non-textured and the textured pins, the textured tool seems more efficient because of smaller friction coefficient than a non-textured pin.

Figure 6.12 : Friction coefficient for different cutting speeds

In the metal cutting process, the concept of friction coefficient is not adequate to depict the sliding conditions and the behaviour of contact in the tool-chip interface. However, the experimental results show that the textured surfaces reduce the friction coefficient which has little implication in the machining process. The usage of a constant friction coefficient for sliding contact in the FEM simulation of metal cutting will not simulate contact conditions similar to the real contact conditions. Hence, it is recommended to consider the contact stresses rather than friction coefficient at the tool-chip interface and their dependence on the parameters [103].

6.5 FEM analysis of tool-chip contact

To study the tool-chip tribological contact region, a FEM model depicting tool-chip relative motion as shown in Figure 6.13 is modelled, where the slider is made of the chip material, and the fixed part is made of the tool material. The material and thermal properties, the contact and frictional conditions of the developed model is exactly the same as described in Section 5.1. In this model, the sliding of chip over the tool rake face is the main focus. The effect of texture on the rake face of the tool in pure sliding of the chip material is studied by this model; the influence of tool edge effect, flank surface contact, shear region effect of the actual cutting process are excluded. The texture units namely dimples, parallel stripes and perpendicular stripes were modelled in the fixed part as shown in Figure 6.14 (b - d). This model is to study the texture in the sliding of chip material over the rake face of the tool. In this model, the texture units are empty and are not filled with lubricants, and no convection of heat is assumed. Therefore the study is equivalent to that of dry cutting process-chip sliding on the rake surface of the tool.

Figure 6.13: Tool-chip sliding contact model

Figure 6.14: Tool-chip contact model with tool surfaces: (a) Non-textured (b) Dimple textured (c) Parallel stripes (d) Perpendicular stripes

Figure 6.15 and Figure 6.16 shows the stress distribution in isometric view and top view for the flat (non-texture), dimple, parallel stripes and perpendicular stripes textured tool rake surfaces. The dimple texture modelled have the dimensions of $50\text{ }\mu\text{m}$ diameter, $50\text{ }\mu\text{m}$ depth and pitch of $100\text{ }\mu\text{m}$ width. The stripes textures modelled have the dimensions of $50\text{ }\mu\text{m}$ in width, $50\text{ }\mu\text{m}$ depth and $50\text{ }\mu\text{m}$ pitch. It can be observed that the stress for the non-texture is about 2-6 times higher than that of textured tool surface. Among the tested textures, dimple texture shows the least stress value, with and relatively uniform distribution over the contact zone.

Figure 6.15: Stress distribution-isometric view (MPa)

Figure 6.16: Stress distribution-top view (MPa)

Figure 6.17 gives the comparative contact distribution of the nontextured and textured surfaces. It can be observed that contact pressure for the non-textured tool is minimum and is one quarter to half the value of textured tool contact pressure. It is understandable that the contact area of the textured surfaces is reduced due to the intermittent spaces of the texture units; thus, the contact pressure for the non-textured surface is higher.

Figure 6.18 provides a comparison on the pressure distribution due to shear stress on the non-textured and textures tool surface. It can be observed that there is not much difference in this pressure distribution in terms of magnitude, and all surfaces have the same level of pressure.

Figure 6.18: Pressure due to shear stress distribution (MPa)

Figure 6.19: Temperature (NT11) °C distribution (MPa)

Temperature (NT11) is an important parameter in tool-chip contact interface. It is expected that non-texture surface should show the highest temperature and textured surface should show some decrement in contact temperature, which is considered as an advantage of the textured surface. Figure 6.19 shows that the temperature for the non-textured surface is the less than the textured tool surfaces. It should be noted that the model here does not consider convection or radiation heat transfer. In actual textured tool surfaces, the heat in the contact zone is transferred to the textured gaps mostly through convection into the cutting fluids and air in the texture units. Additionally, the lubricant or air in the texture space will reduce the overall tool temperature due to its high specific heat capacity. As such, it is understandable that here the textured tool surface shows a higher temperature than that of the non-textured surfaces. It is also to be noted that the texture edges causes restriction to the sliding of the slider particularly for the perpendicular stripes textured surface; hence we can notice the peak temperature rise at

the starting of each cross rib and that is why the magnitude of contact temperature for this surface is the highest.

In actual textured tool metal cutting, the textures tend to get clogged by the workpiece material; this can be observed from Figure 6.20 where the dimple and perpendicular stripes textured tool texture units were filled with aluminium. This clogging action takes place at a very short cutting time, and the rest of the cutting is done with the clogged textured tool. If the textured units are filled with solid/liquid lubricants, air or with workpiece material, it can be expected that the textured tool performs better than the non-textured tool as the friction of the filled material is less than the tool surface, and the heat conductivity of the filled material is higher than that of the tool material. To understand this effect a simulation model is developed with the texture units filled with workpiece material, see Figure 6.20.

Figure 6.20: FEM model with the assumption of textures are filled with workpiece material

Figure 6.21 shows that in the contact zone, for the perpendicular textured tool with textured filled with workpiece material, its temperature is less than that of the non-texture tool. Thus, dissipation of heat is enhanced by the texture units causing the difference in temperature distribution shown in Figure 6.19.

Figure 6.21: Temperature distribution (NT11) °C on tool surface with texture filled with workpiece material

6.6 Summary

This chapter investigates the change in frictional property due to the introduction of texture on a flat surface made of tool material with and without the lubricant in a ball on the flat test. This is conducted in a tribometer with a ball made of steel material. The tribometer experiment gives the friction coefficient for non-textured and textured tool surfaces. It is found to be the dimples textured surface that exhibits a smaller friction coefficient in the presence of lubricant, and the perpendicular textured surface exhibits a smaller friction coefficient in the dry conditions. In any case, the textured surface shows smaller friction than a textured tool. It is to be noted that the friction calculated was between the tool material and the tribometer ball; the tribometer test condition is different from the actual cutting conditions in terms of cutting speed, material flow and temperature.

To address this limitation in the study of the frictional properties at the actual cutting conditions by the tribometer, an in-process tribometer is designed to measure the friction coefficient in an actual cutting environment. The friction coefficient measured from this in process tribometer showed a marginal decrement of friction coefficient for the textured pin at various cutting speed and was found to be dependent on the cutting speed. It is observed that in a machining process, friction coefficient alone cannot define the contact properties. Indeed, by just changing the friction coefficient in Abaqus simulation model, the conduct conditions show no significant changes.

A FEM model is developed to study the texture effect in the tool-chip sliding process alone. It is found that textured tool reduces the contact stress and the dimple textured surface shows the best performance. To study the temperature effect, the model is further developed to avoid the empty spaces on the texture units which are filled with workpiece material. It is found that the temperature for the textured tool is less than that of the non-textured tool in the cutting zone in these conditions.

Chapter 7: Investigation of change in machining phenomena due to micro-textures by AE signals

Metal cutting involves three phenomena namely: rubbing, ploughing and cutting. Rubbing and ploughing are usually undesirable as they cause wastage of energy supplied for cutting into heat and friction. Introduction of texture on the cutting tool surface can modify or reduce the amount of these undesirable phenomena. To identify these phenomena, Acoustic Emission (AE) signals were used. The signals were extracted from the cutting process for the non-textured tool and the frequencies associated with each phenomenon were determined. The difference in the contribution of each phenomena for the textured tool is calculated. This gives a measure of how the texture effect contributes to changing the mechanism during the cutting process, and this can be used to design more effective textured tools.

7.1 Acoustic emission

An AE signal can be defined as an elastic wave, emitted by the solid, which then propagates through it when it is deformed or struck. Therefore, it is an occurrence phenomenon which releases elastic energy into the material. Rapid stress-releasing events generate a spectrum of stress waves in the range of few Hz to several MHz. It can also be generated from sources not involving material failure including friction, cavitation and impact. Thus, acoustic emission is the phenomenon of radiation of elastic waves in solids that occurs when a material undergoes changes in its internal structure, and it is analogous to the source of change. Different AE characteristic signals are analogous to different external forces that act on the same material or the same force exerted on different materials [116, 117].

In a cutting process, when the cutting tool strikes the workpiece with an external force, workpiece material will be displaced which results in a rapid release of localised stress energy. The released energy is primarily in the form of an acoustic emission which generates AE signals that propagate through the material media [116]. The cutting mechanism is associated with three phenomena namely cutting, ploughing and rubbing. Each phenomenon will correspond to a particular frequency of the AE signal. Thus, different AE signals correspond to cutting, ploughing and rubbing which are analogues to different sources/ occurrences and would have different frequencies. The introduction of texture on the rake face of the cutting tool will give rise to some disturbance in the AE emission spectrum. This change due to texture introduction will be reflected in terms of AE signals, and the amount of change can be estimated in terms of percentage difference with the signal obtained from the non-textured tool.

The three types of material deformation/ removal phenomena associated with cutting are shown in Figure 7.1. Rubbing is a process in which no material removal will occur, and all the deformation associated with the rubbing phenomenon is purely elastic. Therefore ideally rubbing will not leave any trace of the mark as all the deformation is elastic. Ploughing is the phenomenon associated with plastic deformation in which the deformation can be permanent. Thus in ploughing only dislocation of material will happen and no removal of material takes place. Cutting phenomena is associated with the removal of material and is associated with chip formation.

Figure 7.1: Phenomena associated with machining

7.2 Assessment of micro-texture effect by AE signal

The assessment of micro-texture effect with respect to a change in the cutting phenomena is difficult to measure. To address this, an attempt is made to measure the texture effect and the corresponding change in the cutting phenomena by using the AE signals from the cutting process.

Micro-textures were made using micro-EDM process on HSS tool and were used to cut workpieces made of Al 6061. Cutting experiments were conducted for both non-textured and textured tools. An AE signal sensor is placed on the workpiece close to the machining region, and the setup is shown in Figure 7.2. The cutting conditions used for the experiments are given in Table 7.1. The sensor used to extract signal from the cutting process is Vs 900 (Vallen Systeme GmbH). Figure 7.3 shows the sensor used and the working range of the sensor.

Figure 7.2: Experimental setup of orthogonal cutting for AE signal analysis

Table 7.1: Cutting conditions and sensor details used in experiment

Experimental Conditions	Value
Width of cut	1 mm
Depth of cut	50 μm
Machining material	Al6061-T6
Acquisition rate	5000 kHz
Sensor Vs900 range	100-850 kHz

Figure 7.3: AE sensor used and its working range

7.3 AE features of the material removal mechanisms

The signal received from the sensor during the cutting process is sent to a data acquisition system, and the signal is filtered for noise and processed. The data obtained are plotted in terms of frequency spectra on the short-time Fourier transform (STFT) plots.

Figure 7.4 (a) and (b) show the comparison of no data signal and the data signal obtained from the cutting process by anon-textured tool in terms of amplitude and time variable, followed by the plot showing the peak amplitude in frequency spectrum; this plot gives the frequency ranges, which corresponds to the different phenomena that occur in the cutting process. The three different significant ranges of the frequency spectrum are shown in Figure 7.4 (d) and Figure 7.5. These figures give the corresponding frequency line spectra for non-textured and textured tool respectively. From these figures, it is observed that there are three phenomena predominantly associated with the cutting process but the corresponding frequency range for each phenomenon is to be identified.

Figure 7.4: AE signal for cutting process by non-textured tool

Figure 7.5: Linear frequency spectrum for textured tool cutting

The linear frequency spectrum with three distinct frequency zones might correspond to the rubbing, ploughing and cutting phenomena.

It is also to be noted that the stiffness of the material increases when it changes from an elastic state to a plastic state and so the natural frequency associated with the material block will also increase. Figure 7.6 shows the change in material property from elastic to plastic.

Figure 7.6: Martial behaviour from elastic to plastic region

It is known that rubbing is purely elastic, and ploughing is associated with plastic deformation. At the end of plastic deformation, fracture occurs, which is associated with material separation. Thus, cutting is associated with fracture. As such, it can be ascertained that the rubbing process is associated with a smaller natural frequency in comparison with that of ploughing and cutting process. Thus, this explanation confirms that the identification of the lower frequency range of the cutting signal corresponds to the rubbing process; this is further confirmed by the pure rubbing tribological experiment.

7.4 Analysis AE signal for energy associated with rubbing

To confirm the frequency of the corresponding phenomena, AE signals were taken for a pure rubbing process by conducting a rubbing experiment in a tribometer system, as shown in Figure 7.7.

Figure 7.7: Experimental setup to capture AE signal in rubbing process.

The signal obtained for the pure rubbing process is shown in Figure 7.8. It can be observed that the rubbing process is associated with a frequency range of 100 ± 50 kHz.

Figure 7.8: Peak amplitude hits in frequency spectrum for pure rubbing process

Figure 7.9: Linear frequency spectrum for pure rubbing process

The process of simulating only the ploughing and cutting phenomena is not achieved as it is always associated with the rubbing process. High negative rake angle tool is used to simulate the ploughing process to deform the workpiece top layer without forming the chip to simulate a pure ploughing process. The signal obtained from such a process does not give a distinct frequency range as rubbing. It should be noted that in the actual cutting process, the chip actually rubs over the rake face of the cutting tool; hence, the major contribution of texture on the rake face would be due to the rubbing phenomenon and not the cutting or ploughing phenomenon. Therefore, further analysis is concerned only with the frequency range of the rubbing process for the textured and non-textured tool. Figure 7.10 gives the schematic of the

procedure followed in the analysis of AE signal obtained from the non-textured and textured tool.

Table 7.2 gives the processing parameters used in the analysis of energy associated with the textured and non-textured tool.

Figure 7.10: Schematic of AE signal analysis

Table 7.2: Signal processing parameters

FFT Parameter	Value
Window length	65536
Number of FFT points/ window	4096
Window function	Hamming

Low-pass filter	20kHz
Hi-pass filter	250kHz

The signal taken in the non-textured tool and textured tool cutting process are filtered for noises through low and hi pass filters, and the window length and number of FFT points are selected to produce the STFT plot. It should be noted that the frequency range associated with the rubbing region only is taken for analysis which is 100-150 kHz. The energy associated with the AE signal for non-textured and textured tools are measured and compared in Figure 7.12 which gives the energy associated with the textured and the nontextured tool in the rubbing frequency region. It should be noted that the y-axis is in a reversed logarithmic scale; hence, the energy for the textured tool is less than that of the non-textured tool. This shows that the acoustic energy which is due to the rapid release of localised stress-energy of the workpiece material for the non-textured tool in the rubbing range is less than that for the textured tool. Thus, the textured tool is efficient in reducing the energy loss due to rubbing, which is a desirable effect of texture and thereby helps in improving the performance of the cutting tool. The energy associated with the frequency range above 250 kHz cannot be distinguished between ploughing and cutting; thus, they are added together and plotted in Figure 7.12 to show the difference.

(a) Frequency line spectrum for non-textured tool

(b) Frequency line spectrum for textured tool

Figure 7.11: Frequency range taken for analysis

Figure 7.12: Acoustic energy associated with non-textured and textured tool

7.5 Summary

The phenomenon involved in the cutting process can be identified by its characteristic frequencies. The frequencies associated with each phenomenon for the non-textured tool is determined. The rubbing characteristic frequency range is identified and separated in the cutting process AE signal. The difference in the textured and the non-textured tool in terms of acoustic energy is measured. The difference in the contribution of each phenomenon for the textured tool with that of the non-textured tool is calculated. This gives a measure of texture effect on changing the mechanism of the cutting process. This can be used to produce more effective textured tools and thereby improve the performance of the cutting tool. The reason behind the texture effect is attributed to friction reduction and contact area reduction in the

tool-chip interface. The AE signals can be used as an effective tool to measure the performance of texture. This can be done in-process and hence, can identify any reduction in texture performance due to clogging or wear.

Chapter 8: Conclusions and future work

In this chapter, the important observations and findings attained are summarised. These are followed by a list of general conclusions attained from work conducted for the thesis. Future works are then presented and discussed.

8.1 Overall summary of work conducted on the thesis

In this thesis, experimental, simulation, tribological and acoustic emission studies have been conducted to understand the effect of micro-textures on the rake face of the cutting tool. Different sets of combination of texture geometry and distribution were produced on the rake face of the cutting tool by EDM and laser. The texture effect is studied by varying the cutting speed and depth of cut. The improvement in performance of a cutting tool is assessed in terms of cutting forces, shear angle, contact area and adhesion of workpiece material on the tool surface. Then the influence of geometry and distribution of texture on the cutting tool performance is studied experimentally using Taguchi method. Different combination of texture parameters, diameter, depth, pitch and edge distance from the cutting were tested. A FEM model is developed to study the texture effect on a cutting tool in more detail. The FEM model is used to study the parameters such as stress and temperature on the cutting zones which are very difficult to study experimentally. The tool-chip interface, where the chip flows over the rake texture surface, is studied using an in-process tribometer system and FEM model to show the texture effect in terms of tribological contact. Finally, a new method to identify the change in cutting phenomena due to the introduction of texture on a cutting tool is proposed using AE signal measurement.

8.2 Assessment of texture effect by experimental investigation

- Micro EDM process conditions were found and proposed to produce micro-textures of size $20 \pm 5 \mu\text{m}$ without much deviation in circularity, whereas laser texturing was found to be a very efficient way of texturing in terms of time and for texturing larger regions.
- The cutting forces on aluminium for the textured tool are found to be less than that for the non-textured tool, and this effect is more pronounced in the presence of a lubricant.
- The rake textured tool is found to have more influence on cutting than the flank textured tool. The textures on the flank face do not show a significant reduction in cutting and thrust forces when compared to the textures on the rake face of cutting tools.
- The texture effect on the cutting tools is found to decrease with an increase in the cutting speed, and the texture effect is not found to be influenced by an increase of depth of cut.
- For the textured tools, the chip curled more than that for the non-textured tool, and the curvature of the curl was more for low cutting speeds. The textured tool produces thinner chips due to an increase in shear angle in comparison to that for the non-textured tool.
- The tool-chip contact area for a textured tool is less than that of a non-textured tool.
- The EDS measurement shows that the adhesion of workpiece material on the tool rake is reduced considerably by the introduction of texture on the rake face of the tool.

8.3 Effect of geometric parameters of textures on cutting tool performance

- The diameter of the texture is found to be the most influential process parameter. It is the most significant texture parameter.
- The suitable combinations of texture parameters for maximum texture effect are identified and proposed with respect to all the responses considered and for the range of parameters considered.
- For all the response parameters, the textured tool shows better performance than the non-textured tool. The difference between the non-textured tool and the textured tool is quite significant in the actual contact area. The actual contact area for the textured tool with the best combination of texture parameters is reduced by 61%.

8.4 FEM investigation on texture effect on cutting process

- A numerical model incorporating J-C plastic model and the J-C damage model is developed using an explicit finite element method to simulate the orthogonal cutting of Al6061-T6. The model is validated in terms of cutting forces and, contact and normal pressure. The model is used to analyse the texture effect in terms of cutting forces, chip formation and stress distribution.
- The texture effect with an increase in the cutting speed is found to have less impact. The depth of cut is found to have more significance because as the depth of cut increases the textures in the tool-chip contact increase.
- Micro textures show improvement in the performance of the tool in terms of cutting forces, chip morphology and stress distribution. The micro texture width and pitch are found to have more influence on the performance of the cutting tool.

- The microtexture makes the chip to curl early resulting in less tool-chip contact length and thereby less friction. This will improve the performance of the tool as the sliding distance over the tool rake reduces and less amount of energy would be spent.
- The simulation study is an effective way to study the effect of texture in terms of various parameters and various conditions with much less cost and time.

8.5 Tribological study of tool-chip contact

- It is found that in a ‘ball on flat’ test dimples textured surface exhibits smaller friction coefficient in the presence of lubricant, and perpendicular textured surface exhibits smaller friction coefficient in dry conditions.
- In-process tribometer results show a marginal decrement of friction coefficient for the textured pin at various cutting speeds.
- Employing the FEM model developed to study the texture effect in the tool-chip sliding process, it is found that textured tool reduces the contact stress when compared to the non-textured tool; the dimple textured surface shows the best performance. To study the temperature effect, the model is further developed to avoid the empty spaces on the texture units which is filled with workpiece material. It is found that the temperature for the textured tool is less than that of the non-textured tool in the cutting zone.

8.6 Acoustic emission signal examination of texture effect on cutting phenomena

- The characteristic frequency range associated with rubbing, ploughing and cutting phenomena is identified. The acoustic energy associated with each phenomenon is calculated for the AE signal for the cutting process.
- The difference in the textured and the non-textured tool in terms of acoustic energy is measured. Any reduction in the measured acoustic energy which is a measure of the texture effect, can be used to measure the effect and efficiency of texture.

8.7 Future work

These areas may be further researched:

- Although an in-depth study on other tool materials have not been conducted, it can be reasonably expected that similar texturing effect can be observed for non-tungsten carbide tool as well, e.g. high-speed steel (HSS). It could, however, be beneficial, to conduct an in-depth investigation in future.
- Taguchi method and ANOVA are used in the optimisation of texture geometry and distribution which can provide the best texture geometry and distribution in discrete values and only in the tested conditions. Texture optimisation can be done more effectively using software like TOSCA; it is an optimization suite which provides structural and flow optimization solutions based on FEA and CFD simulations.
- Validation of the developed finite element model can be extended to include other metrics such as chip thickness, cutting temperatures and strains generated in the

machined surface. Validation using strains and temperatures have been attempted in the literature and measurement of these parameters is difficult for micro cutting.

- The FEM model validated by experimental observations will have a much bigger impact when applied for predictive purposes.
- Frictional interaction at the tool-chip interface is modelled with Coulomb friction using a constant friction coefficient. Advanced friction models more applicable at the interfaces are to be investigated.
- Wear model can be included to investigate the texture effect on reducing wear.
- Lubrication effect in addition to the geometrical effect of texture is to be considered for hybrid model and to include heat transfer in all forms i.e. conduction, convection and radiation heat transfer.
- AE signals obtained from the cutting process by a textured tool can be used to optimise the texture using various signal processing models like artificial neural network or genetic algorithm.

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