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OPTIMIZATION OF CUTTING CONDITIONS FOR SUSTAINABLE MACHINING OF SINTERED POWDER METAL STEELS USING PCBN AND CARBIDE TOOLS

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ABSTRACT OF THESIS

OPTIMIZATION OF CUTTING CONDITIONS FOR SUSTAINABLE MACHINING OF SINTERED POWDER METAL STEELS USING PCBN AND CARBIDE TOOLS

Powder metals are becoming a popular choice in the automotive and other manufacturing industries because of their ability to meet wide ranging product functional requirements without compromising the performance of the product. They offer various advantages, including weight reduction, near net-shape processing capability, and their ability to be sintered to achieve desired properties in the end-product. However, in order to satisfy the product design requirements during manufacturing, they need to be machined to the required tolerances. Machining of powder metals is quite different to machining of traditional metals because of their specific properties, including porosity.

This thesis work deals with the finish machining of powder metal steels in automotive applications, for increased tool-life/reduced tool-wear. Tool-life is affected by a variety of factors such as tool grade selection, tool coating, cutting conditions and tool geometry including cutting edge geometry. This work involves optimization of cutting conditions for plunge cutting and boring operations of automotive powder metal components using PCBN and carbide tools. The cycle time of the process introduces an additional constraint for the optimization model along with the tool-wear criterion. Optimized cutting conditions are achieved for maximum tool-life.

KEYWORDS: Powder metal steel, PCBN, carbide, tool-life, optimization

Kunal J. Joshi

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THESIS

Kunal J. Joshi

The Graduate School

University of Kentucky

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OPTIMIZATION OF CUTTING CONDITIONS FOR SUSTAINABLE MACHINING OF SINTERED POWDER METAL STEELS USING PCBN AND CARBIDE TOOLS

THESIS

A thesis submitted in partial fulfillment of the
requirements for the degree of Master of Science in the
College of Engineering
at the University of Kentucky

By

Kunal J. Joshi

Lexington, Kentucky

Director: Dr. I.S. Jawahir, Professor of Mechanical Engineering

Lexington, Kentucky

2006

To,

My Parents, Family and Friends

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CHAPTER 1

INTRODUCTION AND OVERVIEW OF THE THESIS

1.1. Introduction

The theme of this thesis study is to obtain optimum cutting conditions for maximum tool-life in boring and plunge cutting of powder metal steels using PCBN and carbide tools. Powder metals have been around in the market for quite some time now. However, their potential use in the area of automotive manufacturing is beginning to be appreciated lately. With the automotive industries moving toward addressing the sustainability issues involving reduction in energy consumption, pollution reduction, etc., powder metal components offer a highly attractive light weight property with the additional advantage that they can be easily shaped into various complex parts. Powder metals, unlike conventional metals are considered to be 'difficult to machine' materials, due to their inherent porous properties. From the review of the published literature in the area of powder metal machining, there appears to be lack of fundamental studies in the mechanics and the cutting action of sintered powder metal parts. It has been estimated that about 30% of powder metallurgy structural components made for automotive industries require some form of machining (Holzki, 1996). This high proportion of machining involved with powder metals in the automotive industries and the lack of fundamental knowledge in machining of porous powder metals inspired this thesis work, sponsored by an automotive manufacturer to improve the tool-life in machining of powder metal components used in their manufactured products. The automotive supplier

(will be referred as OEM) was experiencing productivity loss due to shorter tool-life on the machining station used to machine these powder metal components. Because of the shorter tool-life, the machine used to be down for longer periods of time, owing to frequent tool changes and quality checks after each tool change. This problem was exacerbated due to the fact that the life of some tools was half that of the rest of the tools used to machine two different types of powder metal materials. This resulted in significant bottlenecking on the powder metal component machining stations. Hence, a need was felt to fundamentally study and analyze the machining operation and to develop a predictive model for increasing the life of the tools.

In order to understand the behavior of the PCBN and carbide cutting tools, which were used to machine two different grades of powder metals, extensive experimental work was conducted with varying cutting conditions and the tool-wear data was collected to develop a predictive tool-life model. This model along with the tool-wear data was further considered and incorporated into the optimization program, to obtain optimum cutting conditions, which would produce maximum number of components.

1.2. Overview of the Thesis

This research effort presents an extensive experimental work which leads to the development of a predictive model for a major machining performance measure, tool-life, in terms of cutting conditions (cutting speed and feed), in plunge cutting and boring of powder metal steels using PCBN and carbide tools, under flood-cooling conditions. An optimization program was then developed to utilize this tool-life prediction model and

obtain the optimum machining condition parameters, aimed at maximizing tool-life/minimizing tool-wear.

The objectives of the thesis are:

1. Studying the effects of different cutting conditions on tool-life performance measure in plunge cutting and boring of powder metal rings.
2. Understanding the behavior of PCBN tools and carbide tools in machining of porous powder metal components.
3. Developing a predictive model for tool-life in terms of machining parameters (cutting speed and feed), based on tool flank wear criterion.
4. Formulating an optimization problem for finish machining of powder metal steels to achieve optimum cutting conditions, resulting in maximum tool-life/minimum tool-wear.

A brief review of relevant past research publications and the current state-of-the-art in machining of powder metals is presented in Chapter 2.

Chapter 3 describes the extensive experimental work in machining of powder metals. It covers the aspect of simulating an industrial problem in a laboratory environment, efficiently.

Chapter 4 extensively reviews the past published research work in the field of tool-life modeling, and describes how a predictive tool-life model was developed for powder metal steel machining using PCBN and carbide tools.

Chapter 5 covers the programming and optimization aspect of tool-life modeling; it summarizes the work done by previous researchers in the area of machining process optimization. It further, describes the optimization technique employed within the scope of this work.

Chapter 6 summarizes the experimental, modeling and optimization research work completed in this investigation. It also highlights the need for focusing on sustainable machining and how an improvement in the life of cutting tools would affect the overall machining performance in terms of sustainability.

CHAPTER 2

REVIEW OF RELEVANT PREVIOUS RESEARCH WORK ON MACHINING OF POWDER METALS

This chapter reviews the recent and relevant published work in the area of powder metal machining using PCBN and carbide tools. It has been noted that only limited published work exists on machining of powder metals. This chapter covers only a summary of reviews from these papers. The subsequent chapters of this thesis cover reviews of other relevant topics such as modeling of tool-wear and machining optimization. The major variables that influence the machinability of powder metals are:

(a) powder metal material and properties,

(b) cutting tool materials,

(c) cutting conditions,

(d) cutting tool geometry,

(e) coolant application and

(f) type of machining operation.

In what follows, a brief review of these influencing variables and how they affect machining of powder metals will be presented.

2.1. Powder Metals

Powder metals are being considered as attractive materials for usage in manufacturing industries, especially in automotive manufacturing industries. This is primarily due to their near net-shape processing capability and the desirable material properties contributing to product attributes that can be incorporated into the product more readily. Also, they help in reducing the weight of the vehicle and require none or very little subsequent machining and can be formed into various complex shapes. The increase in the powder metal content over the years in an automobile is shown in Figure 2.1.

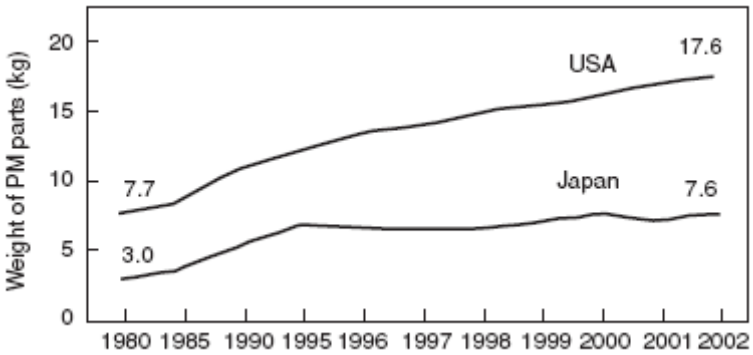


Figure 2.1: Weight of Powder Metal Parts Installed in an Automobile (Ota et al., 2005).

Powder metals are considered to be 'difficult to machine' materials and the tool-life, for example in turning of sintered powder metal steels, becomes shorter than that in turning of the conventional carbon steels. This can be attributed to several processing techniques - resin impregnation, copper infiltration, surface densification, steam or heat treatment, that are employed in making these powder metals. The major difference between conventional metals and powder metals is that the latter has the property of porosity. Porosity greatly reduces a powder metal's conductivity and also acts as a micro-

interruption or impact on the cutting tool, both of which result in lower machinability of powder metals (Young, 2002; Chagnon, 1998). These micro-interruptions require the cutting edge to be tough, while the abrasive property of powder metal particles require the cutting tool to be hard and abrasion-resistant, making PCBN tools suitable for machining powder metals (Young, 2002). To enhance the machinability performance of powder metals, research on understanding the role of additives in powder metals is being actively considered. Chagnon and Gagné (1998) studied the influence of MnS and BN in drilling of forged powder metals. According to them, the addition of MnS and BN enhances the machinability of powder metals, reducing the thrust and torque in drilling with high speed steel drills, accompanied with better chip evacuation. Several researchers have found the benefits in terms of machinability with addition of MnS to the powder metals, in drilling and plunge cutting tests (Lee, 1997; Roy, 1987; Chopra, 1987). Robert-Perron et al. (2005) have shown that machinability of powder metals can be improved by machining them in the 'green state' i.e., before sintering. This technique is known as 'Green Machining'. Age hardening property of powder metals with MnS inclusions has also been investigated by Young (2002).

2.2. Cutting Tools for Machining of Powder Metals

Ferrous powder metals can be classified into three categories depending on their machinability characteristic. These are:

(a) standard powder metals,

(b) high density powder metals, and

(c) hardened powder metals.

Figure 2.2 shows the classification of powder metals (Ota et al., 2005). For machining standard powder metals, carbide, cermet and CBN tools are used. For machining of hardened powder metals, usually CBN tools are used, and for high density powder metals, either carbides or CBN, with characteristics of high toughness and shock resistance, are used.

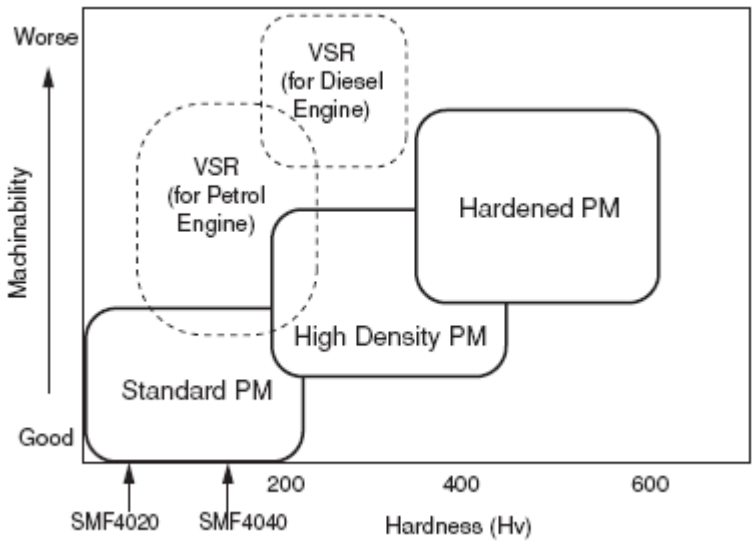


Figure 2.2: Classification of Powder Metals According to their Machinability (Ota et al., 2005).

According to Young (2002), PCBN tools are more suited to machine ferrous powder metals. However, no single PCBN grade is capable of catering for the machining of wide range of compositions in powder metals used in different machining applications. PCBN tools are mainly classified into:

(a) high content PCBN tools, and

(b) low content PCBN tools.

High content PCBN tools contain higher proportion of CBN particles in the binder matrix, while the low content PCBN tools contain a lesser proportion of CBN particles. High content PCBN materials contain 70 percent or more CBN. Low content PCBN materials contain 69 percent or less CBN. Each category has specific physical characteristics that help define the applications they are best suited for. The decision to use either a high or low content PCBN tool depends on the workpiece being machined.

According to Wada (2001), in conventional tool materials, cemented carbide (coated with TiVN PVD), and in hard tools category, CBN tool with TiN binder are the most effective tool materials for turning of sintered stainless steel, in terms of improved tool-life and surface finish.

2.3. Cutting Conditions

The most desirable cutting conditions to be achieved from the predictive tool-life models are different and have to be established for each tool-workpiece material combination irrespective of whether it is for a conventional metal or a powder metal. There does not exist any systematic methodology to predict the optimum cutting conditions for machining of powder metals. Industries have long depended on their experience and intuition in determining the cutting parameters for machining of powder metal components for practical applications.

Rocha et al. (2004) investigated the influence of cutting conditions (speed, feed and depth-of-cut) in machining of ferrous powder metal valve seats using PCBN tools. They

selected certain levels of cutting parameters and suggested the conditions that produced more number of parts without affecting the surface finish of the machined product. According to them, cutting speed was the most influencing parameter on tool-wear and they showed that attrition wear mechanism was predominant at lower cutting speeds, while diffusion was predominant at medium cutting speeds.

According to Young (2001 & 2002), tool-life of PCBN tools, while machining sintered powder metals, reduces at higher speeds and improves at higher feed rates as shown in Figure 2.3.

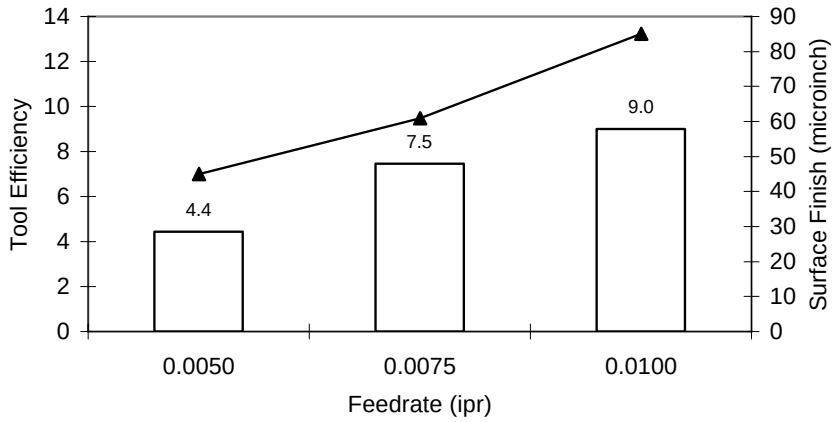


Figure 2.3: Tool-life Improvement with Increased Feed Rate (Young, 2002).

Higher feed rates cause the chips to be thicker and hence carry more heat, dissipating the heat away from the cutting region more rapidly.

According to Šalack et al. (2005), the selection of feed rate is of primary importance during turning of powder metals using PCBN tools and that highest feed rate possible

should be selected and, for carbide tools improved tool-life is gained at lower feeds and lower cutting speeds.

2.4. Cutting Tool Geometry

The selection of optimum cutting tool geometry with correct edge preparation is of utmost importance in any machining operation.

Chen et al., (2005) have recently shown the influence of correct and consistent cutting tool edge geometry in machining of porous sintered tungsten used in dispenser cathodes, to avoid smearing. Also, an improvement in tool-life was recorded by using correct tool geometry. According to Young (2002), PCBN can be a highly productive tool material if proper insert geometries and edge preparations are used. He recommends using negative chamfers and hones for improved PCBN tool performance. Negative rake angles along with honing, provide better cutting edge toughness essential for machining of porous powder metals.

Endres and Loo (2002) have shown the significance of correct edge preparation for better stability in plunge cutting of powder metal steel valve seats. They have related the concept of uncut chip thickness with directional factor in force modeling and have showed that improved stability can be achieved by controlling the cutting edge geometry parameters, i.e., edge radius and chamfer angle, while machining surfaces requiring high lead angles.

2.5. Coolant Application

Another key variable affecting the machining performance of powder metals is the coolant or the cutting fluid used during the operation. Traditionally, the coolant is used to dissipate heat and reduce the temperature at the tool-workpiece interface, thereby reducing the tool-wear. Coolant also tends to lubricate the tool-workpiece interface and facilitate the flushing of chips away from the cutting region. However, PCBN tools used in machining of powder metals do not fare well when used with coolants as shown in Figure 2.4 (Young, 2002). During interrupted machining applications, the coolant quenches the cutting tool as it exits the cut into the interruption causing alternating cooling and heating cycles. PCBN tool materials tend to develop thermal cracks under such conditions.

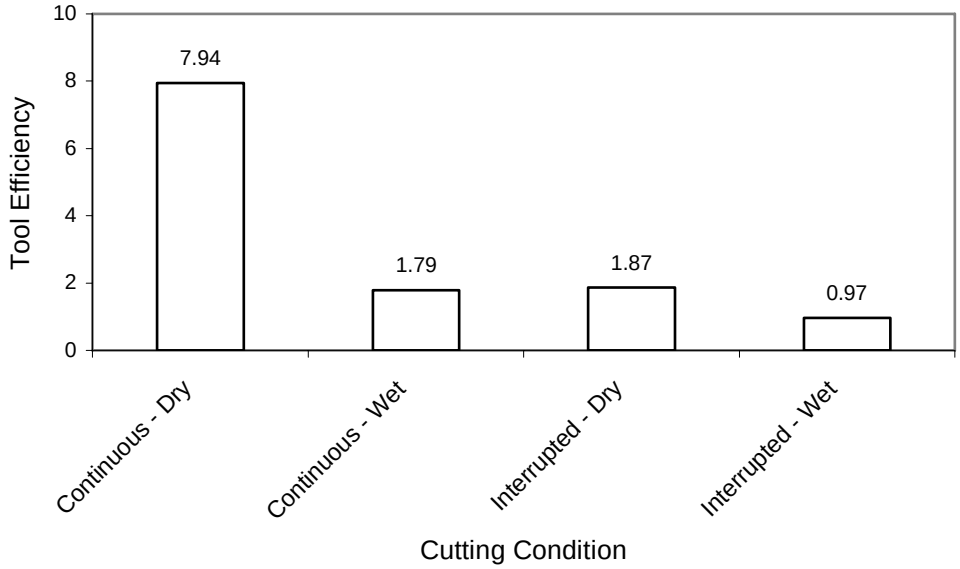


Figure 2.4: Effect of Coolant Application on Machining of Sintered Powder Metals (Young, 2002).

Zurecki, Z. et al. (2003) have shown that by using cryogenic cooling, machinability of high density and low density powder metal improves dramatically. In their experimental demonstration they have showed that a cryogenically-cooled Al_2O_3-based ceramic tool can easily out-perform a flood-cooled PCBN tool, resulting in a reduction in manufacturing costs by decreasing the tooling costs and increased productivity. Moreover, the cryogenic nitrogen cooling technology minimizes the environmental impact of machining operations.

2.6. Type of Machining Operation

In machining of powder metal components, the most frequently used machining operations are drilling, tapping and turning.

Plunge cutting, which is being considered in this investigation, is a machining operation that has not yet received widespread or adequate attention. It is widely used to create chamfers on cylindrical parts. Li et al. (2000) have developed a cutting force model for cylindrical plunge cutting of internal combustion engine valve seats. This force model is based on the relationship between the chip load and the local cutting forces at each individual cutter blade. Authors have also suggested that the resultant forces decrease by adjusting the relative position of the cutter blades in an optimal manner.

Boring, the second operation being considered in this investigation, to a certain extent, can be related to turning. Armarego et al. (2001) have conducted orthogonal cutting tests and quantitatively showed that the basic cutting action and the associated mechanics of

cutting applicable to conventional metals, holds equally good for sintered metallic materials. They have further verified this by conducting experiments and calculating force and power requirements for powder metals based on the predictive models developed for drilling and turning operations in conventional metals.

Overall, it has been observed that very little work has been done in the field of machining of powder metals using PCBN and/or carbide tools for boring and plunge cutting operations under flood-cooling conditions. There is no evidence of any predictive models developed for machining performance measures such as tool-life, chip-breakability, etc. Hence, an attempt is being made in this work to establish a predictive model for tool-life in boring and plunge cutting of powder metal steels, further leading to the optimization of cutting conditions for maximum tool-life/minimum tool-wear.

The following chapter describes the experimental procedure and the setup used to conduct the experiments for the investigation under study.

CHAPTER 3

EXPERIMENTAL WORK

In the present investigation, extensive experimental work in machining of powder metal steel was carried out to establish an interrelationship between a major machining performance measure (tool-life) and the cutting parameters (cutting speed and feed). This interrelationship was developed for plunge cutting and boring operations under flood-cooling conditions. This chapter describes the experimental setup and the experiment design used for this investigation. The observations made during the experimentation and the practical problems experienced are also highlighted in this chapter.

3.1. Experimental Setup

This tool-life investigation work was inspired by the productivity loss experienced by the project sponsor (will be referred as OEM), who machines powder metal rings in automotive applications. The work material used for the investigation was powder metal steel, which was made in the form of rings. Two different sets of rings, Ring A and Ring B, with different diameters were used for the investigation. The hardness of rings A and B was measured to be 210-300 HV and 170-270 HV respectively. Figure 3.1 shows the rings A and B.

Figure 3.1: Powder Metal Rings A and B.

The chemical constituents of the work material are shown in the Table 3.1.

Table 3.1: Material Constituents of Rings A and B.

Ring	**Material Constituents**							
A	C	Si	Cr	Mo	Mn	Ni	Co	Fe
B	C	-	-	Mo	-	Ni	Co	Fe

At the OEM's facility, these powder metal rings are press-fitted into a sub-assembly and then machined on a transfer line station, where these sub-assemblies are stationary while the tooling head rotates. Two different operations, plunge cutting and boring are performed on these powder metal steel rings. Three different angles, viz. 30°, 45° and 75° are generated on the surface of these rings as shown in Figure 3.2.

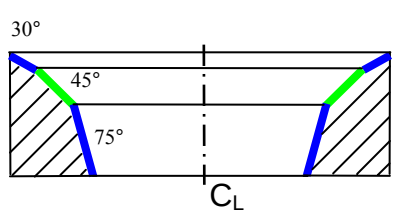
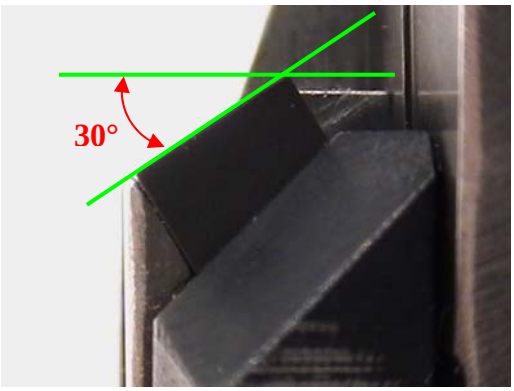
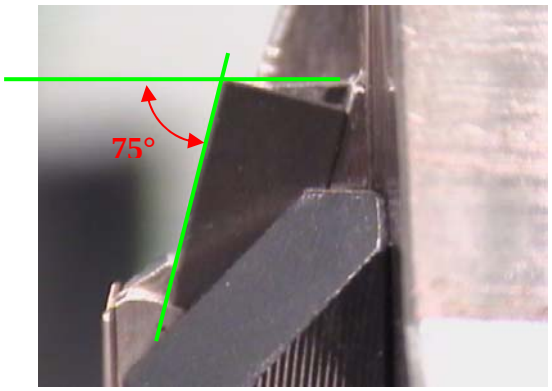


Figure 3.2: Three Different Angles Machined on the Rings.

Three different cutting tools are required to machine these rings, A and B. Each tool is mounted on the outer periphery of the tooling head, approximately 120° apart, and are oriented at specific angles as shown in Figure 3.3, corresponding to the surface to be generated. The relative position of the tool inserts along the periphery of the tooling head is critical, since an optimal location of the tools can reduce the maximum resultant force that acts on the spindle (Li et al., 2000).



(a) 30° Insert



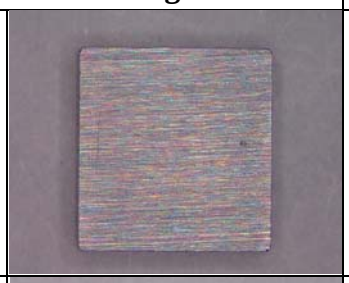
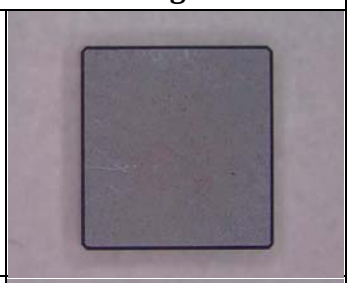
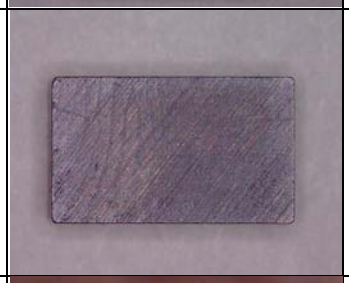
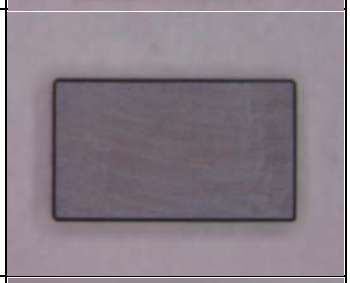
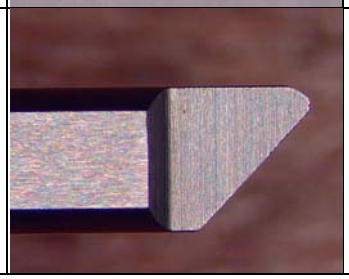
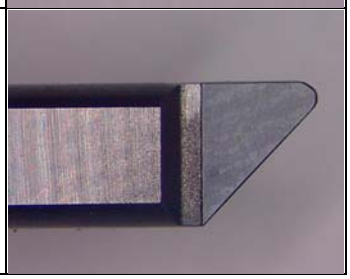
(b) 75° Insert

(c) 45° Insert

Figure 3.3: Orientation of Tool Inserts on Tooling Head.

The tools used to machine Ring A are sintered carbides, whereas the tools used to machine the Ring B are PCBN (Polycrystalline Cubic Boron Nitride) brazed on a carbide substrate. Table 3.2 shows the tools used to machine Rings A and B.

Table 3.2: Tools Used to Machine Rings A and B.

Tool Inserts for Ring A		Tool Inserts for Ring B	
30° Insert (Uncoated Carbide)		**30° Insert** (Uncoated PCBN)	
75° Insert (Coated Carbide)		**75° Insert** (Uncoated PCBN)	
45° Insert (Uncoated Carbide)		**45° Insert** (Uncoated PCBN)	

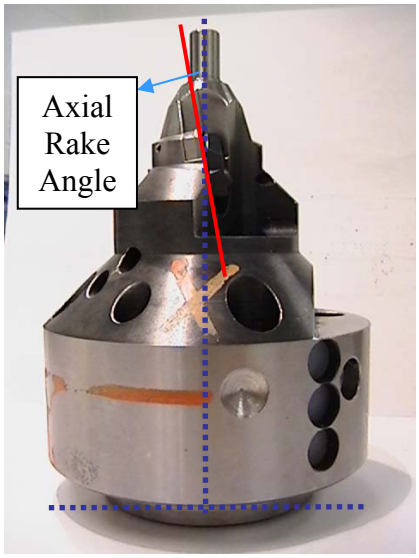
The effective angles of the tools change when they are mounted on the tooling head. The tool-in-hand and the tool-in-use geometry for carbide and PCBN tools are given in Tables 3.3 and 3.4. Statistical variations of effective angles of the tools were obtained by measuring three different tooling heads, using a DEA Gamma coordinate measuring machine (CMM) equipped with TF Scan software. Figure 3.4 shows the method of measuring these angles on the tooling head, and Tables 3.5 (a) and (b), show the values of these measurements and their statistical variations.

Table 3.3: Geometry Parameters for Tools Used in the Machining of Ring A.

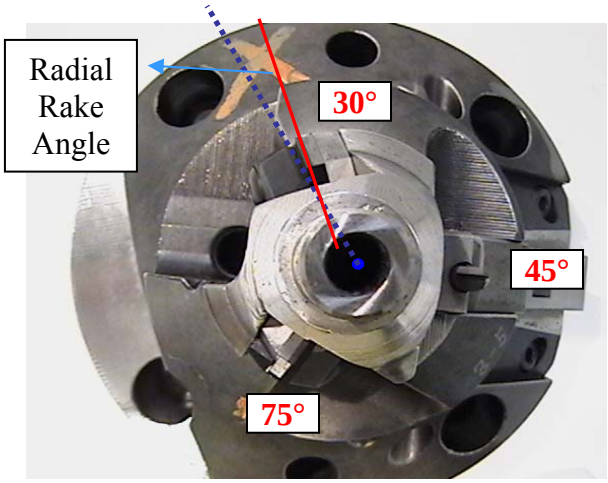
	Surface Machined	Tool Material	Geometry Parameters	
			Tool-in-hand Angles	**Tool-in-use Angles**
Ring A	30	Uncoated Carbide	Cutting Edge Radius r_n = 10 - 15 µm	Angle of Inclination i = 8.5°
			Back Rake Angle γ_p = 0°	Normal Rake Angle α_n = -5°
			Clearance Angle α_p = 0°	Clearance Angle = 5°
	45	Uncoated Carbide	Cutting Edge Radius r_n = 10 - 15 µm	Effective Major Cutting Edge Angle K_{re} = 90°
			Nose Radius r_ε = 0.4 mm	Effective Minor Cutting Edge Angle $K_{re'}$ = 15°
			Major Cutting Edge Angle K_r = 45°	Effective Back Rake Angle γ_{pe} = 0°
			Minor Cutting Edge Angle $K_{r'}$ = 60°	
			Back Rake Angle γ_p = 0°	
			Primary Clearance Angle α_p = +12°	
	75	Coated Carbide	Cutting Edge Radius r_n = 20 - 25 µm	Angle of Inclination i = 2.6°
			Back Rake Angle γ_p = +0°	Normal Rake Angle = -9.7°
			Clearance Angle α_p = 0°	Clearance Angle = 9.7°

Table 3.4: Geometry Parameters for Tools Used in the Machining of Ring B.

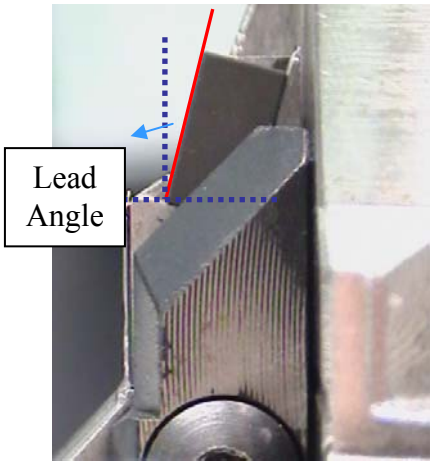
	Surface Machined	Tool Material	Geometry Parameters	
			Tool-in-hand Angles	**Tool-in-use Angles**
Ring B	30	PCBN	Cutting Edge Radius r_n = 18 - 23 μm	Obliquity Angle/Angle of Inclination i = 8.5°
			Back Rake Angle γ_p = -15° (chamfer angle)	Normal Rake Angle α_n = -20° (considering chamfer)
			Clearance Angle = 0°	Clearance Angle = 5°
			K-land Chamfer Angle = -15°	
			K-land Chamfer Width = 0.1 mm	
	45	PCBN	Cutting Edge Radius r_n = 15 - 20 μm	Effective Major Cutting Edge Angle K_{re} = 90°
			Nose Radius r_ε = 0.4 mm	Effective Minor Cutting Edge Angle $K_{re'}$ = 15°
			Major Cutting Edge Angle K_r = 45°	Effective Back Rake Angle γ_{pe} = -15°
			Minor Cutting Edge Angle $K_{r'}$ = 60°	
			Back Rake Angle γ_p = -15° (chamfer angle)	
			Primary Clearance Angle α_p = 12°	
			K-land Chamfer Angle = -15°	
			K-land Chamfer Width = 0.1 mm	
	75	PCBN	Cutting Edge Radius r_n = 18 - 22 μm	Obliquity Angle/Angle of Inclination i = +2.6°
			Back Rake Angle γ_p = -15° (chamfer angle)	Normal Rake Angle α_n = -24.7° (considering chamfer)
			Clearance Angle α_p = 0°	Clearance Angle = 9.7°
			K-land Chamfer Angle = -15°	
			K-land Chamfer Width = 0.12 mm	



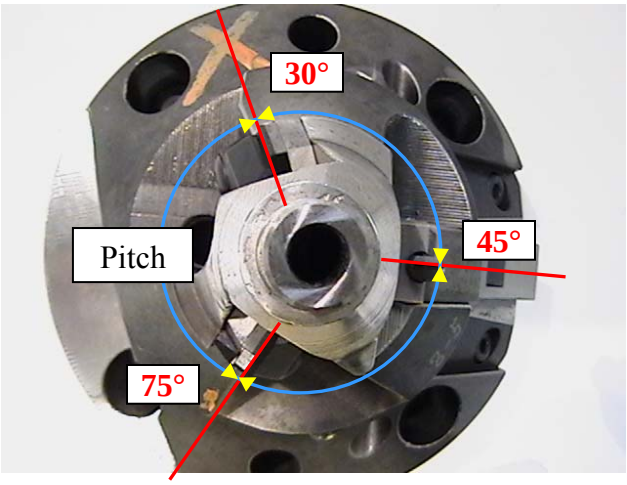
(a) Axial Rake Angle



(b) Radial Rake Angle



(c) Lead Angle



(d) Pitch Angle

Figure 3.4: Critical Geometry Parameters Measured on the Tooling Head.

Table 3.5: Statistical Variations in Tooling Head Parameters.

(a) Statistical Variations of Plunge Cutting Inserts on Three Different Tooling Heads.

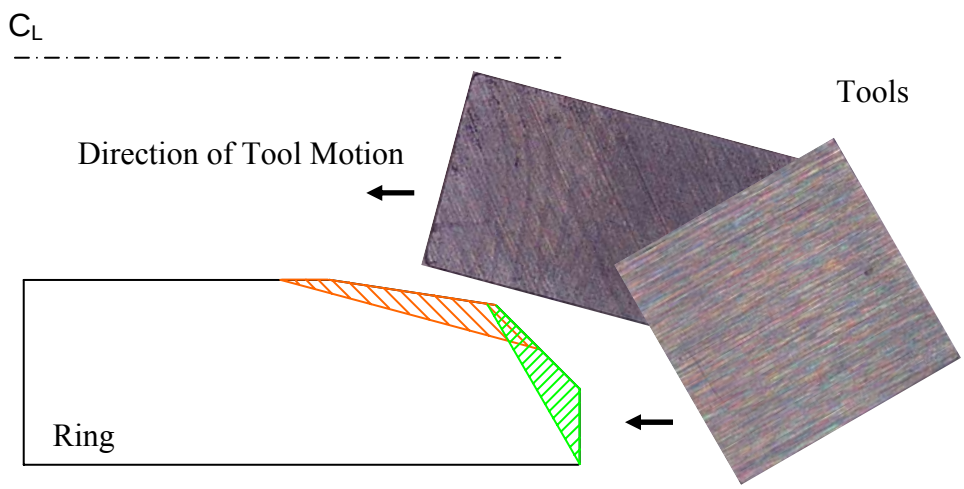
Measured Angle	Tool Insert							
	30°				75°			
	T1	T2	T3	% Var	T1	T2	T3	% Var
Radial Rake	4.991	5.021	4.987	0.680	9.558	9.770	9.686	2.220
Axial Rake	8.527	8.835	8.241	7.210	2.624	2.656	2.550	4.160
Lead Angle	31.508	30.901	31.114	1.960	15.056	15.701	14.636	7.270

(b) Statistical Variation of Pitch Angle for Three Different Tooling Heads.

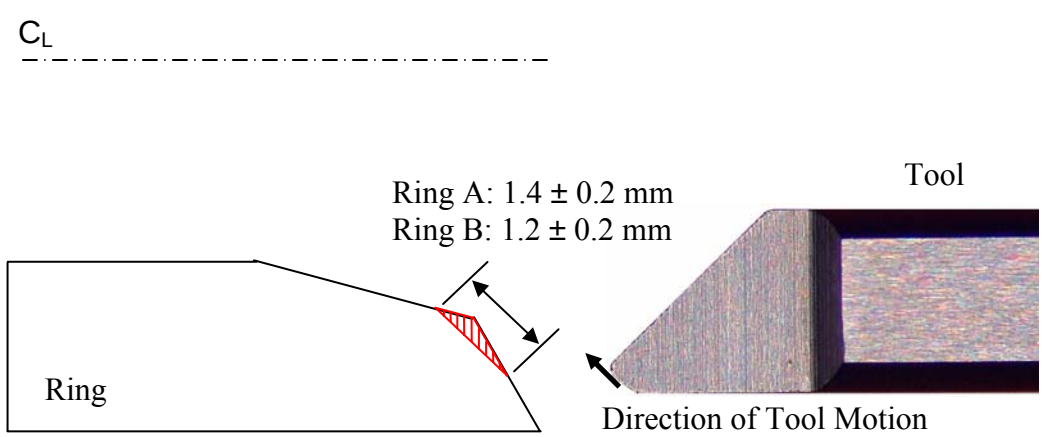
Pitch				
	T1	T2	T3	% Var
30° -75°	130.243	130.251	130.284	0.030
75° - 45°	118.915	119.770	119.686	0.720
45° - 30°	110.841	109.979	110.030	0.780

The tooling head can be compared with a milling cutter in some ways, even though the functions of both are completely different. The 30° and the 75° surfaces are cut by plunge cutting operation, whereas the 45° surface is generated by the boring operation. A special attachment on the tooling head facilitates the movement of the boring tool in the traverse manner, while the tooling head rotates. A push rod attached to the machining station helps to move this attachment at the 45° angle. The boring operation succeeds the plunge

cutting operation. When the plunge cut commences, the 75° tool engages first, followed by the 30° tool. After the plunge cutting operation is completed, the tooling head backs off a little and the boring tool comes into position and moves at a traverse angle to generate the 45° surface. Figures 3.5 (a) and (b) show the amount of material being removed by plunge cutting and the boring tools.



(a) Portion of the Material Machined by Plunge Cutting Tools



(b) Portion of the Material Removed by Boring Tool

Figure 3.5: Material Removed in Machining by Plunge Cutting and Boring Tools.

After these sequences of operations, machining of the press-fitted ring is completed and the sub-assembly moves on to the next station for subsequent operations. This is how these rings are machined in a production line environment at the OEM's facility. Each sub-assembly part holds eight rings each of Ring A and Ring B. Thus a total of 16 tooling heads are required to machine all of Rings A and B, and each tooling head holds three tools. The tool change is dictated by the dimensional change in the width of the 45° surface. The tool change time at the end of its life is quite high. To make it worse, the tool-life of the tools used to machine Ring A is found to be half that of the tools used to machine Ring B, resulting into huge loss of productivity. This problem inspired the author to conduct a tool-life improvement study to improve the life of the tools used for machining Rings A and B. In order to conduct this study, offline experiments were performed in the laboratory so as not to disrupt the OEM's production line.

The operation similar to the one being performed at the OEM's facility was replicated in the laboratory environment at the Machining Research Laboratory of the University of Kentucky. Since the tool-life study involves enormous amount of resources and time, a highly productive and efficient way of performing the experiments was considered. A fixture was designed and manufactured to hold 12 rings, six each of Rings A and B, as shown in Figure 3.6. This fixture was mounted on the bed of HAAS VF-2, 20 HP and 5000 rpm Vector Dual Drive vertical machining center, as shown in Figure 3.7. A special adapter was made to hold the customized tooling head to the spindle of the machine. Trial plunge cuts were taken to test the performance of this system. Unfortunately, the long overhang and the heavy mass of the tooling head, combined with the high rotational

speeds, resulted in some chatter during machining. The initial runout of the machine spindle got cumulated at the free end of the tooling head, resulting in undesirably large amount of chatter observed on the workpiece. This problem was identified after performing a thorough root cause analysis of the complete setup.

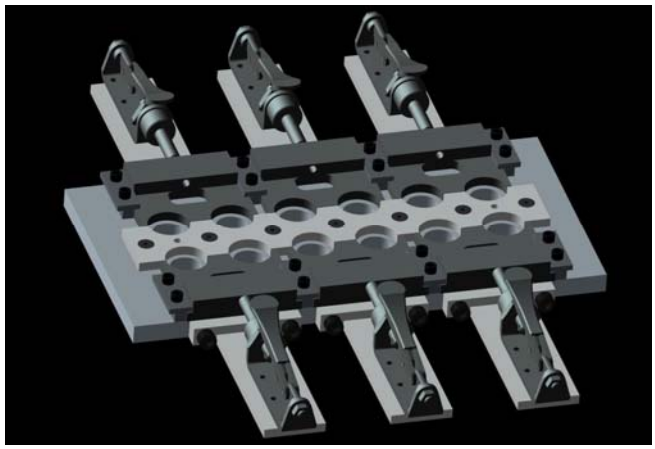


Figure 3.6: 3-D Model of the Fixture Designed to Hold the Rings on the Vertical Machining Center.

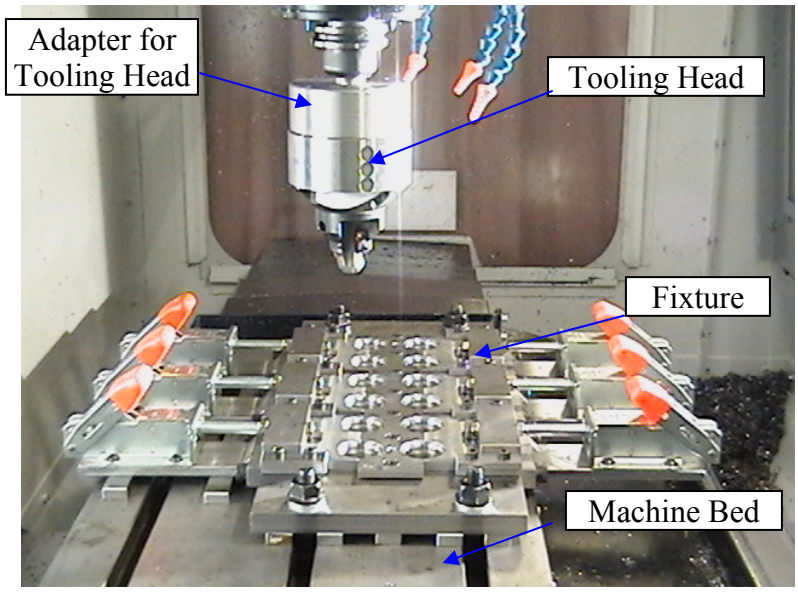


Figure 3.7: Setup on the Haas VF-2 Vertical Machining Center.

Due to this initial setback, it was decided to shift the experimental setup to the turning center. Experiments were now conducted on a HAAS SL-20, 20 HP and 4000 rpm Vector Dual Drive turning center. Again, special adapters were manufactured to hold the customized tooling heads onto the turret of the turning center. Figure 3.8 shows the new experimental setup.

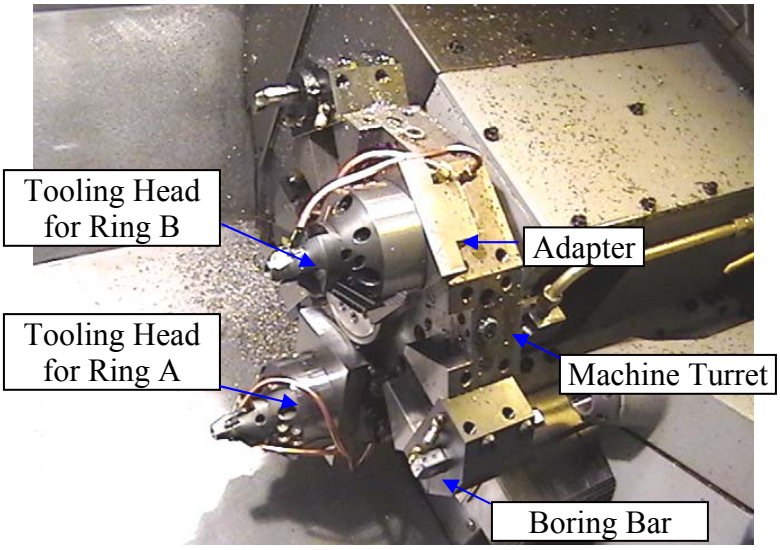


Figure 3.8: Experimental Setup on the Haas SL-20 Turning Center.

Soft jaws attached to the Kitagawa 8 inch chuck were bored to size to hold the rings. To accommodate the larger diameter workpiece, Ring B, the jaws need to be re-bored. Customized tooling heads were used to carry out the plunge cutting operation. A separate boring bar was used to perform the boring operation, since the machine was not equipped with a special attachment to push the boring tool at 45° angle. The disadvantage of this setup was that only one ring could be machined at a time. The operation remains relatively similar to when the tooling head is rotating and the workpiece is stationary, as in the case of OEM's production facility. Each ring was used for only one single pass cut, to avoid large strain hardening of the work material. After the setup was ready, trial cuts

were taken and surface roughness on the rings was measured to ensure that the part quality adhered to the quality requirements of the OEM, and to compare the stability of the machining process to that of the OEM's.

Figure 3.9 shows the surface roughness profile, R_z, measured on Ring B, which is considerably less than the OEM specified upper limit of 6 µm. This confirms the stability of the experimental setup, compared to the OEM's production machining operation.

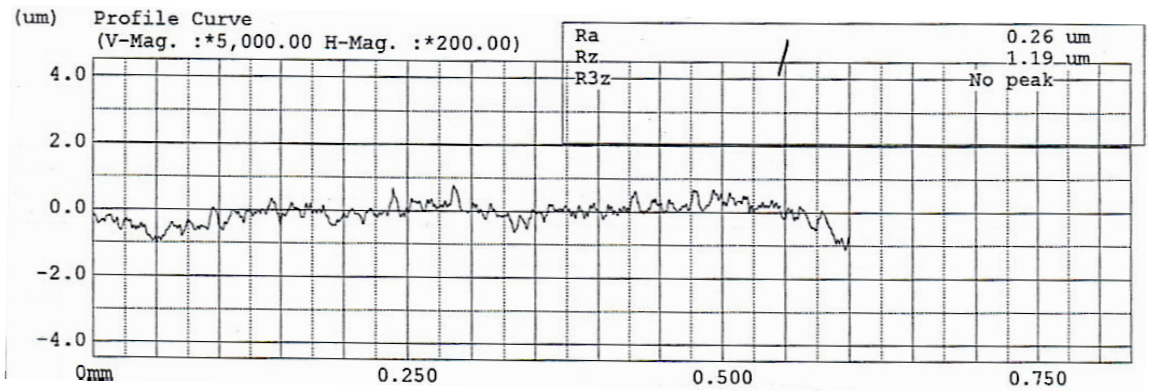


Figure 3.9: Surface Roughness Profile for the Machined Ring B.

Once the stability of the setup was confirmed, a baseline experiment was conducted and the wear was measured at regular intervals of parts and compared with the progressive tool-wear experiments conducted at the OEM's production facility. The progressive tool-wear experiments were conducted at OEM's production facility in the initial phase of the investigation to study the tool-wear pattern, establish the tool-wear criteria, and to determine if the tool had the potential to perform beyond its current capacity.

The basic objective of the experimental work was to determine the regression constants and the coefficients, required for the tool-life evaluation.

3.2. Experimental Procedure

In the current investigation, the cutting parameters for machining of powder metal steel rings considered are cutting speed and feed. The depth-of-cut was kept constant for each set of machining conditions. Hence, it was excluded from the tool-life equation. The coolant used during the machining operations was Yumate HEC-30 water miscible cutting fluid, supplied by the OEM.

3.2.1. Experimental Design

In any experimental investigation, the results depend, to a large extent, on the way in which the data was collected. The most preferred method of experimentation utilized by researchers is a full factorial set of experiments, where experiments are carried out for all combinations of variables. A full factorial design of experiment (DOE) measures the response of every possible combination of factors and factor levels. These responses are analyzed to provide information about every main effect and every interaction effect. In this study, the process variables considered are cutting speed and feed. Four levels each of cutting speed and feed are selected, resulting into 4^2 numbers of experiments. Table 3.6 shows all combinations of the experimental conditions. The upper and the lower levels for the cutting speed and feed were selected so as to obtain a variation of about ± 20% in the current cycle time. The other two intermediate levels were selected in between the upper and the lower levels.

Table 3.6: Design of Experiments for Rings A and B.

Ring A		
30° & 75°		
Expt #	RPM	Mm/rev
1	1224	0.071
2	1224	0.078
3	1224	0.089
4	1224	0.096
5	1339	0.071
6	1339	0.078
7	1339	0.089
8	1339	0.096
9	1541	0.071
10	1541	0.078
11	1541	0.089
12	1541	0.096
13	1656	0.071
14	1656	0.078
15	1656	0.089
16	1656	0.096

(a)

Ring A		
45°		
Expt #	RPM	mm/rev
1	1014	0.064
2	1014	0.07
3	1014	0.081
4	1014	0.087
5	1109	0.064
6	1109	0.07
7	1109	0.081
8	1109	0.087
9	1276	0.064
10	1276	0.07
11	1276	0.081
12	1276	0.087
13	1372	0.064
14	1372	0.07
15	1372	0.081
16	1372	0.087

(b)

Ring B		
30° & 75°		
Expt #	RPM	Mm/rev
1	1296	0.063
2	1296	0.066
3	1296	0.073
4	1296	0.076
5	1368	0.063
6	1368	0.066
7	1368	0.073
8	1368	0.076
9	1512	0.063
10	1512	0.066
11	1512	0.073
12	1512	0.076
13	1584	0.063
14	1584	0.066
15	1584	0.073
16	1584	0.076

(c)

Ring B		
45°		
Expt #	RPM	mm/rev
1	1800	0.041
2	1800	0.043
3	1800	0.047
4	1800	0.05
5	1900	0.041
6	1900	0.043
7	1900	0.047
8	1900	0.05
9	2100	0.041
10	2100	0.043
11	2100	0.047
12	2100	0.05
13	2200	0.041
14	2200	0.043
15	2200	0.047
16	2200	0.05

(d)

Once the experiments were designed, all 16 experiments were carried out randomly. After mounting all the tools onto the tooling head and the boring bar, it was ensured that the depth-of-cut was kept constant for the experiment. The width of 45° surface (maintained at 1.2 ± 0.2 mm for the Ring A and at 1.4 ± 0.2 mm for the Ring B) was measured each time the tool was changed, using a Unitron (NSM-Series) microscope equipped with Microcode II (Boeckeler Instruments) XY stage for linear measurements. The tools were removed after regular intervals of parts and wear was measured on each of the tools. For the Ring A, 300 parts were machined for each experimental condition and three data points for wear were taken. For the Ring B, 400 parts were machined for each experimental condition and four data points were collected. More parts had to be machined for Ring B, since it was difficult to observe wear on the PCBN tools at lesser number of parts.

3.2.2. Tool-wear Measurement

At each data point, the cutting tool was removed from the machine and tool-wear on the insert was measured using Keyence microscope (Magnification: 25X – 175X) and the Nikon L-UEPI (Magnification: 5X – 100X) equipped with an external 'Spot Insight' light and an Image-Pro Express software, located in the University of Kentucky College of Engineering at the University of Kentucky. Initially flank wear and crater (rake face) wear were the major wear parameters measured, but later on it was determined that the flank wear was a more dominant type of tool-wear in this case and hence crater wear was neglected. The dominance of flank wear has been pictorially shown in the Figure 3.10.

Also, since the tool change was governed by the change in dimensions of the 45° surface, flank wear was considered as the dominant form of wear.

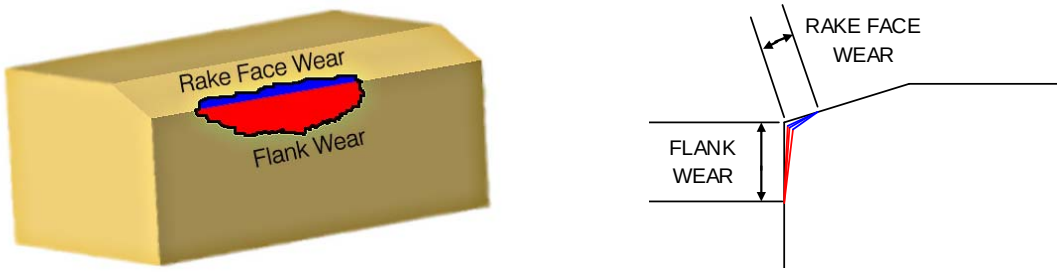
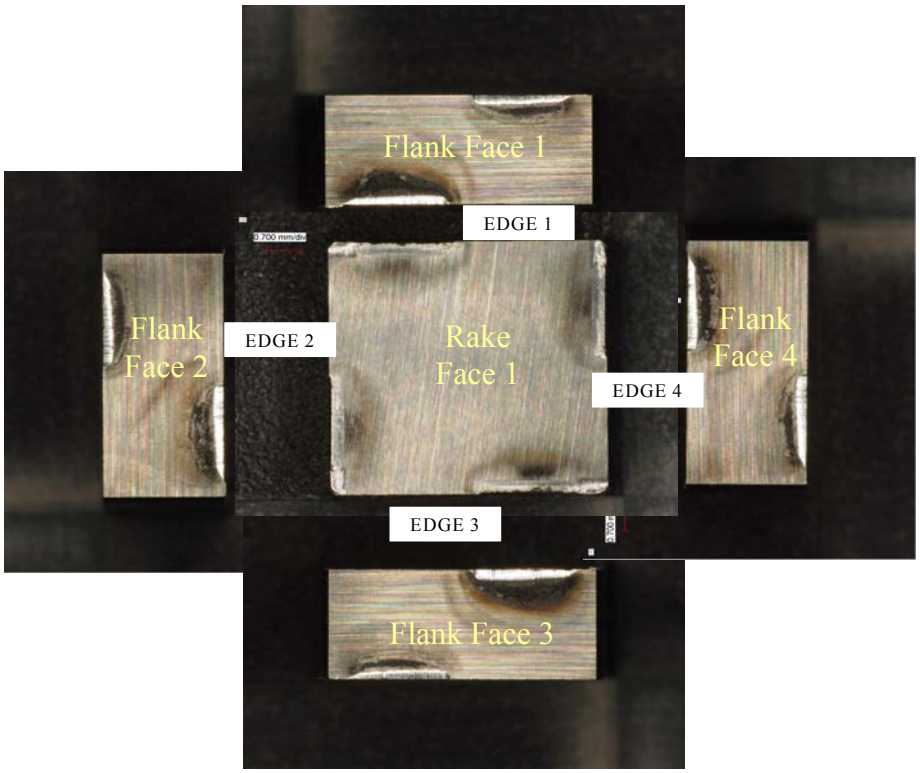


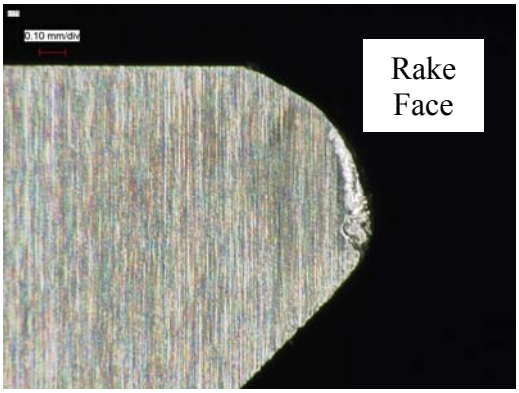
Figure 3.10: Dominance of Flank Wear over Rake Face Wear.

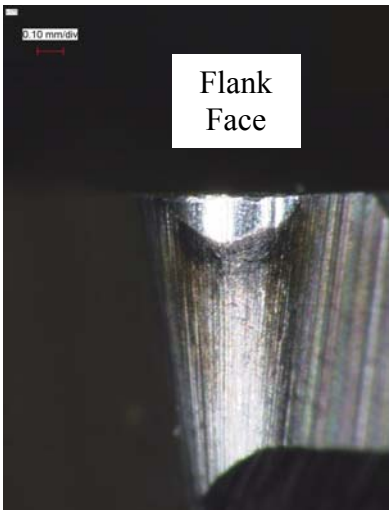
The observed general tool-wear patterns for the tools used to machine Ring A are shown in Figures 3.11 (a), (b) and (c). As can be noticed, 30° tool has eight cutting edges; 75° tool has four cutting edges, while the 45° tool has a single cutting edge.



(a) Wear Pattern for 30° Tool

(b) Wear Pattern for 75° Tool

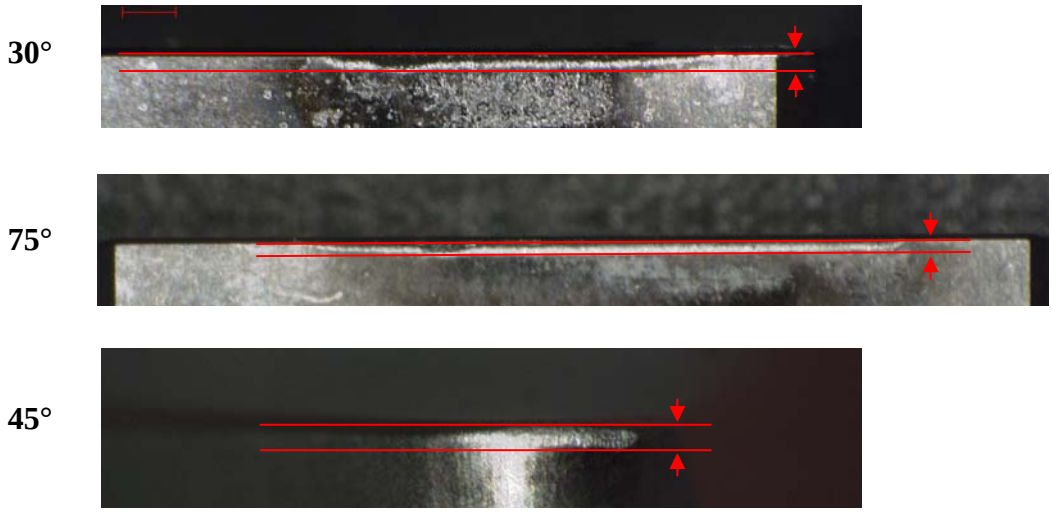




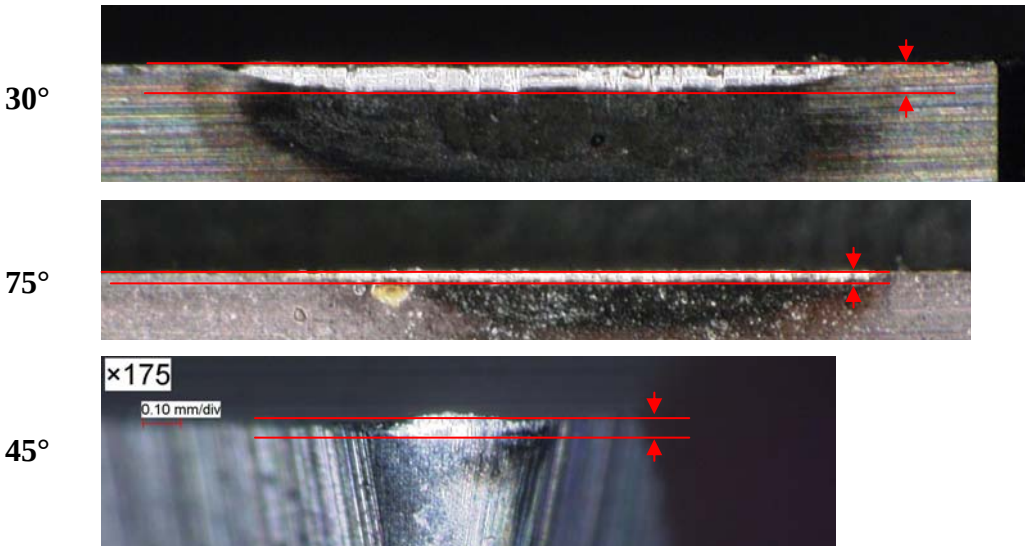
(c) Wear Pattern for 45° Tool

Figure 3.11: Observed General Wear Patterns for Tools Used in Machining of Ring A.

The dimensional accuracy criterion could have been considered as the tool-wear criterion, but difficulties arise when measuring the dimensions, and hence dimensional change is related with the measurement of tool-wear-land or the flank wear, which is easier to measure. Figure 3.12 shows the method of measuring tool flank wear on the tools used in machining Rings A and B.



(a) PCBN Tools



(b) Carbide Tools

Figure 3.12: Method of Flank Wear Measurement for PCBN and Carbide Tools.

After finalizing the experimental setup and developing the experimental procedure, the next step is to develop a tool-life model based on the collected experimental data. The following chapter introduces the machining performance measures and reviews the tool-life modeling techniques that have been published for flat-faced and grooved tools. It then explains the methodology for developing a tool-life model for the case under investigation.

CHAPTER 4

DEVELOPMENT OF TOOL-LIFE MODEL FOR PLUNGE CUTTING AND BORING OPERATIONS

4.1. Introduction to Machining Performance Measures

The primary goal of modeling of machining operations is to be able to quantitatively predict the performance of machining operations accurately. Modeling can facilitate effective planning of machining operations to achieve optimum productivity, quality and cost. According to Armarego et al. (2000), modeling can be classified into two distinct categories depending on the approach to study the process of machining, namely:

i. a direct experimental or 'empirical' approach to study and estimate the various technological performance measures and the effect of the influencing variables on the complex machining operations; and

ii. a fundamental or theoretical approach to study the scientific phenomena involved in the cutting process and develop mechanics of cutting models and analyses for the various technological performance measures for the highly simplified machining operations.

The machining performance can be classified as 'technological' and 'commercial'. The technological machining performance covers the aspects such as accuracy of shape, dimensions, surface roughness, surface integrity, etc.; whereas, the commercial machining performance covers the aspects such as machining time, cost, throughput time, defects, etc. The technological machining performance measures, directly or indirectly

affect the commercial machining performance measures. The technological machining performance is limited by a large number of variables involved in machining processes, which are shown in Figure 4.1 (Da et al., 1997).

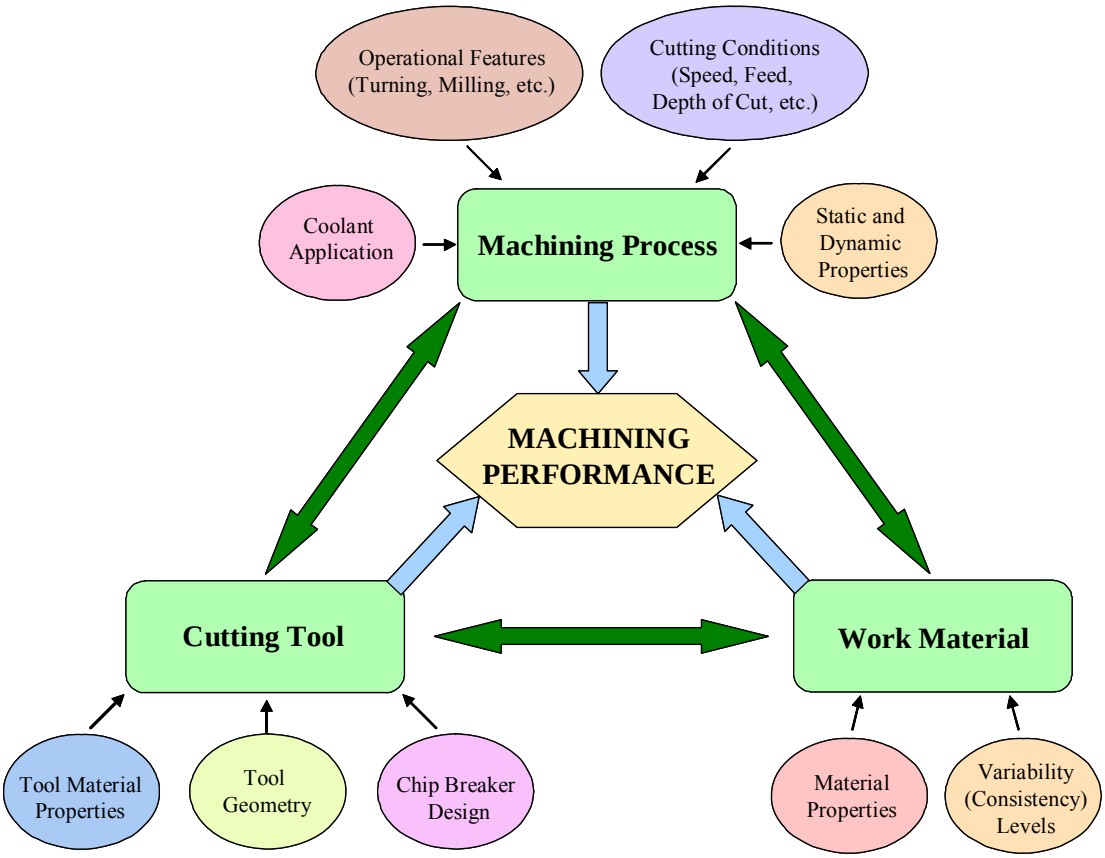


Figure 4.1: Factors Influencing Machining Performance Measures (Da et al., 1997).

Figure 4.2 shows the interrelationships of major technological performance measures (Wang et al., 2002). These major technological performance measures (tool-life/tool-wear, part accuracy, surface roughness, cutting force/power consumption, chip form/chip breakability) are related to the major operational variables (feed, speed and depth-of-cut) through empirical equations, the input data for which is obtained from experimentations.

According to a major CIRP study by van Luttervelt et al., (1998), the major hindrances in the modeling of machining operations are attributed to:

a. Lack of fundamental understanding of basic mechanisms and the interactions of cutting tools and the work material.

b. Great variety and complexity of real machining operations.

The desirability levels of these technological performance measures are given in Figure 4.3.

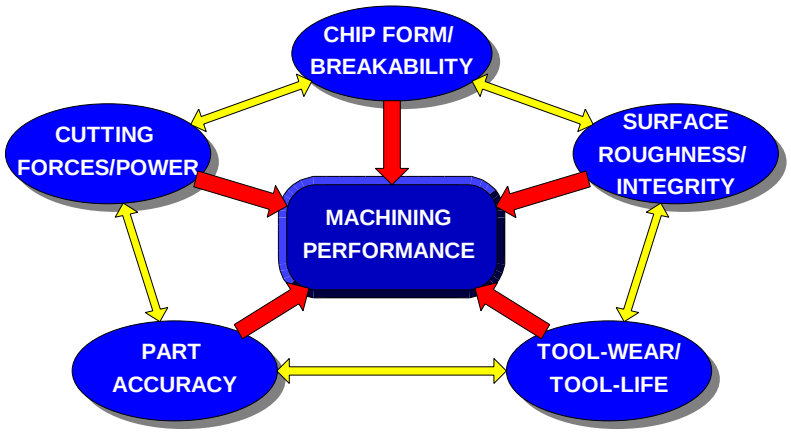


Figure 4.2: Machining Technological Performance Measures (Wang et al., 2002).

Machining Performance Measure	*Desired Level*
Cutting Forces/ Power/ Torque	Minimum
Tool-wear/ Tool-life	Minimum/ Maximum
Chip Form/ Chip Breakability	Disposable/ Maximum
Surface Roughness/ Surface Integrity	Minimum/ Maximum
Part Accuracy	Maximum

Figure 4.3: Desirability Levels of Technological Machining Performance Measures.

Due to the non-availability of adequate technological performance data, and the relevant equations, the development of the optimization strategies has been slow. Fortunately, with the advancements in computing technology, the complex optimization analyses and selection strategies can be developed and encoded in user-friendly computer application software. Fang and Jawahir (1994) performed a set of experiments in turning of AISI 4140 steel with a standard TMNA type cutting tool to obtain results illustrating the effects of nine different factors on machining performance measures. These factors are: cutting speed, depth-of-cut, feed rate, normal rake angle, inclination angle, tool cutting edge angle, nose radius, work material chemical composition and chip-breaker type. Some of these factors cannot be quantitatively evaluated by a single variable. It was observed from the results that all these factors affect machining performance measures in 42 different ways and at different rates and the relationships are too complex to be expressed as analytical functions. The variables influencing the complex machining system are shown in Figure 4.4 (Jawahir et al., 2003). According to a survey conducted by CIRP in 1998, 31% of the modeling efforts deal with turning, 24% with milling, 13% with drilling, 20% with single straight edge orthogonal cutting, and 9% with single straight edge oblique cutting (van Luttervelt et al., 1998).

Since currently available metal cutting theories are unable to explicitly represent all relationships between cutting conditions and machining performance measures, experiments were carried out to establish predictive relationships of the machining performance measures for boring and plunge cutting of powder metal steel rings.

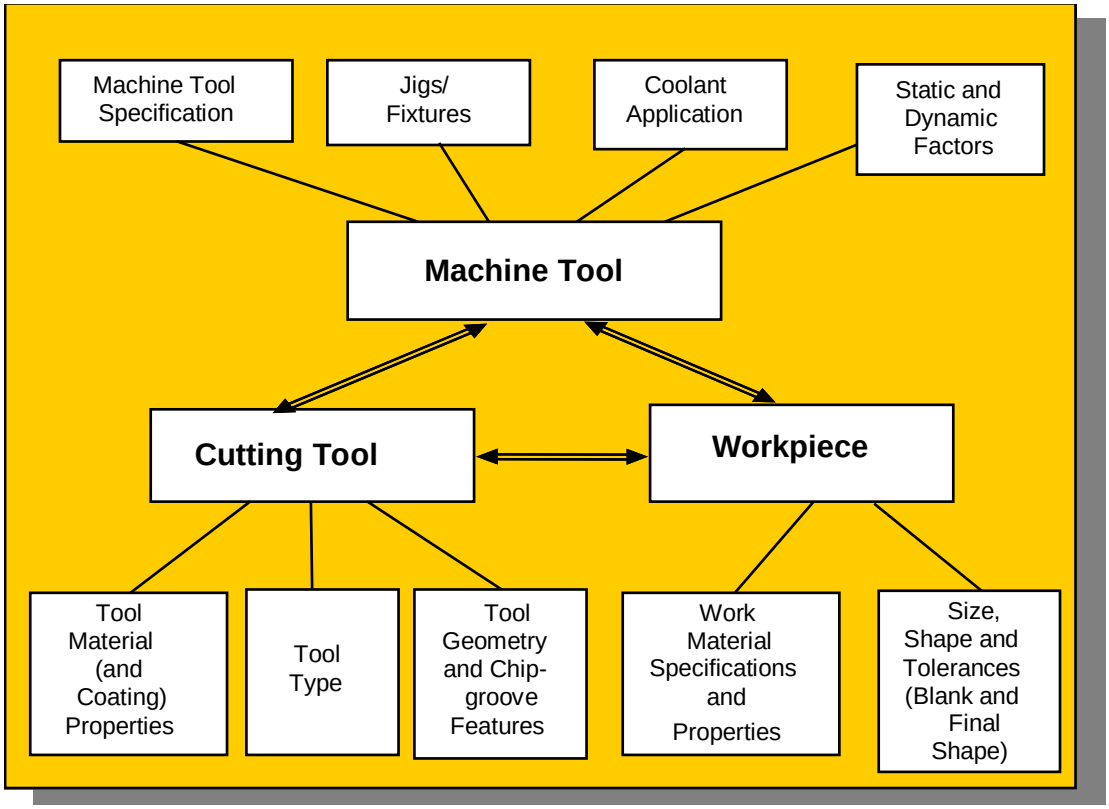


Figure 4.4: Variables Influencing the Complex Machining System (Jawahir et al., 2003).

4.2. Tool-wear/Tool-life

Tool-life is one of the most important economic considerations in metal cutting industry. Tool-wear and tool-life play an important role in process planning and machining optimization involving economic operations.

According to Armarego and Brown (1969), the effective end-of-life of the tool can be judged based on:

a. chipping or fine cracks developing at the cutting edge,

b. wear-land size on the clearance face,

c. crater depth, width or other parameters of the crater in the rake face,

d. a combination of (b) and (c),

e. volume or weight of material worn off the tool,

f. total destruction of the cutting tool,

g. limiting value of surface finish produced on the component,

h. limiting value of change in component size,

i. fixed increase in cutting forces or power required to perform a cut.

In finishing operations, the surface finish and dimensional accuracy are more critical, and the tool fails when the specified conditions can no longer be achieved. Although enormous research has been done to predict tool-life of cutting tools, there still seems to be a huge scope for further refinement in the accuracy of these models so as to meet the requirements of the metal cutting industry. Majority of the tool-life prediction equations developed until today have been empirical-based, and researchers are aiming at developing a universal prediction model devoid of empiricism.

4.2.1. Tool-wear Mechanisms

In today's automated industry era, it is most desirable to have the tool-life as long as possible. However, the complex machining conditions limit the tool-life, and hence the metal cutting industry would like to have a "fair prediction" of tool-life so as to insure timely tool changes for uninterrupted machining and to avoid significant loss of productivity. The tool fails due to complex tool-wear mechanisms. Following are the commonly known tool failure mechanisms which may occur simultaneously during the machining operations.

Adhesion wear mechanism: Adhesive wear is produced by the formation and subsequent shearing of welded junctions between two sliding surfaces. During machining, welded joints are formed between the tool and the workpiece due to the friction effects. When these joints fracture, small fragments of tool material get torn and carried away on the underside of the chip or the machined work surface.

Abrasion wear mechanism: Abrasive wear occurs due to the mechanical action of the underside of the chip rubbing against the tool face and thus removing the tool material particles.

Diffusion wear mechanism: Diffusion wear occurs when atoms in a metallic crystal lattice move from a region of high atomic concentration to one with low concentration region. Diffusion is a temperature-dependent process. In machining, where high temperatures are generated at the tool-workpiece interface, the atoms move from the tool material to the workpiece material.

Fatigue wear mechanism: Fatigue wear occurs when the tool is subjected to fluctuating cyclic loads. In machining, the chips formed during metal cutting can generate dynamic loading and unloading conditions on the cutting tool, eventually leading to fatigue failure of the tool.

Since these wear mechanisms may simultaneously contribute to tool-wear, it is difficult to determine the dominant form of wear mechanism during the machining process. Although, various tool-wear mechanisms exist, it is generally known that the gradual or the progressive tool-wear is produced by temperature-dependent mechanisms. Tools wear by the process of attrition on both rake and clearance faces and sometimes by chipping of the cutting edge. Studies of the tool flank wear have shown that the wear-land growth

follows three stages: initial wear, steady/progressive wear and severe/catastrophic wear, as shown in Figure 4.5. Numerous explanations for this behavior of the cutting tools have been put forward by a number of researchers, based on the various tool-wear mechanisms.

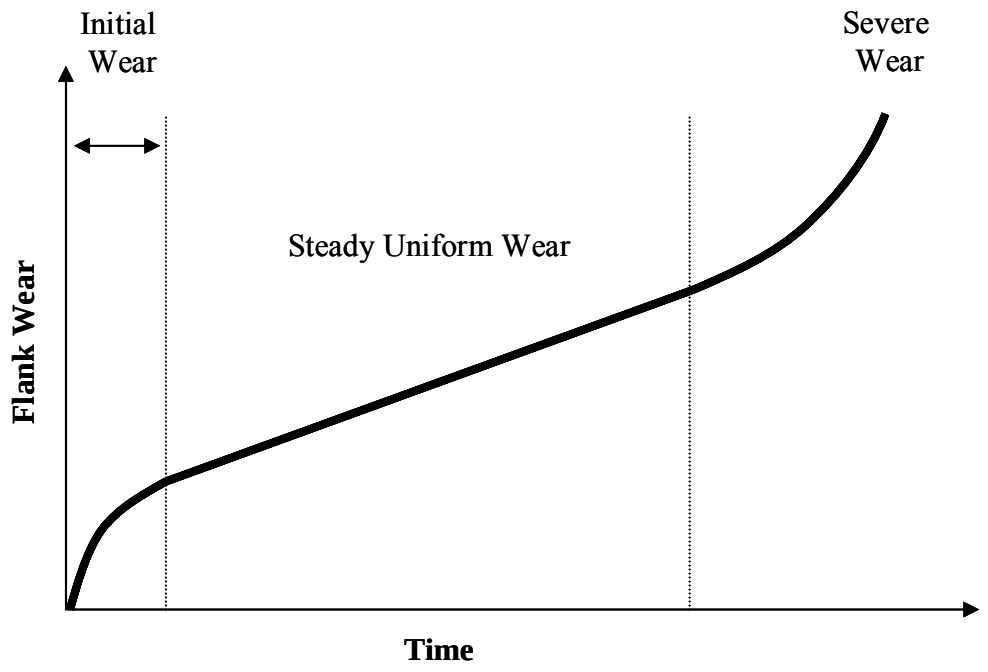
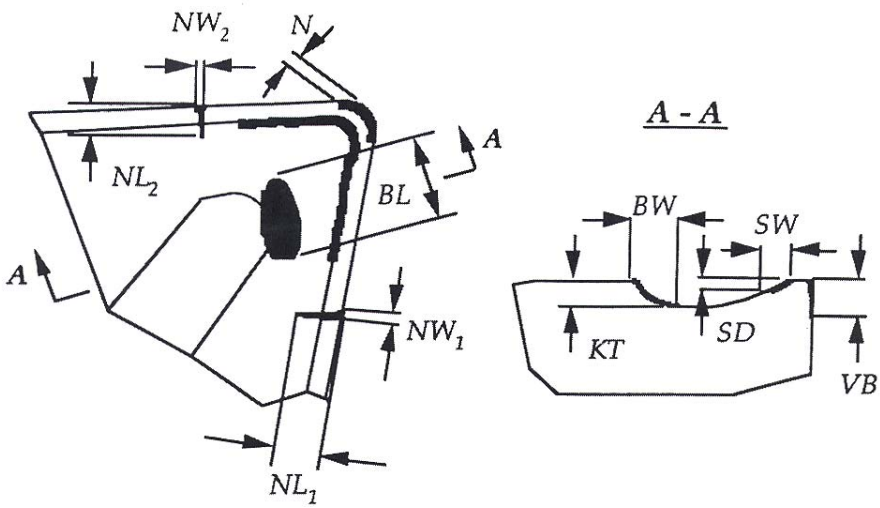


Figure 4.5: Three Stages of a Typical Tool-wear Curve.

The international standard on turning recognizes flank wear, crater wear, and notch wear as the major tool-wear parameters for determining the life of the uncoated flat-faced tool (ISO-3685, 1993).

However, Jawahir et al. (1995, 1997) have comprehensively identified 11 different wear parameters that can be measured on a worn out grooved cutting tool as shown in Figure 4.6.



VB	=	Flank wear
BW	=	Width of groove backwall wear
BL	=	Length of groove backwall wear
KT	=	Depth of groove backwall wear
SW	=	Width of secondary face wear
SD	=	Depth of secondary face wear
N	=	Nose wear
NL_1	=	Notch wear length on main cutting edge
NW_1	=	Notch wear width on main cutting edge
NL_2	=	Notch wear length on secondary cutting edge
NW_2	=	Notch wear width on secondary cutting edge

Figure 4.6: Measurable Tool-wear Parameters in a Grooved Tool for Turning (Jawahir et al., 1995, 1997).

The tool-wear mechanisms in machining with grooved tools are very complex in nature, which makes it difficult to develop an accurate predictive model. Also, it has been found through experiments that the grooved tools fail even before the flank wear reaches the tool-wear criterion. In many instances, the grooved tool fails due to unfavorable chip flow resulting from inappropriate chip-groove designs and selection of cutting conditions (Jawahir et al., 1995).

4.2.2. Tool-wear Criterion

Tool-wear criterion or the tool failure criterion is the set value of wear limit which is used to define the end-of-life of the tool. From the experimental point of view, the wear-land growth suggests that a fixed value of wear can be used as a tool failure criterion. However, the tool-wear criterion depends on the machining operation under consideration. From the tool geometry shown in Figure 4.7, the following equations can be derived,

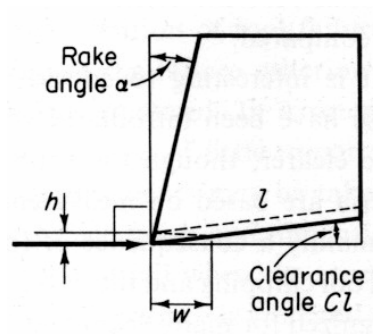


Figure 4.7: Flank Wear on the Clearance Face (Armarego and Brown, 1969*)*.

$$h = \frac{w \tan Cl}{1 - \tan\alpha \tan Cl} \tag{4.1}$$

$$W = \frac{bw^2 \tan Cl}{2(1 - \tan\alpha \tan Cl)} \tag{4.2}$$

$$W' \cong lbw \sin Cl \tag{4.3}$$

where,

h = Change in dimensional size (mm)

w = Wear-land size (mm)

α = Rake angle (degree)

Cl = Clearance angle (degree)

l = Nominal length (mm)

b = Width of cut (mm)

W = Volume of tool worn (mm^3)

W' = Volume of material to be ground to re-sharpen the tool (mm^3)

The wear-land size chosen as the tool failure criterion depends on the dimensional accuracy, surface finish, maximum permissible forces and the tool regrind costs. Hence, for finishing operations a small wear-land is chosen, while a larger wear-land is used for roughing operations. The major tool-wear criteria considered in machining operations, and their limitations are discussed below:

1. **Surface finish criterion:**
   - Requires complicated and portable surface analyzers.
   - The scatter in the surface finish values may require an increased number of observations.
2. **Dimensional-accuracy criterion:**
   - May be a practical proposition.
   - Difficulties can arise when measuring awkward dimensions.
3. **Force/Power criterion:**
   - A tool dynamometer, coupled to a data acquisition system is required.
   - Power indicators on the machine tool may also be used.

4.3. Tool-life Modeling Methodologies and Approaches

The major machining variables that affect tool-life performance are (Armarego and Brown, 1969):

(i) cutting conditions,

(ii) tool geometry,

(iii) tool material,

(iv) work material, and

(v) cutting fluid.

Initial efforts in developing an empirical tool-life equation is attributed to Frederick W. Taylor, who, based on large experimental observations, proposed a tool-life prediction equation in 1907 (Taylor, 1907). He found the cutting speed to be the most influential factor in determining the tool-life. He observed that high as well as low cutting speeds were undesirable, since the former led to frequent tool replacement, while the latter gave less productivity. This inspired him to develop a relationship between tool-life and cutting speed, described as,

$$VT^n = C_t \tag{4.4}$$

where,

T = Tool-life (min)

V = Cutting speed (sfpm)

C_t = Empirical constant equal to the cutting speed for one minute of tool-life

N = Empirical constant determined from the slope of log V Vs. log T

This equation can be represented by a straight line when plotted on logarithmic coordinates, as shown in Figure 4.8. From this, n is found from the slope and C_t is the intercept on the velocity axis when the tool-life is one minute.

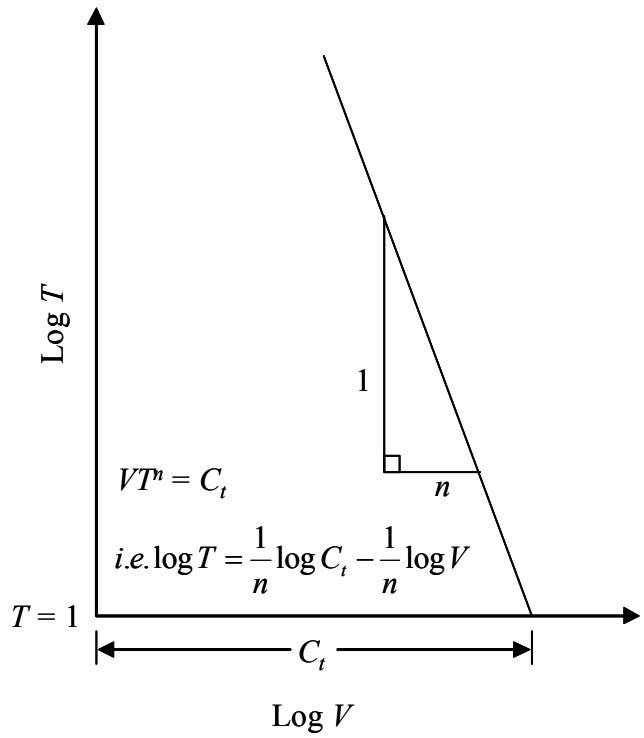


Figure 4.8: Graphical Representation of Taylor's Tool-life Equation (Armarego and Brown, 1969).

Based on Taylor's research, a large domain of specific knowledge has been acquired and many tool-wear/tool-life equations have been developed through analytical modeling and experimental observations.

A variation of Taylor's tool-life equation is written as (Boothroyd and Knight, 1989; Schey, 2000),

$$\left(\frac{V}{V_R}\right) = \left(\frac{T_R}{T}\right)^n \tag{4.5}$$

where,

T = Tool-life (min)

T_R = Reference tool-life (min)

V = Cutting speed (sfpm)

V_R = Reference cutting speed for tool-life T_R = 1 min

C, n = Empirical constants

An extended version of Taylor equation is usually considered a good approximation to predict tool-life T (Cook, 1973). It is expressed in terms of cutting speed V, feed f and depth-of-cut d, with empirical constants C, n, m, and l as (Da et al., 1998),

$$T = \frac{K}{V^{1/n} f^{1/n_1} d^{1/n_2}} \tag{4.6}$$

It has been suggested from experimental work and temperature analysis that the tool-life is directly related to the tool's temperature. The relationship between the tool-life and temperature is suggested by several researchers (Mills and Redford, 1983; Oxley, 1989; Arsecularatne, 2002), as:

$$\theta T^n = C \tag{4.7}$$

where,

θ = Tool temperature

C, n = Empirical constants

Colding (1959) used a dimensional analysis to suggest a tool-life relationship in which he considered tool-life to be a direct function of temperature. Furthermore, he included the

concept of equivalent chip thickness (ECT). His variation of tool-life equation is represented as,

$$y = K - \frac{(x-H)^2}{4M} - (N_0 - Lx)z \qquad (4.8)$$

where,

x = Equivalent chip thickness (ECT)

y = ln V

z = ln T

K, H, M, N_0 and L are empirically determined; feed, depth-of-cut, lead angle and nose radius are integrated into a single parameter ECT.

Efforts to include the geometry parameters into the basic Taylor equation (Equation 4.4) resulted into the following equation (Venkatesh, 1986),

$$T = CV^n f^m d^p r^q s^t i^u j^x \qquad (4.9)$$

The above equation is highly empirical, requiring excessive tool-life tests to determine the constants – C, n, m, p, q, t, u and x.

A number of investigators have also shown a relationship between the work material hardness and the tool-life. It is an extended version of Taylor's equation, including the cutting speed and the material hardness, and is represented as (Wang and Wysk, 1986; Hoffman, 1984),

$$V = \frac{C}{T^m f^y d^x (BHN/200)^n} \qquad (4.10)$$

where, the constants – C, m, y, x and n are determined experimentally.

All the tool-life equations discussed above are developed for flat-faced carbide tools and they rely on empiricism.

The tool-life prediction equation developed for a grooved tool incorporates the influence of chip-flow and coating effect on tool-life (Jawahir et al., 1995). In this work, the Taylor tool-life equation was modified by adding variables for the chip-groove effect and the coating effect factors.

$$T = T_R W_g \left(\frac{V_R}{V} \right)^{W_C \frac{1}{n}} \tag{4.11}$$

where,

$$W_c = n/n_c \tag{4.11 (a)}$$

$$W_g = \frac{km}{f^{n_1} d^{n_2}} \tag{4.11 (b)}$$

T = Tool-life (min)

T_R = Reference tool-life (min)

V = Cutting speed (sfpm)

V_R = Reference cutting speed for tool-life T_R = 1 min

W_g = Coating effect factor

W_c = Chip-groove effect factor

n = Taylor's tool-life exponent

n_c = Actual tool-life slope modified by the coating effect

m = Machining operation factor

n_1, n_2 and k are empirical constants.

Subsequently, Jawahir et al. (1997) developed and established a new methodology for determining tool-life in turning with coated grooved tools.

More recently, a novel tool-life equation for the CBN tools has been developed through experimentation. Experimental results show that the tool-life curve takes a dromedary shape when plotted against cutting speed while machining almost all ferrous metals. In the Figure 4.9, the curve 1 shows the continuous decrease of tool-life as function of cutting speed, v_c , i.e., the Taylor relation, however, in reality, curve 2 is more representative and occurs in every case of cutting ferrous materials with CBN tools (Mamalis et al., 2005).

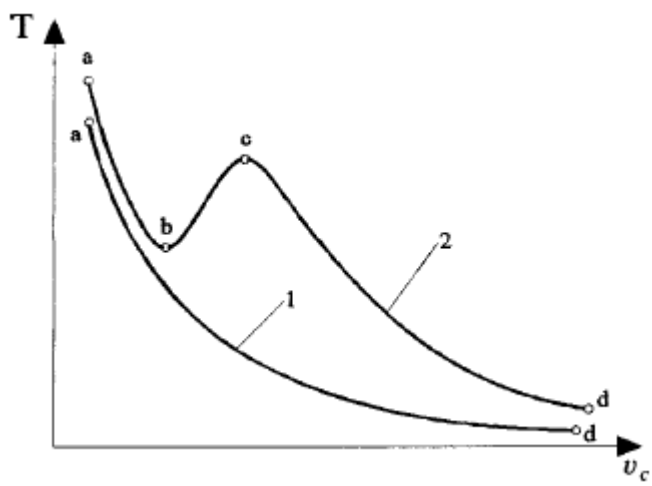


Figure 4.9: Comparison of Taylor Tool-life Curve and the Dromedary Tool-life Curve (Mamalis et al., 2005).

They also showed that the Taylor relation and other tool-life relations describe tool-wear only in a very narrow range of cutting speed, between v_{C12} and v_{C23}, as shown in Figure 4.10.

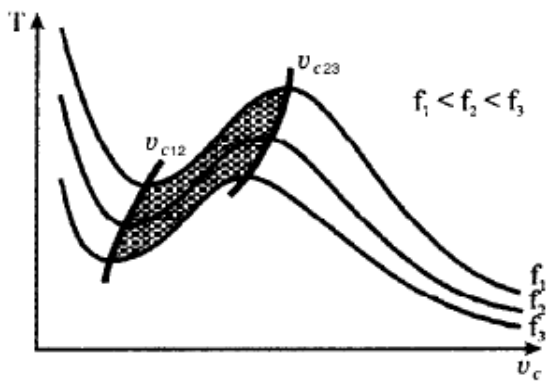


Figure 4.10: Typical Tool-life Curve for Ferrous Materials

(Mamalis et al., 2002, 2005).

Hence, a new relation for tool-life, which is valid in the whole cutting speed range, was presented as,

$$T = \frac{C_{T_1}}{V_c^{\,3} + C_{T_2} V_c^{\,2} + C_{T_3} V_c} \qquad (4.12)$$

where,

T = Tool-life (min)

V_c = Cutting speed (sfpm)

C_{T_1}, C_{T_2} and C_{T_3} are constants depending on cutting conditions, workpiece materials, tool material, geometry, etc.

Arsecularatne et al. (2006), in their recent study showed the dominant form of tool-wear mechanisms for tungsten carbide, PCBN and PCD tools, based on the experimental observations of various renowned researchers. They found that the dominant form of tool-wear mechanism for WC/steel tool-work material combination is diffusion, while for the PCBN/hardened steel, it is chemical wear. More experimental results and hence

further research is required to determine the dominant tool-wear mechanism for PCD/MMC tool-work material combination. For the PCBN/hardened steel material they concluded that the tool temperature and tool-life results can be very well represented by Arrhenius type wear rate equation,

$$\frac{dW_c}{dt} = D_c e^{-E_C / K_C T_f} \qquad (4.13)$$

where,

W_c = Mass loss due to chemical wear

dt = Time

T_f = Tool flank temperature

D_c, E_c and K_c constants.

Several major milestones have been achieved over the years, in the development of tool-life equations for machining processes. Cutting speed has been identified as the primary parameter affecting the tool-life, followed by feed and depth-of-cut. Hence, in studying the optimization of machining processes it is necessary to know the relationship between tool-life and cutting conditions.

4.4. Empirical Modeling of Tool-life for Current Investigation

For the problem being investigated here, a set of progressive tool-wear experiments were conducted in the initial part of the study. The objective of the progressive tool-wear experiments was to,

1. study the tool-wear pattern,

2. establish the tool-wear criterion, and
3. determine if tool had the potential to perform beyond its current capacity.

Based on these experiments, it was observed that the tool-wear curve was fairly linear up to the tool-wear criterion. This could be explained, since in production machining operations the manufacturers tend to build in a factor of safety into the tool-life, so as not to produce any defective components. It is more economical for them to under-utilize the tools, rather than to produce defective parts. Manufacturing companies prefer a shorter, but known/predictable tool-life, rather than a longer and unpredictable tool-life performance. This helps them to schedule timely tool changeovers.

The OEM maintained a set value for the life of the tools, after which the tools were replaced with new ones, independent of whether or not the tool had reached its total end-of-life or not. The progressive tool-wear for Rings A and B was recorded for six data points. For Ring A, the tool was removed and tool-wear was measured after every 150 parts until it reached its end-of-life of 900 parts. Whereas for Ring B, the tool-wear was measured at a regular interval of 300 parts until it reached its end-of-life of 1800 parts. The tool-wear criterion was established at 900 parts for Ring A and at 1800 parts for Ring B.

The behavior of the tool-wear curve helps to identify the type of tool-life equation that can be used for any particular application. Once the rate of tool-wear at the OEM's production facility was known, a baseline experiment was conducted in the laboratory to

see if the tool-wear pattern obeys that of the production facility. Up to 600 parts were machined for Ring B and 300 parts for Ring A. Due to the amount of time required to machine each part individually and the limitation of the availability of the number of parts, full life of the tools could not be tested in the laboratory. The tool-wear pattern for the baseline experiment showed similar trend to that of the progressive tool-wear tests conducted at the OEM's shop floor.

The absolute values of the tool-wear varies for the laboratory experiments when compared with the shop floor values because the dynamic conditions of the machines being used in the lab and the shop floor are different. The machine in the lab is newer, well maintained, more stable and rigid compared to the machine on the shop floor which runs continuously in order to meet the production requirements.

After the baseline experiment was conducted, the actual experiments with varying cutting conditions were performed. Full factorial experiments were conducted to study the influence of speeds and feeds on the behavior of tool-wear. The depth-of-cut was maintained constant for all experiments.

Since the tool-life curve for these experiments was observed to be linear, the tool-life equation that has been used here is,

$$w = k + \gamma P' \tag{4.14}$$

or, $$P' = \frac{w - k}{\gamma} \tag{4.15}$$

where,

w = Tool-wear criterion (mm)

P' = Tool-life/Parts machined per experiment up to tool-wear criterion (parts)

k = Intercept on wear axis (mm)

γ = Slope of wear curve

The wear value for each data point is plotted on the graph of wear Vs. number of parts. Considering the wear curve as linear, the slope and the intercept for the curve are obtained. From the slope and the intercept values, maximum number of parts that can be machined with the given cutting conditions are predicted until the tool-wear criterion. Similar methodology for determining the tool-life has been suggested by Armarego and Brown (1969), as shown in Figure 4.11.

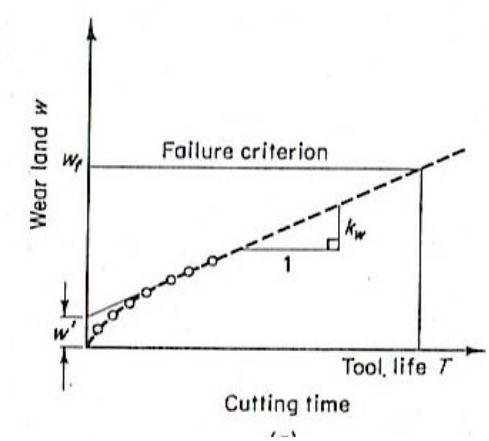


Figure 4.11: Methodology for Determining Tool-life (Armarego and Brown, 1969).

The tool-life can be determined using the Equation (4.16),

$$T = \frac{w_f - w'}{k_w} \tag{4.16}$$

where,

T = Tool-life (min)

w_f = Tool-wear criterion (mm)

w' = Wear-land intercept (mm)

k_w = Slope of wear curve

This procedure is repeated for all 16 experiments. This method thus gives P_1 through P_{16}, or the maximum number of parts that can be predicted per each experiment. Once the values of P_1 through P_{16} are obtained, the following equation is used to evaluate the optimized cutting conditions for maximum tool-life or minimum tool-wear.

$$P = CN^{\alpha} f^{\beta} \tag{4.17}$$

where,

P = Maximum predicted parts per each experiment (P_1 through P_{16}) (parts)

N = Speed (rpm)

f = Feed (mm/rev)

C, α and β are constants.

A first order multiple regression analysis method is then applied to obtain the values of the empirical constants.

After understanding the tool-wear pattern, developing an empirical prediction model for tool-life, conducting experiments and collecting tool-wear data, the next logical step towards improving the process efficiency and economics was to develop an optimization program to determine the optimum cutting conditions that can provide improved

machining performance measures (tool-life, surface roughness, etc.). The next chapter discusses the optimization techniques used for machining operations and the development of optimization program for the case under investigation.

CHAPTER 5

OPTIMIZATION OF CUTTING CONDITIONS FOR MAXIMUM TOOL-LIFE IN BORING AND PLUNGE CUTTING OPERATIONS

5.1. Introduction

After conducting the machining experiments and developing the empirical models, the next logical step towards improving process efficiency is to optimize the machining parameters to achieve the desired objective. This sequence is shown in Figure 5.1. Figure 5.2 shows the well-established three phases in predictive modeling of machining operations for practical applications. The third or the final phase for any successful modeling approach would be to determine the optimal process conditions.

The actual cutting conditions used in everyday metal cutting applications are rarely optimal. This is largely due to the lack of relevant information about the machining performance measures and how they relate to cutting conditions. The practical tendency to use recommended rather than optimal conditions has been shown to result in substantial penalties in production rates and costs per component which should be eliminated in the modern capital-intensive automated machining systems with higher proportions of productive time utilization (Armarego et al., 2000). Therefore, efforts should be made to achieve optimum machining conditions if a better product is desired at higher productivity and lower costs.

This chapter describes the development of an objective function for optimization and then presents the optimization results for plunge cutting and boring operations.

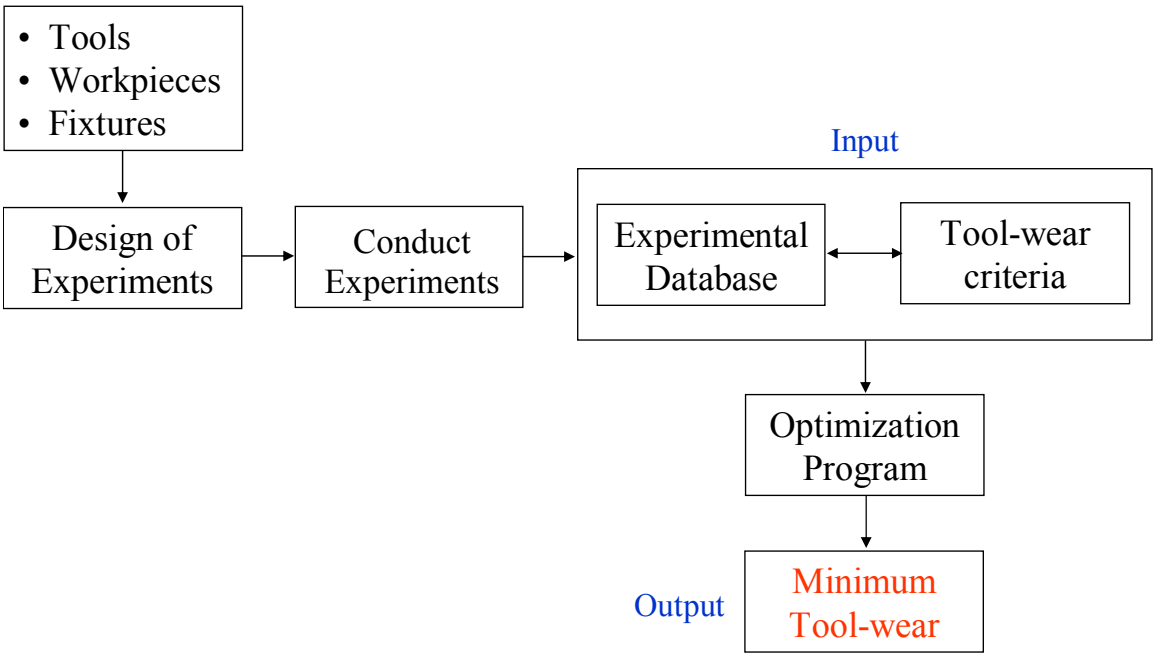


Figure 5.1: Logical Sequence of Approach toward Machining Process Optimization for Minimum Tool-wear.

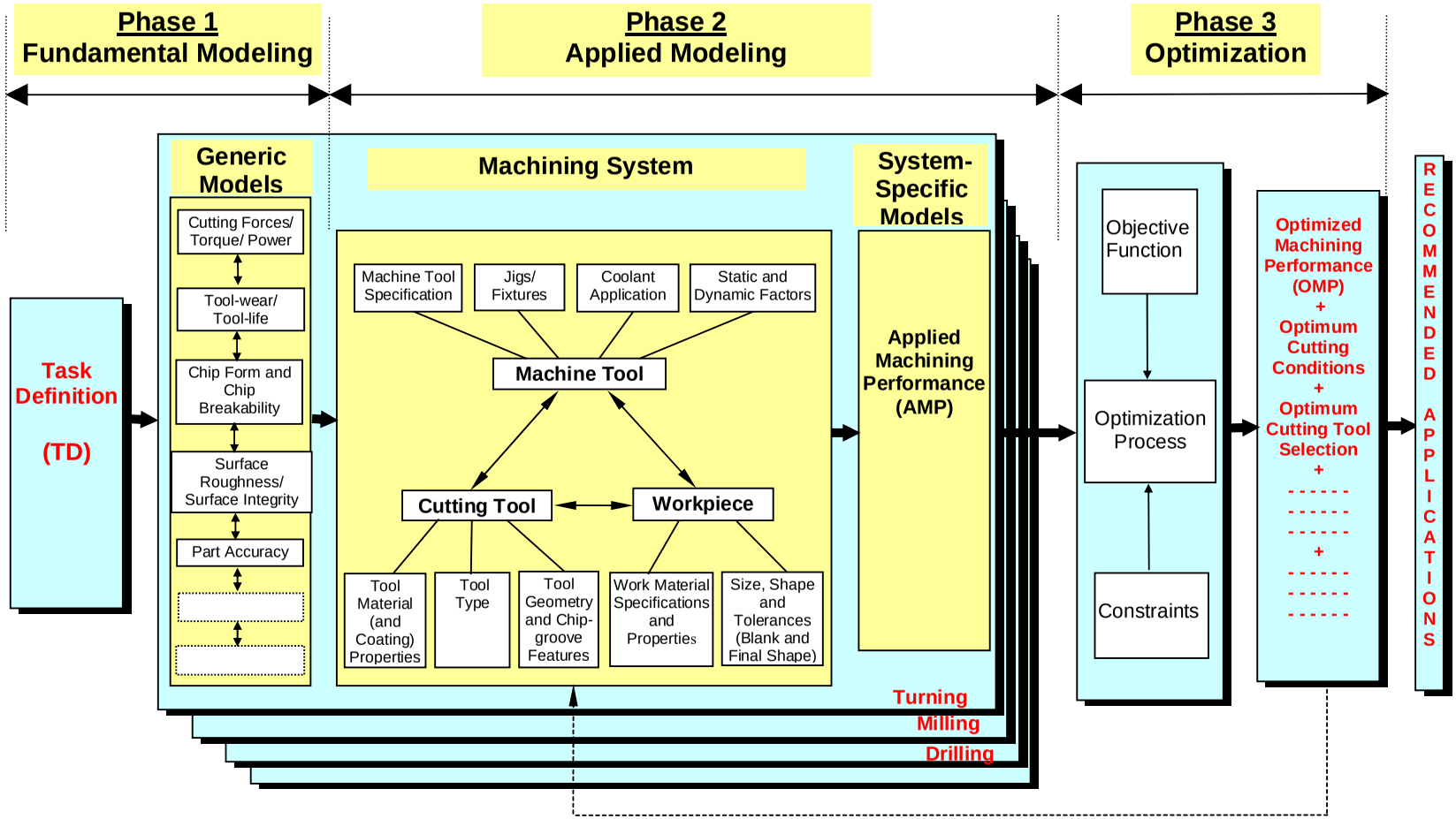


Figure 5.2: Three Phases of Predictive Modeling for Machining Operations (Jawahir et al., 1997).

5.2. Optimization Techniques Used for Machining Operations in the Past

Optimization methods in metal cutting processes have been widely used in the manufacturing industries for continual improvement of machining processes and the output quality of the machined products. However, determination of optimal cutting conditions through cost-effective mathematical models is a complex research endeavor, and over the years, the techniques of modeling and optimization have undergone substantial development and expansion (Mukherjee and Ray, 2006). Most machining experimental procedures, at some time during their development, have been subjected to optimization. More than likely this optimization procedure has been the old one-factor-at-a-time method. The primary challenge for machining process optimization often stems from the fact that the procedure is typically highly constrained and highly non-linear, involving mixed integer-discrete-continuous design variables (Zhang et al., 2006). A large number of optimization techniques have been developed by researchers to determine optimal cutting conditions for machining operations. These may be classified as (Mukherjee and Ray, 2006):

a. conventional optimization techniques, and

b. non-conventional optimization techniques

Figure 5.3 shows the classification of the optimization techniques used in the area of metal cutting.

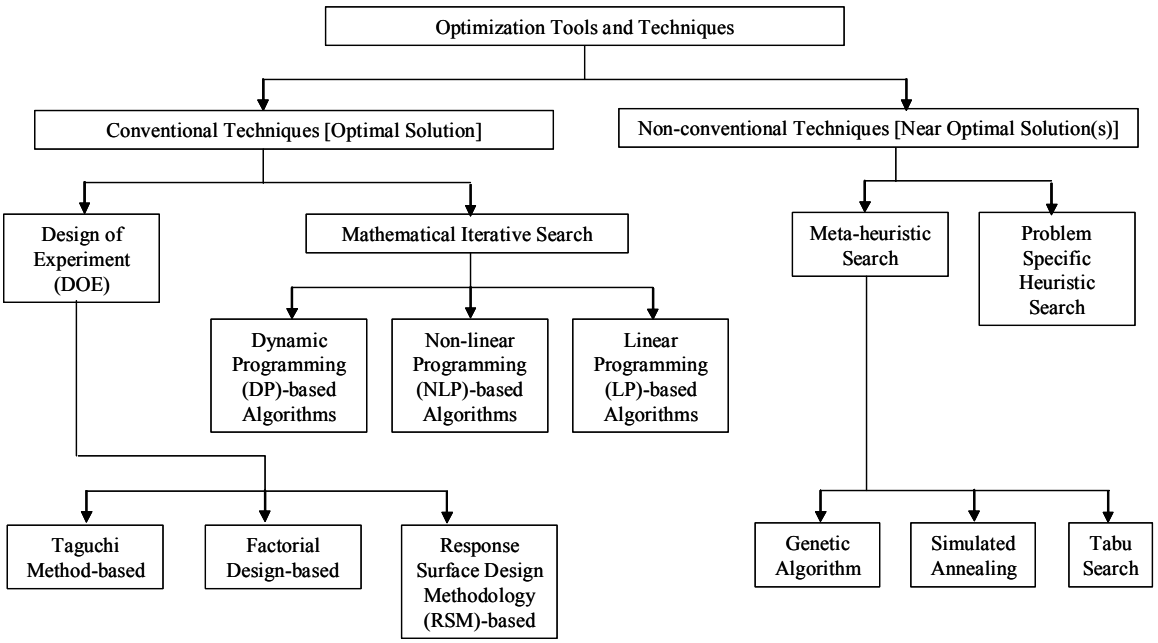


Figure 5.3: Classification of Optimization Techniques in Metal Cutting Processes (Mukherjee and Ray, 2006).

5.2.1. Traditional Algorithms in Optimization of Turning

Traditional mathematical programming techniques such as linear programming, integer programming, dynamic programming and geometric programming have been long used to solve machining optimization problems. Extensive literature exists on optimization of machining processes largely focusing on maximum production rate and minimum cost (Ermer, 1997). Gilbert (1950) studied the optimization of machining parameters in turning with respect to maximum production rate and minimum production cost as criteria. Linear programming was used in the early stage of machining process optimization (Ermer and Patel, 1974), but it can only deal with the linear equations. Geometric Programming (GP) has also been widely adopted (Ermer, 1972; Eskicioglu et al., 1985; Gopalakrishnan and Al-Khayyal, 1991). Its major disadvantage is its

requirement that the objective function and constraints must be in the polynomial form. Non-linear programming (NLP) has been extensively applied for more general non-linear machining optimization problems. For example, the successive quadratic programming (SQP) method (Wen et al., 1992) and an iterative Newton's method (Xiao et al., 1992) were applied to optimize grinding processes; while the generalized reduced gradient (GRG) method (Jha and Hornik, 1995) was used to optimize tool geometry and cutting condition in plain milling processes. Da et al. (1997, 1998) and Sadler et al. (1998, 1999) have used NLP techniques for turning operations. Agapiou (1992) used a dynamic programming model to determine the optimum value of the objective function (weighted sum of production cost and time) and the number of passes.

5.2.2. Non-traditional Algorithms in Optimization of Machining Operations

Traditional optimization techniques are mostly gradient-based, and they pose many limitations in application to today's complex machining models. They cannot deal with integer/discrete design variables as integer design variables have to be approximated from continuous values. Hence, many new algorithms based on random search techniques are being used in solving machining optimization problems. These algorithms are called non-traditional algorithms. Genetic algorithms (GA), simulated annealing (SA) and ant colony optimization (ACO) are some of the non-traditional algorithms used for optimization problems.

Several of the recent optimization techniques used for metal cutting applications have been compiled in the Table 5.1 (Mukherjee and Ray, 2006; Aggarwal and Singh, 2005).

Table 5.1: Review of Recent Optimization Techniques Used for Machining Operations.

Modeling and Optimization Approaches	Application Areas (As Reported in Literature)	Number of Objective Function(s) Considered	Number of Operational Stage(s) Considered	Remarks
Statistical Regression	Lathe turning (*Hassan & Suliman, 1990*)	one	one	none
	Finished turning (*Feng & Wang, 2002*)	one	one	fractional factorial design
	Turning overlays (*Brozek, M., 2005*)	one	one	none
Artificial Neural Network (ANN)	Creep feed grinding (*Sathyanarayan et al., 1992*)	three	one	GRG method
	Abrasive flow machining (*Petri et al., 1998*)	two	one	none
	Honing (*Feng et al., 2002*)	five	one	paired t-test and F-test
	Turning (*Zuperl & Cus, 2003 & 2006*)	three	one	none
	Turning (*Zuperl et al., 2004*)	three	one	ANN and OPTIS routine
Fuzzy Set Theory	End milling (*Ip, 1998*)	two	one	none
	Down milling (*Al-Wedyan et al., 2001*)	one	one	surface plot
Taguchi Method	Lathe turning (*Youssef et al., 1994*)	one	one	full factorial design
	Turning (*Yang & Tarng, 1998*)	two	one	S/N ratio, ANOVA
	Turning (*Hong & Lian, 2001*)	one	one	S/N ratio, ANOVA and F-test
	Face milling (*Lin, 2002*)	three	one	none

	Surface grinding (*Shaji and Radhakrisnan, 2003*)	two	one	none
	Turning (*Davim, 2003*)	three	one	multiple regression, orthogonal array, ANOVA
	End-milling (*Ghani et al., 2004*)	two	two	Orthogonal Array, S/N ratio, Pareto ANOVA
	Turning (*Singh & Kumar, 2006*)	four	one	ANOVA, S/N ratio
Response Surface-design Methodology (RSM)	Finish turning (*Taramen, 1974*)	three	one	central composite model
	Turning (*Lee et al., 1996*)	two	one	simulation method
Mathematical Iterative Search Algorithm	Turning (*Arsecularatne et al., 1992*)	one	one	direct search
	Multi-pass turning (*Tan and Creese, 1995*)	two	our	lagrange multipliers
	Turning (*Agapiou, 1992*)	one	one and two	Nelder-Mead simplex algorithm; dynamic programming
	Multi-pass turning (*Tan and Creese, 1995*)	one	three	sequential linear programming
	Milling (*Tolouei-Rad & Bidhendi, 1997*)	three	one	method of feasible directions
	Turning (*Da et al., 1997*)	one	one	NLP
	Turning (*Prasad et al., 1997*)	one	one	geometric and linear programming
	Finish turning (*Da et al., 1998*)	five	one	NLP, feasible search direction using exterior penalty function
	Finish turning (*Sadler et al., 1998, 1999*)	five	one	NLP, SQP

	Turning (*Cakir & Gurarda, 1998*)	one	two	dynamic programming and feasible direction search
	Turning (*Choudhury & Rao, 1999*)	one	one	penalty function method, Cauchy Steepest Ascent
	Turning (*Meng et al., 2000*)	one	one	direct search, machining theory
	Face milling (*Baek et al., 2001*)	one	one	bi-section method
	Face milling (*Wang & Armarego, 2001*)	one	one	none
	Turning (*Sarfaraz, 2004*)	two	one	goal programming
Genetic Algorithm (GA)	Turning (*Khan et al., 1997*)	one	one & two	GA, SA, CSA
	Milling (*Liu & Wang, 1999*)	one	one	none
	Milling (*Shunmugam et al., 2000*)	one	three	GA
	Multi-pass turning (*Onwubolu &Kumalo, 2001*)	one	two	SA, LP, and fuzzy set
	Multi-pass turning (*Wang & Jawahir, 2002*)	five	two	GA
	Turning (*Suresh et al., 2002*)	one	one	RSM, GA
	CNC turning (*Cus & Balic, 2003*)	three	one	none
	Contour turning (*Saravanan et al.,2003*)	one	three	none
	Face milling (*Wang et al., 2004*)	five	three	Taguchi method, GA
	Milling (*Baskar, N. et al., 2005*)	one	one	SA, GA, TS, continuous ACO
	Milling (*Wang, Z.G., et al., 2005*)	one	two	parallel GSA

	Milling (*Reddy & Rao, 2005*)	one	one	Taguchi, RSM, GA
	Grinding (*Zhang et al., 2006*)	one	one	GA, MIEA
	Turning (*Satishkumar, S. et al., 2006*)	one	two	SA, GA, ACO
	End milling (*Reddy & Rao, 2006*)	one	one	Taguchi, RSM, GA
	Multi-tool milling (*Baskar et al., 2006*)	three	one	GA, hill climbing, memetic algorithm
Simulated Annealing (SA)	NC multi-pass turning (*Chen & Tsai, 1996*)	one	two	Hookes and Jeeves pattern search
	Drilling (*Lee et al., 1998*)	two	one	SA
	CNC cylinder stock turning (*Chen & Su, 1998*)	one	four	none
	Continuous Turning (*Su & Chen, 1999*)	one	two	Hookes and Jeeves pattern search, SA
	High speed milling (*Juan et al., 2003*)	one	one	SA, polynomial network
	End-milling (*Juan et al., 2003*)	one	one	RSM, SA
Tabu Search (TS)	Drilling (*Kolahan & Liang, 1996*)	one	one	none

As can be seen from the above table, a variety of optimization techniques dealing with linear/non-linear, unconstrained/constrained, convex/non-convex, etc., have been employed to determine optimum cutting conditions for machining operations. The purpose of these techniques is to locate a global optimum in a reasonable amount of time. For highly non-linear, non-convex problems, multiple feasible regions and multiple local optimal points, within these regions, exist. Hence, a robust technique such as exhaustive enumeration needs to be utilized so as to ensure that the global optimum does not escape. The following section covers the exhaustive enumeration technique as applied to the current investigation.

5.3. Optimization Methodology Used for Current Investigation

5.3.1. Exhaustive Enumeration/Search Algorithm

One of the oldest approaches to problem solving with the help of computers is brute-force enumeration and search. It generates and inspects all data configurations in a large state space that is guaranteed to contain the desired solution(s). The best solution is obtained by scanning the list of feasible solutions in the above investigation for the maximum value. Although exhaustive search is conceptually simple and often effective, such an approach to problem solving is sometimes considered inelegant. The continuing increase in computing power and memory sizes has revived interest in brute-force techniques for a good reason (Nievergelt, 2000). However, the problem with the exhaustive enumeration technique is that it can be used only for a limited set of variables, since the effort required to examine all possible solutions involves large amounts of computation. Nevertheless,

the best optimization technique is complete or exhaustive enumeration (Venkataraman, 2001).

5.3.2. Generic Algorithm for Exhaustive Enumeration

A generic methodology (Venkataraman, 2000) to solve an optimization problem using the exhaustive enumeration technique has been described in this section. Objective function f is to be minimized with respect to the variables X, Z and Y, given the constraints h and g. This methodology employs a nested loop iterative function using If…End logical operators. The objective function is evaluated for every allowable combination of the variables and checked against the constraint, to verify if its value has been minimized. The objective function evaluation strategy using exhaustive enumeration technique is given below.

$f^* = \inf$, X = [0, 0, …, 0]

For every allowable combination of (y_1, y_2, …, y_{nd}) => (Y_b)

Optimization problem:

Minimize: f(X, Z), $[X]_{n_C}$;$[Z]_{n_Z}$

Subject to: h(X, Z) = [0]; $[h]_l$

g(X, Z) ≤ [0]; $[g]_m$

$x_i^l \le x_i \le x_i^u;\ i = 1, 2, \ldots, n_c$

$z_i \in Z_{d_i};\ [Z_{d_i}]_{z_i}$

If h(X^*, Y_b) = [0] and

If g(X^*, Y_b) = [0];

If f(X^*, Y_b) < f^*

then, $f^* \leftarrow f(X^*, Y_b)$

$X \leftarrow X^*$

$Y \leftarrow Y_b$

End If

End If

End If

End For

5.3.3. Formulation of Optimization Problem for Current Investigation

The objective of this investigation is to maximize the number of parts that can be machined before the cutting tool reaches its end-of-life. In other words, optimum values of cutting parameters (cutting speed and feed) need to be found which will maximize the number of parts that can be machined with a single tool, without exceeding the stipulated cycle time allocated to the machining station. Hence the objective function here is to maximize the number of parts, variables are speed and feed, and the constraint is the cycle time and the variables themselves. This is formulated in a mathematical form below.

Objective function: Maximize $P = CN^{\alpha} f^{\beta}$

where, regression coefficients - C, α, β are determined from the equation, $w = k + \gamma P'$

P' = number of parts per each experiment

w = tool-wear criterion (mm)

N = speed (rpm)

f = feed (mm/rev)

Subject to:

$$\Delta t = \Delta t_p + \Delta t_b \leq 0.7 \text{ (sec)}$$

$$-10\% N_c \leq N \leq +10\% N_c \text{ (rpm)}$$

$$-10\% f_c \leq f \leq +10\% f_c \text{ (mm/rev)}$$

where,

N_c = current speed (rpm)

f_c = current feed (mm/rev)

t_p = cutting time for plunge operation

t_b = cutting time for boring operation

A generic flowchart for the optimization program is shown in the Figure 5.4.

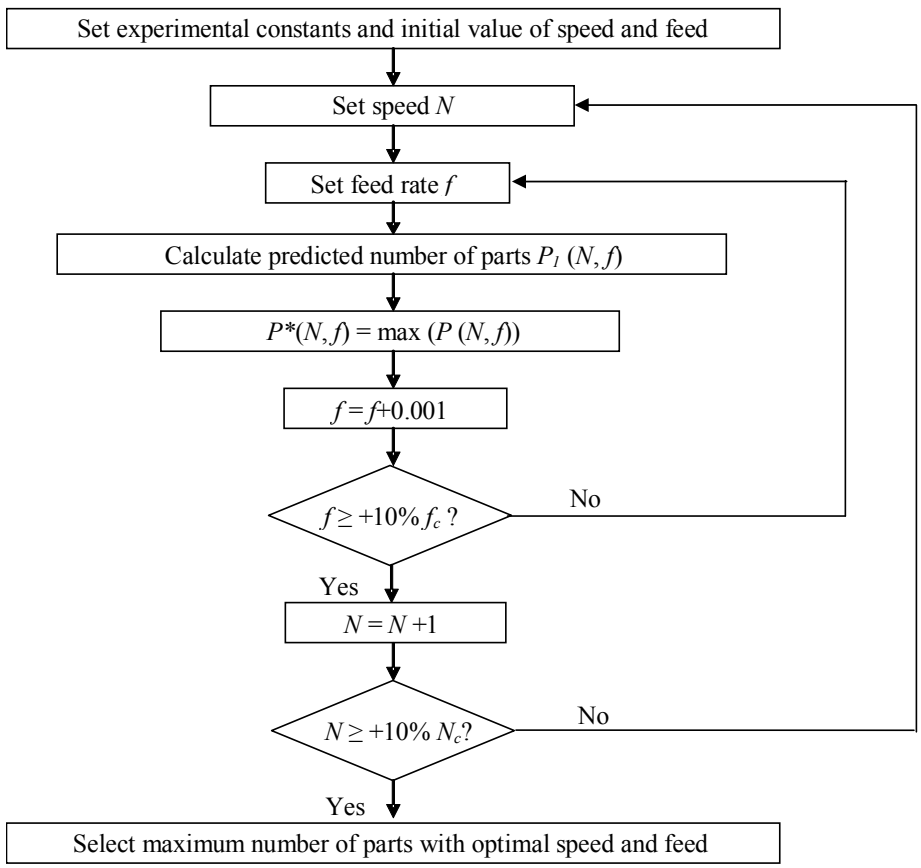


Figure 5.4: Generic Flowchart Depicting the Proposed Optimization Strategy.

5.4. Experimental Results

The following section presents and discusses the results obtained from the optimization of cutting conditions for plunge cutting and boring of powder metal steel, when using carbide and PCBN tools under flood-cooling condition.

5.4.1. PCBN 30° Insert

Table 5.2 shows the factors – speed and feed, and their levels considered in designing the experiments. Table 5.3 shows the entire set of 16 experiments.

Table 5.2: PCBN 30° - Factors and Their Levels Selected for Experimentations.

Level / Parameter	1	2	3	4
Speed (rpm)	1296	1368	1512	1584
Feed (mm/rev)	0.063	0.066	0.073	0.076

Table 5.3: Design of Experiment for PCBN 30° Insert.

30° (PCBN)		
Expt #	**RPM**	**mm/rev**
1	1296	0.063
2	1296	0.066
3	1296	0.073
4	1296	0.076
5	1368	0.063
6	1368	0.066
7	1368	0.073
8	1368	0.076
9	1512	0.063
10	1512	0.066
11	1512	0.073
12	1512	0.076
13	1584	0.063
14	1584	0.066
15	1584	0.073
16	1584	0.076

Table 5.4 shows the measured values of progressive flank wear for three inserts at regular intervals of parts. The progressive wear tests were conducted at the OEM's shop floor. The tool tips are changed after 1800 parts are machined. The value of the wear at the end of 1800 parts, determines the tool-wear criterion.

Table 5.4: Measured Progressive Flank Wear Values for PCBN 30° Insert.

	Flank Wear (mm) for Corresponding Number of Parts					
Parts / Tool #	**300**	**600**	**900**	**1200**	**1500**	**1800**
1	0.0195	0.0398	0.053	0.0553	0.0884	0.0917
2	0.0243	0.0418	0.0464	0.0619	0.0752	0.0859
3	0.0265	0.0309	0.0464	0.0619	0.0752	0.0859

To compare the wear pattern of the tools at the University of Kentucky's Machining Research Laboratory, with that of the progressive tool-wear tests, a baseline experiment was ran at the same cutting conditions as that of the OEM's production shop floor. The values of the flank wear measured for the laboratory conditions are shown in Table 5.5.

Table 5.5: PCBN 30° Insert - Flank Wear Values for Baseline Experiment.

Parts / Tool #	**300**	**450**	**600**
1	0.0177	0.0270	0.0350

A comparison plot has been developed to compare the wear trend for the OEM and the laboratory conditions, as shown in Figure 5.5. The wear curve for the OEM condition over the total life of the tool, 1800 parts, is observed to be linear. In the laboratory, 600

parts were machined and the wear curve was extrapolated up to the tool-wear criterion, and compared with the wear curve for the progressive tool-wear tests. The amount of time and the availability of work material limited the number of parts that could be machined in the laboratory to verify the tool-wear behavior for the lab and the production shop floor conditions. Also, no repetitions were performed due to aforementioned difficulties. However, extensive wear measurements were taken painstakingly to eliminate/reduce errors in measurements. From this comparison plot it can be observed that even though the wear values for lab conditions are less compared to the OEM wear values, when the wear curve is extrapolated, the lab condition gives a little less number of parts for the same condition. Hence, a compensation factor was included in the optimization program to compensate for this loss of parts.

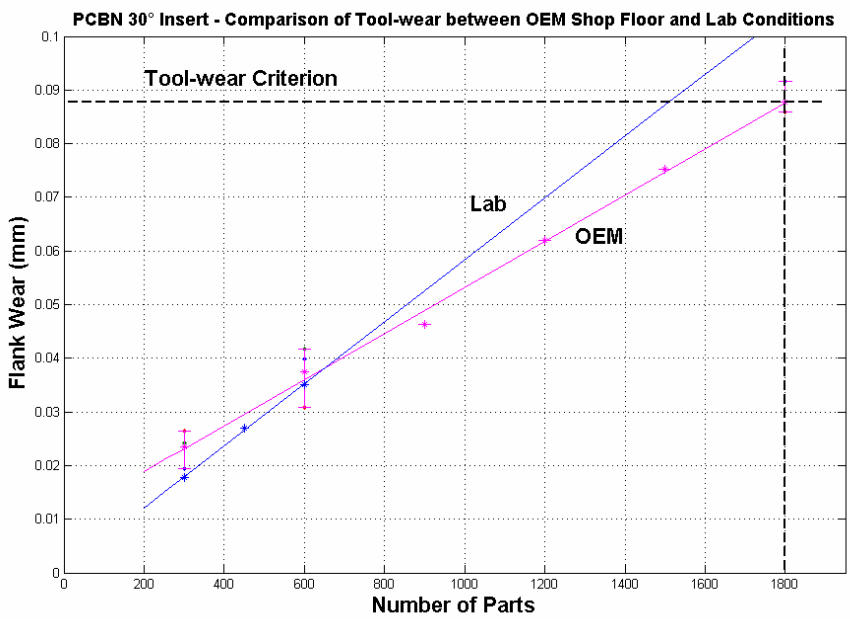


Figure 5.5: Tool-wear Comparison Plot between OEM Shop Floor and the UK Lab Conditions for PCBN 30° Insert.

After the baseline was established for the laboratory conditions, the experiments were performed and wear measurements were recorded for four data points at regular intervals of parts. The recorded wear values are shown in Table 5.6.

Table 5.6: Measured Flank Wear Values for PCBN 30° Insert.

Expt #	Flank Wear (mm) for the Corresponding Number of Parts			
	200	300	350	400
1	0.0132	0.0157	0.0190	0.0220
2	0.0141	0.0163	0.0275	0.0311
3	0.0151	0.0177	0.0204	0.0235
4	0.0154	0.0182	0.0215	0.0259
5	0.0160	0.0176	0.0175	0.0225
6	0.0183	0.0215	0.0244	0.0283
7	0.0150	0.0182	0.0237	0.0267
8	0.0141	0.0166	0.0210	0.0270
9	0.0173	0.0217	0.0265	0.0305
10	0.0157	0.0167	0.0205	0.0280
11	0.0150	0.0182	0.0195	0.0270
12	0.0167	0.0173	0.0215	0.0262
13	0.0125	0.0141	0.0240	0.0271
14	0.0139	0.0151	0.0211	0.0255
15	0.0145	0.0160	0.0190	0.0251
16	0.0157	0.0168	0.0275	0.0324

After conducting the experiments and recording the wear data, an optimization program based on exhaustive enumeration technique was developed using Matlab version 7.0 (R14). The tool-wear data was used to calculate the regression coefficients required for Equations (4.14) and (4.17). The sample code for the optimization program is given in the Appendix. Based on these regression coefficients, a response curve for tool-life, in terms of number of parts, was obtained for the variables of speed and feed. The 2-D and the 3-D plots for this response is given in Figures 5.6 and 5.7, respectively.

As can be observed from these plots, the contour lines for the number of parts move toward the lesser speed and lesser feed region.

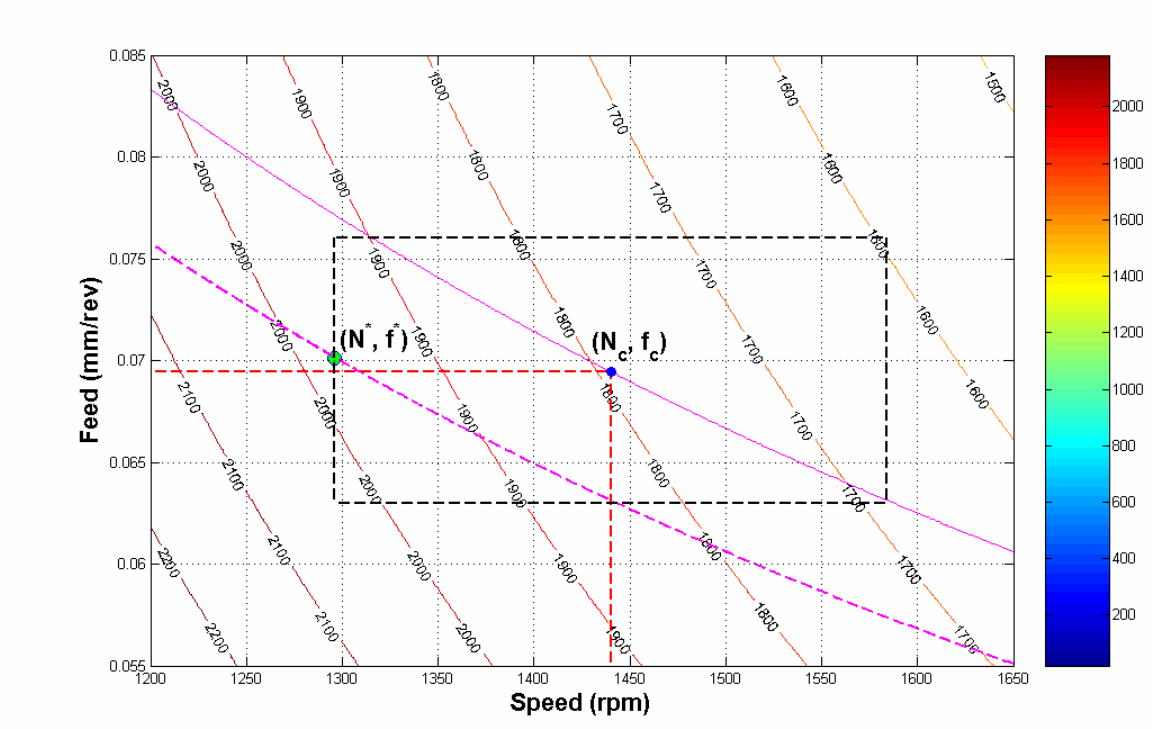


Figure 5.6: 2-D Contour Plot for PCBN 30° Insert.

In Figure 5.6, the X-axis shows the speed values whereas the Y-axis shows the feed values. The black dashed lines represent the experimental boundary conditions, within which the experiments were conducted. The dashed red lines show the current cutting conditions for the operation. The blue dot represents the number of parts that are predicted for the current cutting conditions based on the tool-wear data that was collected for the 16 experiments. The magenta line passing through the blue dot shows the current cutting/machining time, whereas the dashed magenta line represents the constraint set at +10% increment in the cutting time. The value of the tool-life is shown on the contour lines and can also be interpreted from the vertical color bar shown next to the figure. As

can be observed in the above figure, the maximum number of parts can be obtained at lesser speed and lesser feed. However, the number of parts are restricted by the cycle time constraint, and the maximum tool-life is obtained at least speed and a feed slightly higher than the current operational feed. The green dot represents the maximum number of parts that can be obtained for the optimum values of speed and feed.

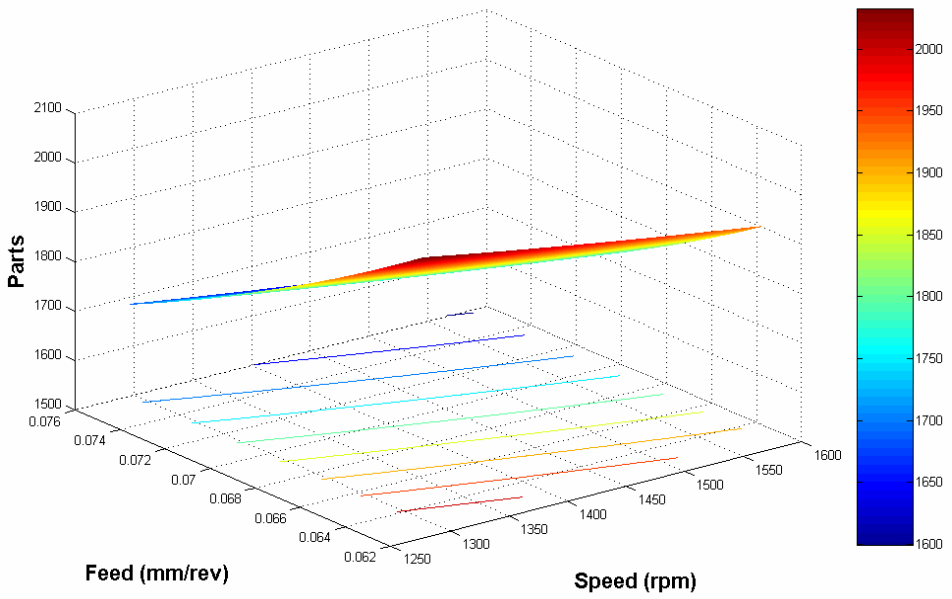


Figure 5.7: 3-D Surface Plot for PCBN 30° Insert.

A similar methodology for determining maximum tool-life for PCBN and carbide tools has been developed and the results are shown in Sections 5.4.2 - 5.4.6. The wear values for PCBN 75°, 45°, carbide 30°, 75°, 45° inserts are shown in Tables 5.11, 5.16, 5.21, 5.26 and 5.31. The comparison plots for the inserts are shown in Figures 5.8, 5.11, 5.14, 5.17 and 5.20 respectively. The 2-D plots are shown in Figures 5.9, 5.12, 5.15, 5.18 and 5.21, while the 3-D plots are shown in Figures 5.10, 5.13, 5.16, 5.19 and 5.22 respectively.

5.4.2. PCBN 75° Insert

Table 5.7: PCBN 75° - Factors and Their Levels Selected for Experimentations.

Level / Parameter	1	2	3	4
Speed (rpm)	1296	1368	1512	1584
Feed (mm/rev)	0.063	0.066	0.073	0.076

Table 5.8: Design of Experiment for PCBN 75° Insert.

75° (PCBN)		
Expt #	**RPM**	**mm/rev**
1	1296	0.063
2	1296	0.066
3	1296	0.073
4	1296	0.076
5	1368	0.063
6	1368	0.066
7	1368	0.073
8	1368	0.076
9	1512	0.063
10	1512	0.066
11	1512	0.073
12	1512	0.076
13	1584	0.063
14	1584	0.066
15	1584	0.073
16	1584	0.076

Table 5.9: Measured Progressive Flank Wear Values for PCBN 75° Insert.

	Flank Wear (mm) for Corresponding Number of Parts					
Parts / Tool #	300	600	900	1200	1500	1800
1	0.0391	0.057	0.0782	0.0826	0.0913	0.1021
2	0.0434	0.0608	0.0721	0.0831	0.0913	0.0987
3	0.0478	0.0592	0.0652	0.0782	0.0913	0.1043

Table 5.10: PCBN 75° Insert - Flank Wear Values for Baseline Experiment.

Parts / Tool #	300	450	600
1	0.04	0.049	0.057

Table 5.11: Measured Flank Wear Values for PCBN 75° Insert.

Expt #	Flank Wear (mm) for the Corresponding Number of Parts			
	200	300	350	400
1	0.0298	0.0327	0.0379	0.0430
2	0.0242	0.0275	0.0305	0.0350
3	0.0207	0.0231	0.0287	0.0345
4	0.0210	0.0245	0.0267	0.0305
5	0.0261	0.0324	0.0350	0.0403
6	0.0251	0.0272	0.0290	0.0345
7	0.0221	0.0268	0.0303	0.0334
8	0.0133	0.0265	0.0292	0.0320
9	0.0307	0.0349	0.0372	0.0410
10	0.0177	0.0225	0.0272	0.0325
11	0.0220	0.0287	0.0301	0.0355
12	0.0224	0.0265	0.0311	0.0355
13	0.0250	0.0290	0.0333	0.0375
14	0.0211	0.0270	0.0336	0.0365
15	0.0201	0.0267	0.0315	0.0350
16	0.0277	0.0329	0.0353	0.0390

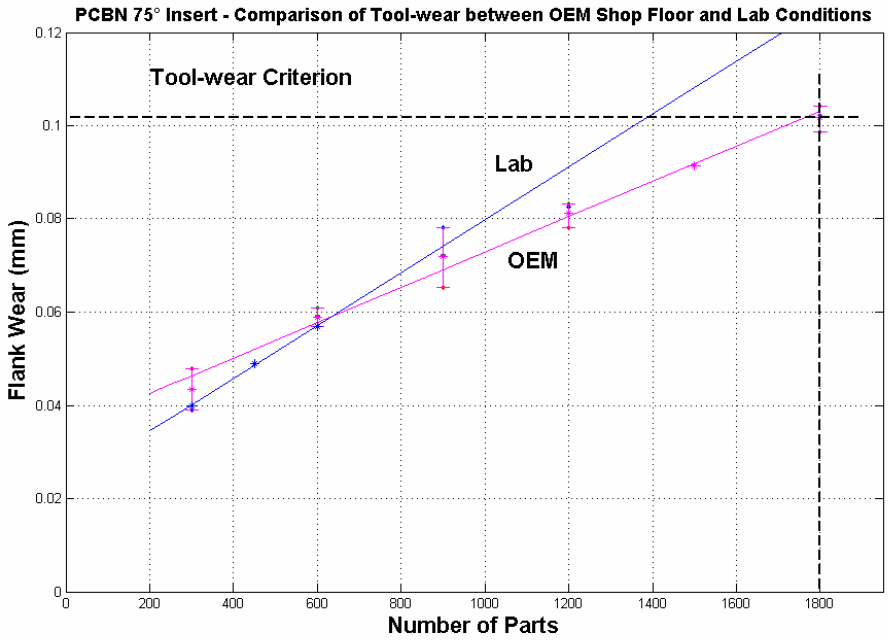


Figure 5.8: Tool-wear Comparison Plot between OEM Shop Floor and Lab Conditions for PCBN 75° Insert.

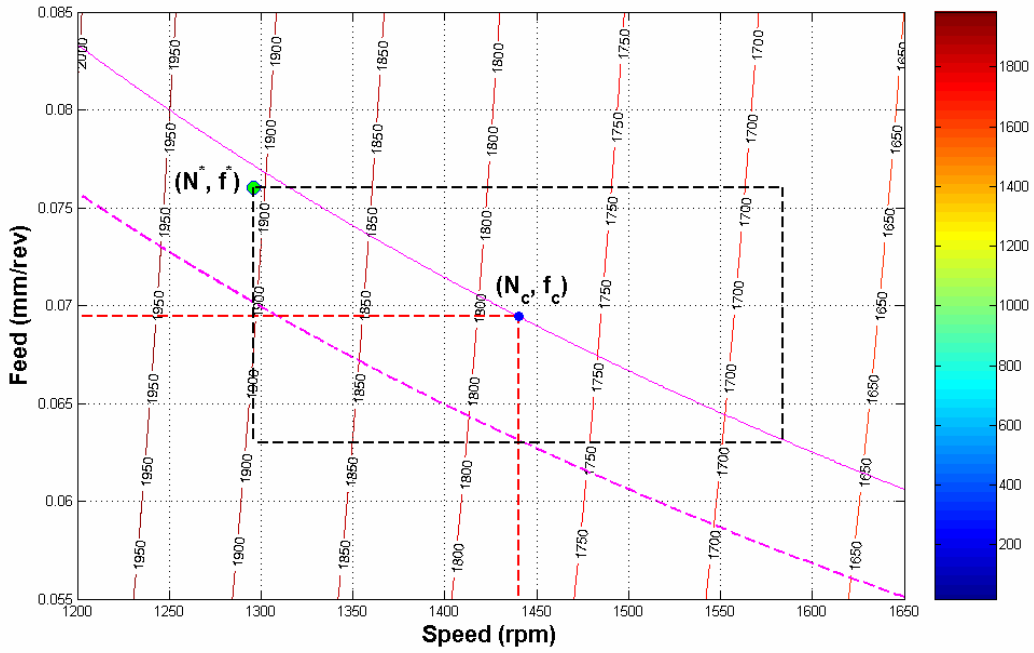


Figure 5.9: 2-D Contour Plot for PCBN 75° Insert.

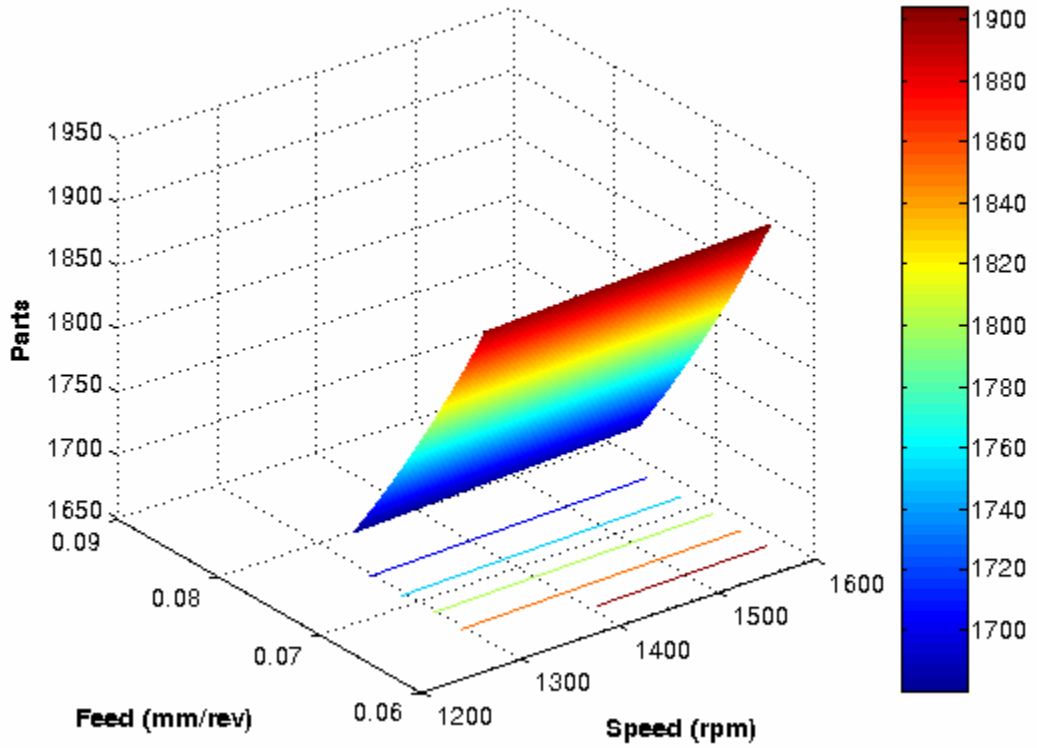


Figure 5.10: 3-D Surface Plot for PCBN 75° Insert.

5.4.3. PCBN 45° Insert

Table 5.12: PCBN 45° - Factors and Their Levels Selected for Experimentations.

Parameter \ Level	1	2	3	4
Speed (rpm)	1800	1900	2100	2200
Feed (mm/rev)	0.041	0.043	0.047	0.050

Table 5.13: Design of Experiment for PCBN 45° Insert.

45° (PCBN)		
Expt #	**RPM**	**mm/rev**
1	1800	0.041
2	1800	0.043
3	1800	0.047
4	1800	0.050
5	1900	0.041
6	1900	0.043
7	1900	0.047
8	1900	0.050
9	2100	0.041
10	2100	0.043
11	2100	0.047
12	2100	0.050
13	2200	0.041
14	2200	0.043
15	2200	0.047
16	2200	0.050

Table 5.14: Measured Progressive Flank Wear Values for PCBN 45° Insert.

	Flank Wear (mm) for Corresponding Number of Parts				
Parts / Tool #	300	600	900	1200	1500
1	0.0463	0.0829	0.0905	0.0975	0.1312
2	0.0390	0.0609	0.0902	0.1073	0.1390
3	0.0512	0.0613	0.0908	0.1024	0.1437

Table 5.15: PCBN 45° Insert - Flank Wear Values for Baseline Experiment.

Parts / Tool #	300	450	600
1	0.042	0.06	0.066

Table 5.16: Measured Flank Wear Values for PCBN 45° Insert.

Expt #	Flank Wear (mm) for the Corresponding Number of Parts			
	200	300	350	400
1	0.0543	0.0647	0.0681	0.0695
2	0.0532	0.0624	0.0649	0.0668
3	0.0539	0.0589	0.0649	0.0695
4	0.0512	0.0556	0.0571	0.0612
5	0.0502	0.0600	0.0658	0.0751
6	0.0531	0.0625	0.0635	0.0670
7	0.0533	0.0599	0.0602	0.0668
8	0.0508	0.0543	0.0560	0.0577
9	0.0514	0.0600	0.0624	0.0656
10	0.0486	0.0566	0.0588	0.0635
11	0.0512	0.0520	0.0577	0.0647
12	0.0485	0.0556	0.0568	0.0658
13	0.0531	0.0566	0.0624	0.0693
14	0.0427	0.0497	0.0508	0.0554
15	0.0428	0.0566	0.0614	0.0625
16	0.0485	0.0561	0.0566	0.0612

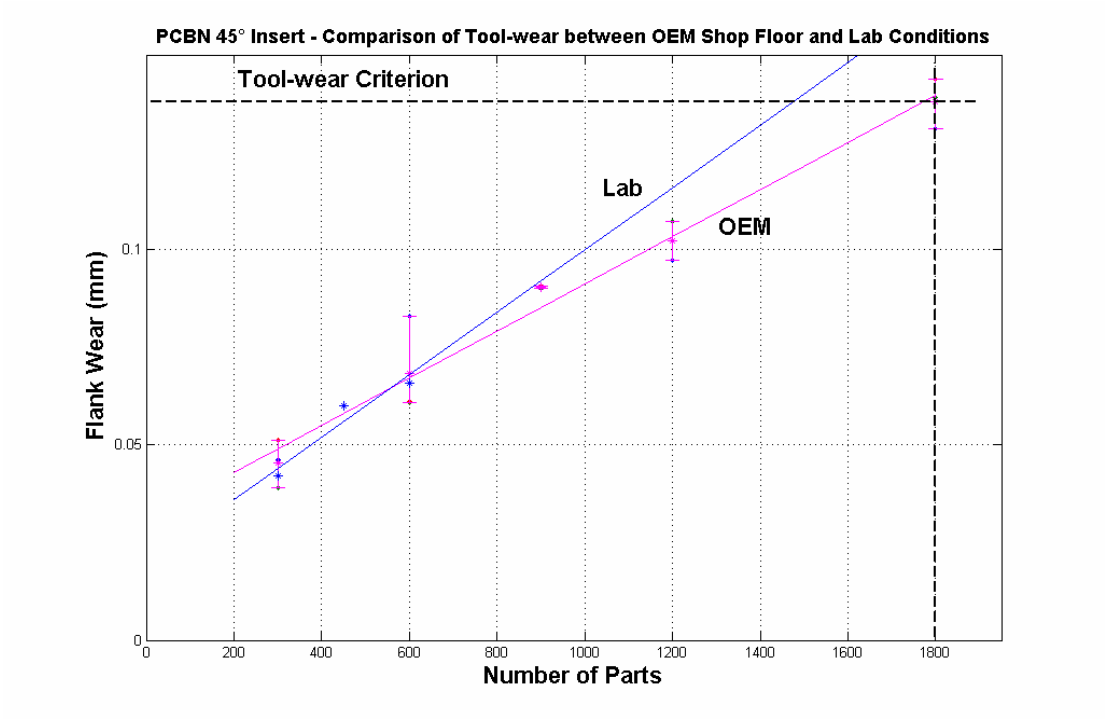


Figure 5.11: Tool-wear Comparison Plot between OEM Shop Floor and Lab Conditions for PCBN 45° Insert.

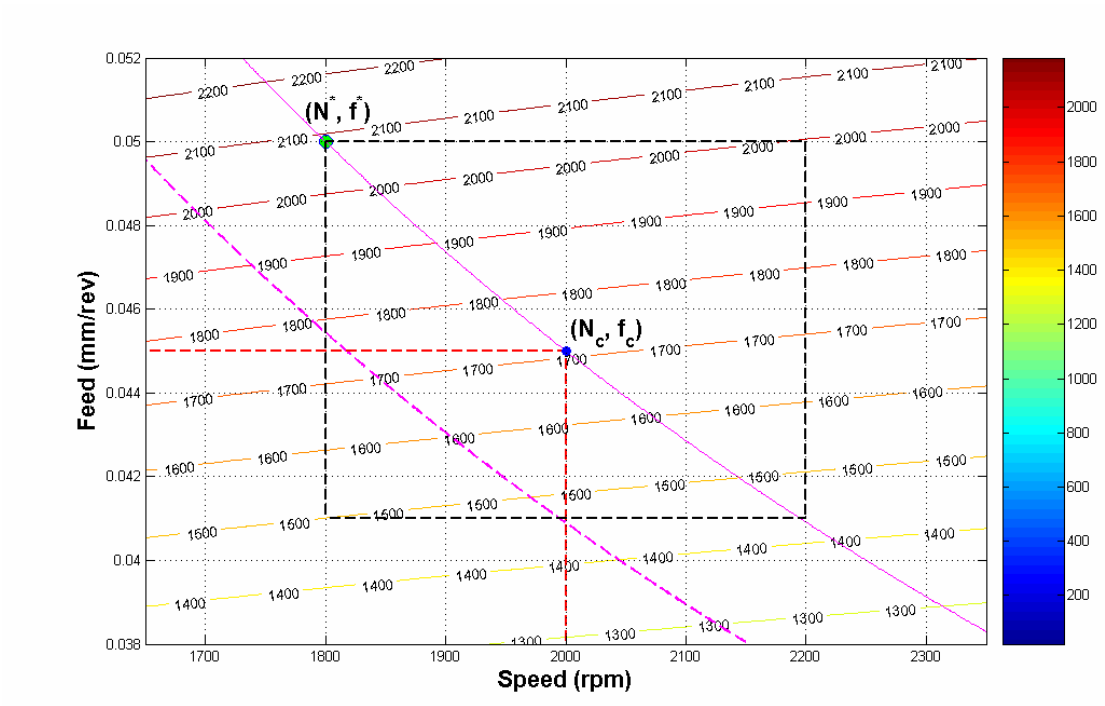


Figure 5.12: 2-D Contour Plot for PCBN 45° Insert.

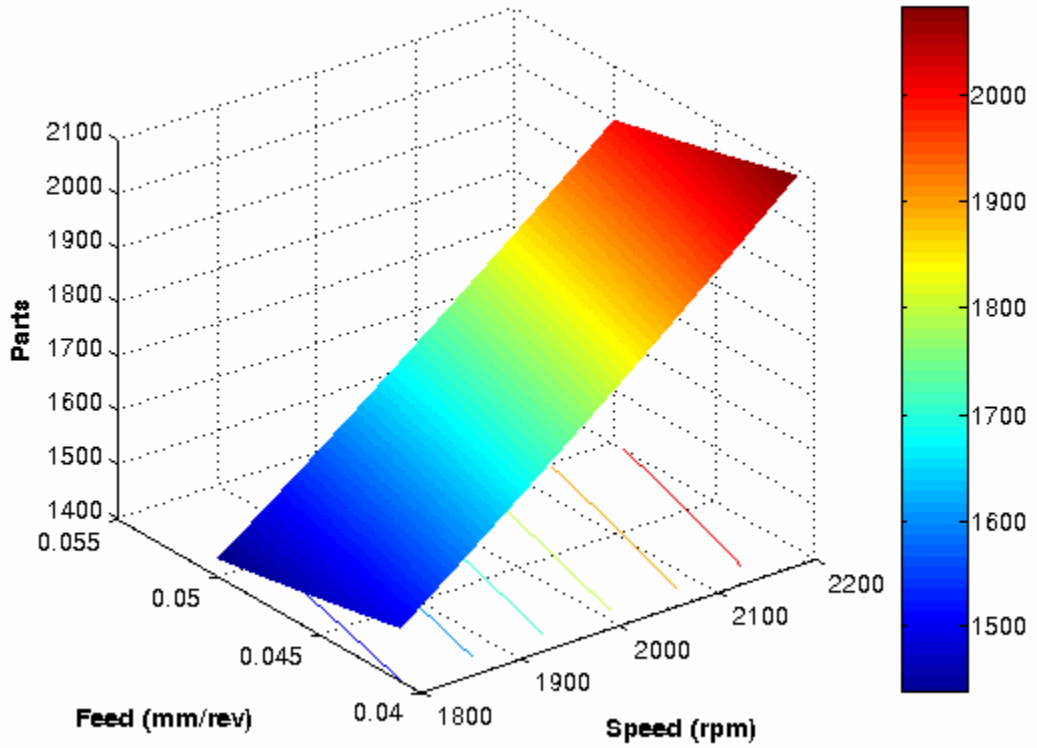


Figure 5.13: 3-D Surface Plot for PCBN 45° Insert.

5.4.4. Carbide 30° Insert

Table 5.17: Carbide 30° - Factors and Their Levels Selected for Experimentations.

Parameter \ Level	1	2	3	4
Speed (rpm)	1224	1339	1541	1656
Feed (mm/rev)	0.071	0.078	0.089	0.096

Table 5.18: Design of Experiment for Carbide 30° Insert.

30° (Carbide)		
Expt #	**RPM**	**mm/rev**
1	1224	0.071
2	1224	0.078
3	1224	0.089
4	1224	0.096
5	1339	0.071
6	1339	0.078
7	1339	0.089
8	1339	0.096
9	1541	0.071
10	1541	0.078
11	1541	0.089
12	1541	0.096
13	1656	0.071
14	1656	0.078
15	1656	0.089
16	1656	0.096

Table 5.19: Measured Progressive Flank Wear Values for Carbide 30° Insert.

	Flank Wear (mm) for Corresponding Number of Parts					
Parts / Tool #	150	300	450	600	750	900
1	0.0973	0.1460	0.1637	0.1903	0.2123	0.2309
2	0.0913	0.1217	0.1416	0.1681	0.2145	0.2297
3	0.0796	0.1150	0.1460	0.1726	0.2256	0.2304

Table 5.20: Carbide 30° Insert - Flank Wear Values for Baseline Experiment.

Parts / Tool #	75	150	225	300
1	0.053	0.077	0.091	0.099

Table 5.21: Measured Flank Wear Values for Carbide 30° Insert.

Expt #	Flank Wear (mm) Values for Corresponding Number of Parts		
	50	100	200
1	0.0465	0.0526	0.0597
2	0.0422	0.0534	0.0623
3	0.0436	0.0544	0.0692
4	0.0451	0.0533	0.0676
5	0.0431	0.0543	0.0683
6	0.0370	0.0504	0.0728
7	0.0398	0.0511	0.0656
8	0.0372	0.0474	0.0766
9	0.0479	0.0593	0.0774
10	0.0636	0.0719	0.0864
11	0.0454	0.0565	0.0906
12	0.0448	0.0656	0.0766
13	0.0512	0.0655	0.0806
14	0.0571	0.0720	0.0862
15	0.0531	0.0754	0.0880
16	0.0526	0.0656	0.0836

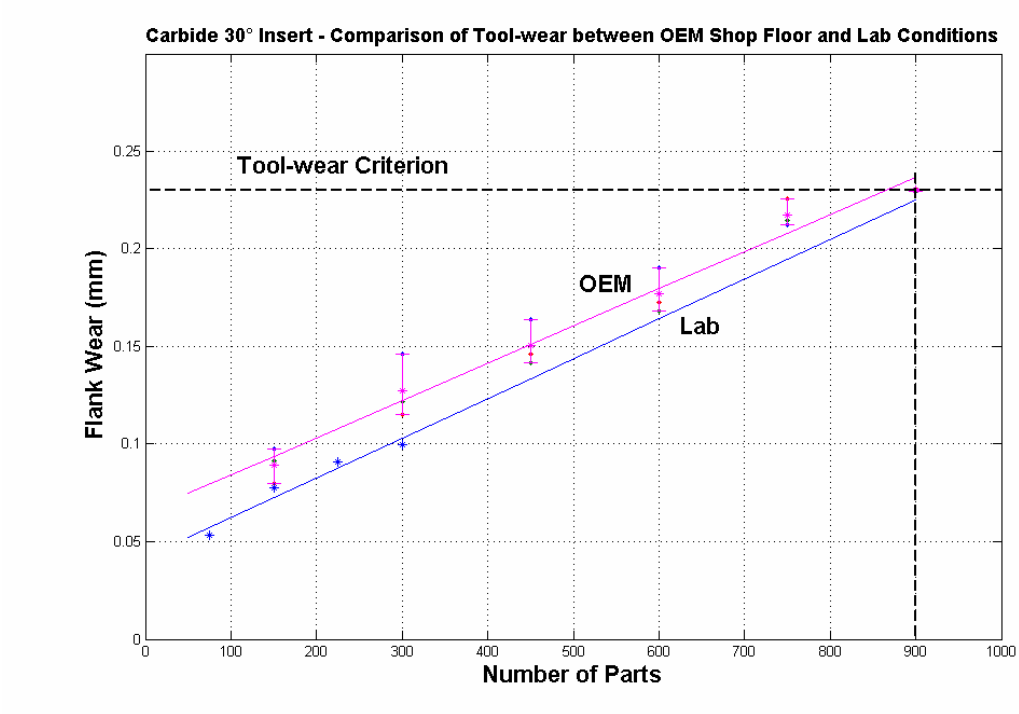


Figure 5.14: Tool-wear Comparison Plot between OEM Shop Floor and Lab Conditions for Carbide 30° Insert.

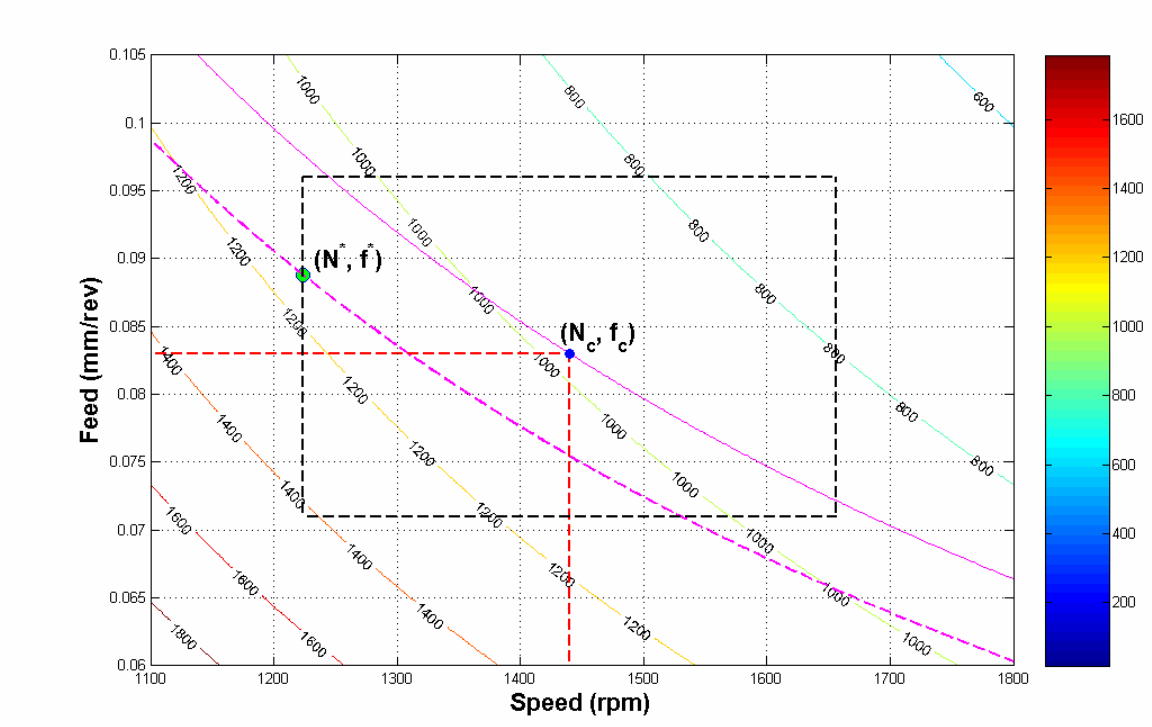


Figure 5.15: 2-D Contour Plot for Carbide 30° Insert.

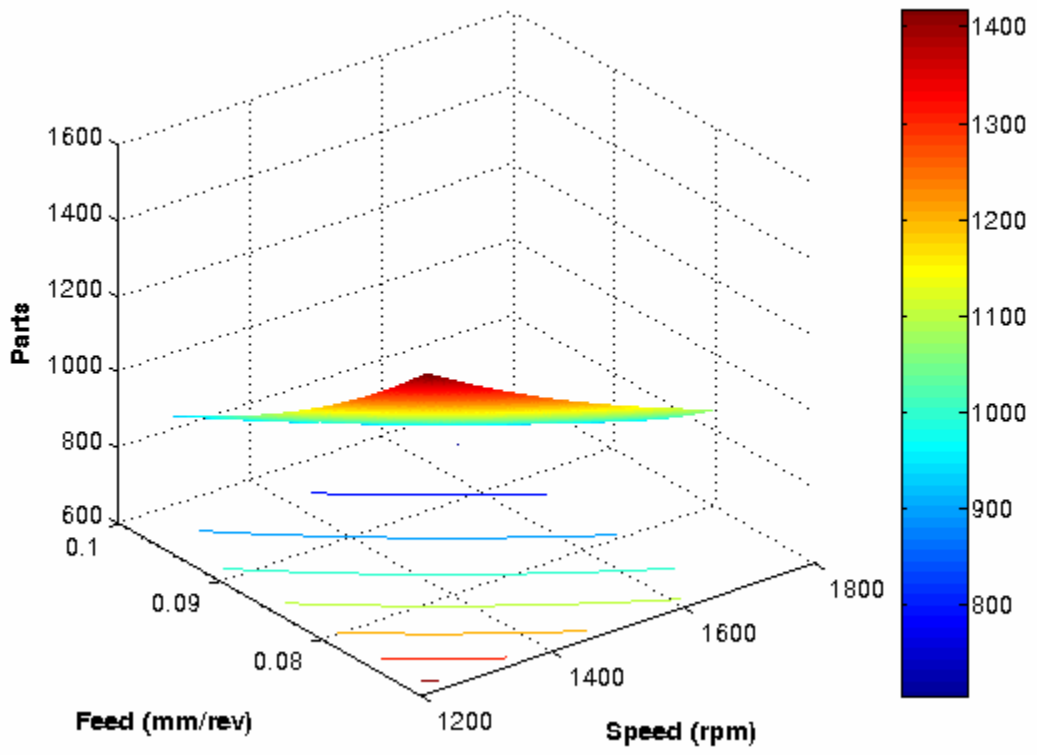


Figure 5.16: 3-D Surface Plot for Carbide 30° Insert.

5.4.5. Carbide 75° Insert

Table 5.22: Carbide 75° - Factors and Their Levels Selected for Experimentations.

Level / Parameter	1	2	3	4
Speed (rpm)	1224	1339	1541	1656
Feed (mm/rev)	0.071	0.078	0.089	0.096

Table 5.23: Design of Experiment for Carbide 75° Insert.

75° (Carbide)		
Expt #	**RPM**	**mm/rev**
1	1224	0.071
2	1224	0.078
3	1224	0.089
4	1224	0.096
5	1339	0.071
6	1339	0.078
7	1339	0.089
8	1339	0.096
9	1541	0.071
10	1541	0.078
11	1541	0.089
12	1541	0.096
13	1656	0.071
14	1656	0.078
15	1656	0.089
16	1656	0.096

Table 5.24: Measured Progressive Flank Wear Values for Carbide 75° Insert.

	Flank Wear (mm) for Corresponding Number of Parts					
Parts / Tool #	150	300	450	600	750	900
1	0.0609	0.0783	0.0913	0.1000	0.1076	0.1235
2	0.0739	0.0870	0.0957	0.1043	0.1087	0.1230
3	0.0783	0.0826	0.0913	0.1087	0.1147	0.1217

Table 5.25: Carbide 75° Insert - Flank Wear Values for Baseline Experiment.

Parts / Tool #	75	150	225	300
1	0.054	0.068	0.072	0.079

Table 5.26: Measured Flank Wear Values for Carbide 75° Insert.

Expt #	Flank Wear (mm) Values for Corresponding Number of Parts		
	50	100	200
1	0.0587	0.0674	0.0708
2	0.0311	0.0398	0.0526
3	0.0492	0.0607	0.0647
4	0.0292	0.0366	0.0499
5	0.0036	0.0096	0.0156
6	0.0192	0.0311	0.0431
7	0.0312	0.0407	0.0467
8	0.0311	0.0372	0.0464
9	0.0192	0.0245	0.0432
10	0.0181	0.0321	0.0487
11	0.0251	0.0406	0.0613
12	0.0216	0.0293	0.0432
13	0.0289	0.0372	0.0567
14	0.0231	0.0334	0.0513
15	0.0346	0.0431	0.0502
16	0.0261	0.0437	0.0513

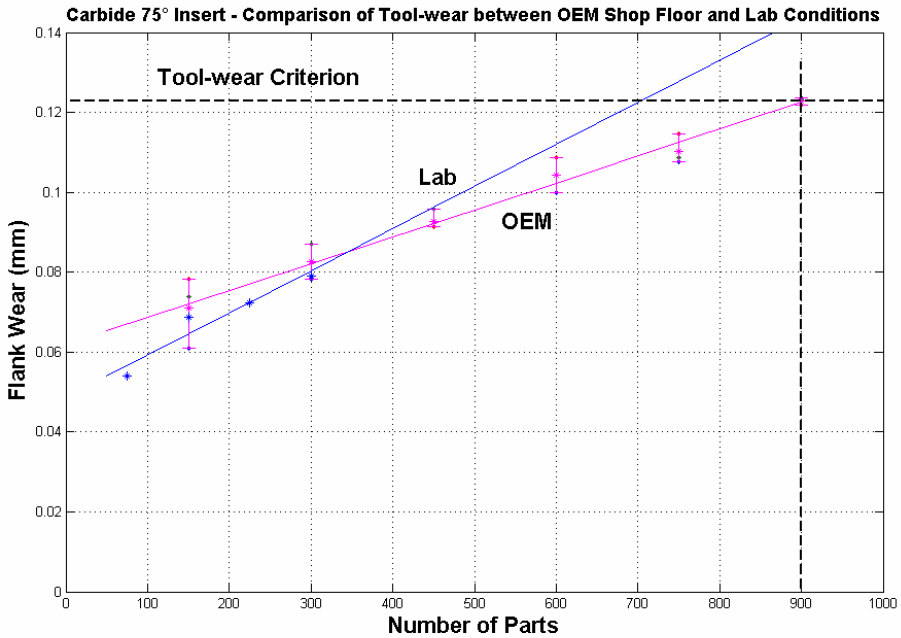


Figure 5.17: Tool-wear Comparison Plot between OEM Shop Floor and Lab Conditions for Carbide 75° Insert.

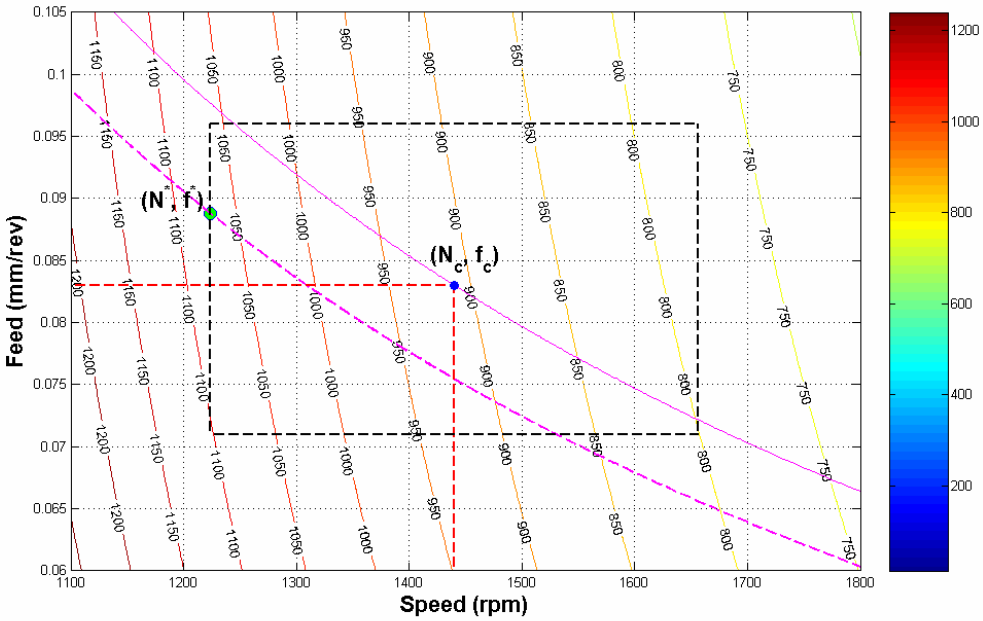


Figure 5.18: 2-D Contour Plot for Carbide 75° Insert.

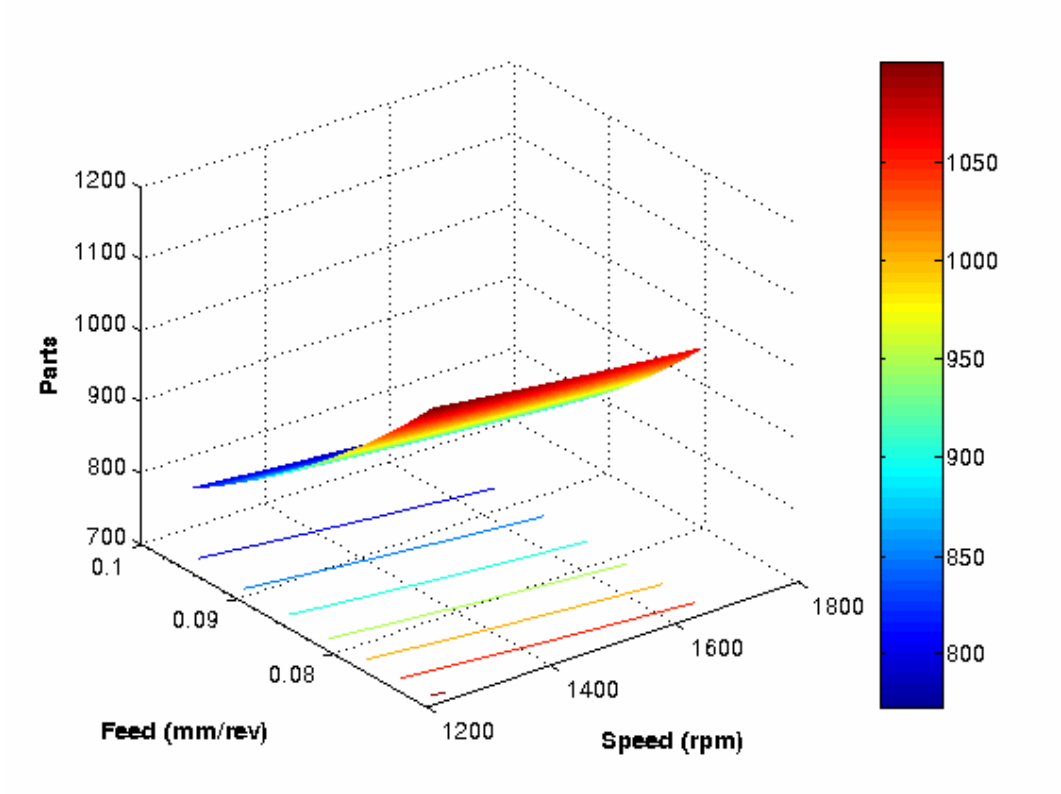


Figure 5.19: 3-D Surface Plot for Carbide 75° Insert.

5.4.6. Carbide 45° Insert

Table 5.27: Carbide 45° - Factors and Their Levels Selected for Experimentations.

Level / Parameter	1	2	3	4
Speed (rpm)	1014	1109	1276	1372
Feed (mm/rev)	0.064	0.070	0.081	0.087

Table 5.28: Design of Experiment for Carbide 45° Insert.

45° (Carbide)		
Expt #	**RPM**	**mm/rev**
1	1014	0.064
2	1014	0.07
3	1014	0.081
4	1014	0.087
5	1109	0.064
6	1109	0.07
7	1109	0.081
8	1109	0.087
9	1276	0.064
10	1276	0.07
11	1276	0.081
12	1276	0.087
13	1372	0.064
14	1372	0.07
15	1372	0.081
16	1372	0.087

Table 5.29: Measured Progressive Flank Wear Values for Carbide 45° Insert.

	Flank Wear (mm) for Corresponding Number of Parts					
Parts / Tool #	300	600	900	1200	1500	1800
1	0.0538	0.0753	0.0780	0.1004	0.1146	0.1439
2	0.0538	0.0659	0.0853	0.0951	0.1097	0.1390
3	0.0538	0.0806	0.0844	0.0962	0.1170	0.1292

Table 5.30: Carbide 45° Insert - Flank Wear Values for Baseline Experiment.

Parts / Tool #	75	150	225	300
1	0.0393	0.04855	0.05317	0.06473

Table 5.31: Measured Flank Wear Values for Carbide 45° Insert.

Expt #	Flank Wear (mm) Values for Corresponding Number of Parts		
	50	100	200
1	0.0293	0.0366	0.0402
2	0.0378	0.0414	0.0476
3	0.0366	0.0427	0.0500
4	0.0415	0.0446	0.0512
5	0.0341	0.0439	0.0524
6	0.0390	0.0415	0.0487
7	0.0415	0.0451	0.0585
8	0.0378	0.0437	0.0524
9	0.0414	0.0476	0.0512
10	0.0427	0.0463	0.0521
11	0.0402	0.0487	0.0537
12	0.0397	0.0476	0.0536
13	0.0390	0.0487	0.0561
14	0.0402	0.0512	0.0573
15	0.0463	0.0500	0.0546
16	0.0512	0.0524	0.0621

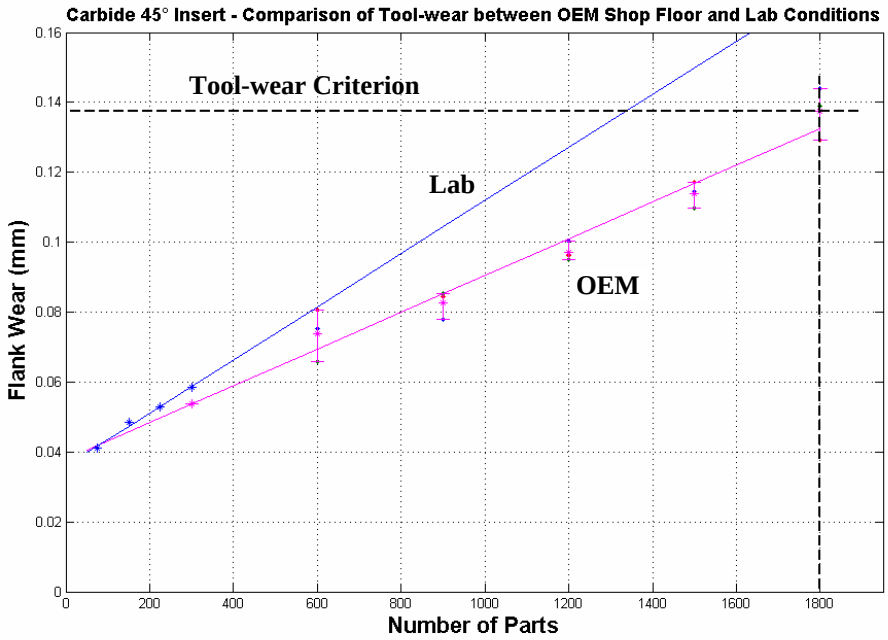


Figure 5.20: Tool-wear Comparison Plot between OEM Shop Floor and Lab Conditions for Carbide 45° Insert.

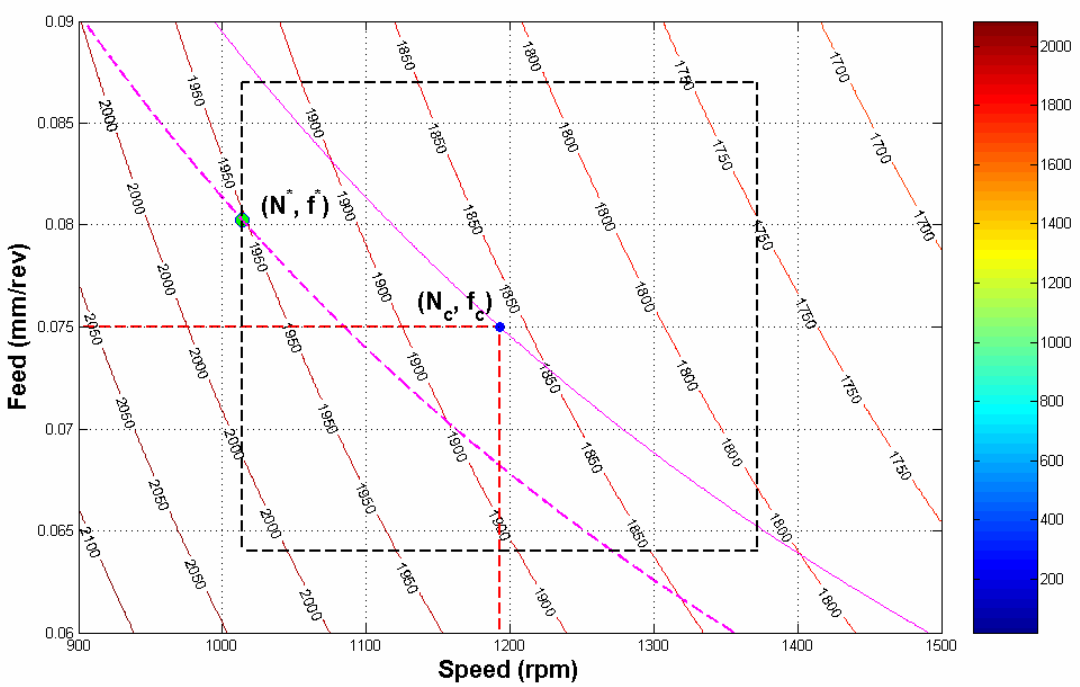


Figure 5.21: 2-D Contour Plot for Carbide 45° Insert.

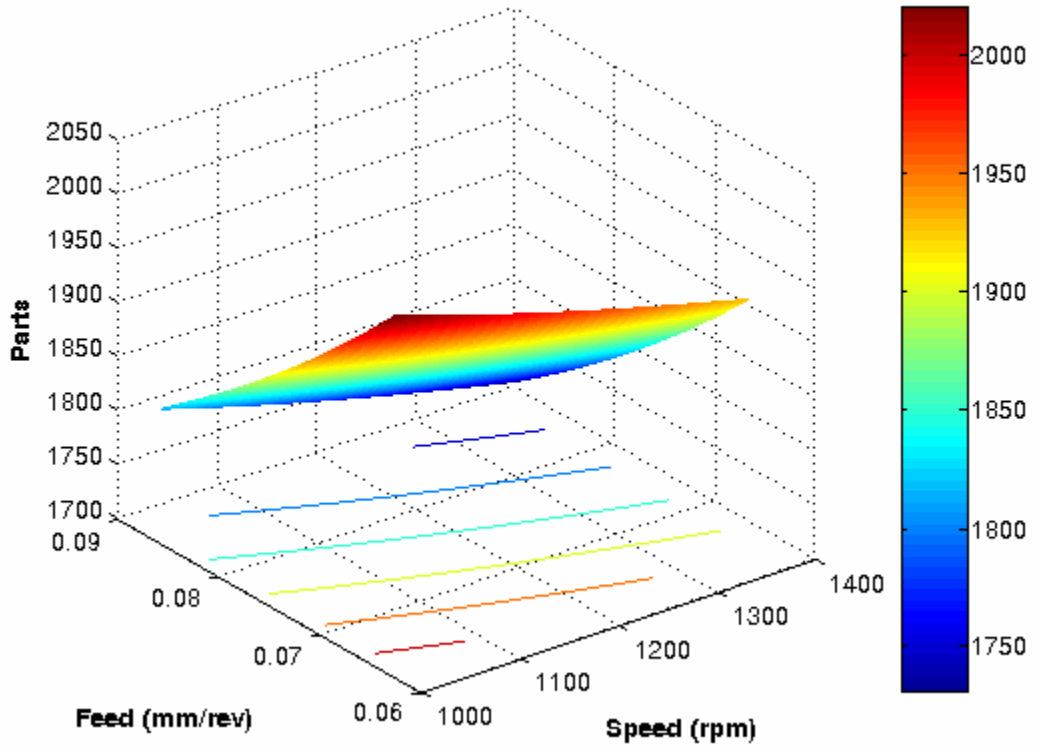


Figure 5.22: 3-D Surface Plot for Carbide 45° Insert.

5.5. Results and Discussion

The Table 5.32 summarizes the results obtained from the optimization of cutting conditions for boring and plunge cutting of powder metal steel rings, machined using PCBN and carbide tools, under flood-cooling condition. An increase in tool-life in the range of 5-27 % is obtained just by changing the cutting conditions to optimum values, without upsetting the cycle time of the machining line. A general trend can be observed for PCBN and carbide tools, in terms of tool-life. For PCBN 75° and 45° tools, an increase in tool-life is achieved at lesser speed and higher feed. This trend is consistent

Table 5.32: Summary of Cutting Conditions Optimization Results.

	PCBN 30°	PCBN 75°	PCBN 45°	Carbide 30°	Carbide 75°	Carbide 45°
Optimum speed *(rpm)*	1296	1296	1800	1224	1224	1014
Optimum feed *(mm/rev)*	0.070	0.076	0.050	0.089	0.089	0.081
Predicted tool-life *(parts)*	1970	1905	2085	1150	1070	1950
Current tool-life *(parts)*	1800	1800	1800	900	900	1800
Gain due to optimization *(parts)*	170	105	285	250	170	150
Gain due to optimization *(%)*	9.44	5.83	15.83	27.77	18.88	16.67
Cutting time for optimum conditions *(s)*	3.49	3.21	3.19	3.13	3.13	3.84
Current cutting time *(s)*	3.18	3.18	3.16	2.85	2.85	3.49
Increase in cutting time *(s)*	0.31	0.03	0.03	0.28	0.28	0.35
Total cutting time = Plunge + Boring *(s)* (Current conditions)	6.34			6.34		
Total cutting time = Plunge + Boring *(s)* (Optimum conditions)	6.68			6.97		
Increase in overall cutting time *(s)*	0.34			0.63		

with the results obtained by Young (2000) for PCBN tools when machining ferrous powder metals. While for the carbide tools, tool-life improvement is gained at lesser speed and lesser feed, which is in accordance to the general conception for carbide tools. Even though the increase in tool-life is not by much, it still is a small step forward towards continuous improvement of the machining operations. Improvements can lead to savings in terms of economy, society and environment. With the rising awareness of sustainability principles in product and process manufacturing, industries are focusing on ways to reduce the resources and improve the process efficiency by introducing the concepts of total product and process sustainability. With the legislative (mostly environmental) and societal drivers in place, industries want to achieve maximum profits by reducing the cost of production, achieving deeper market penetration, and at the same time provide the products to the end users at a lesser cost and better quality. The mindset of the companies has been changing in the recent years and they are starting to consider sustainability in totality, i.e. include all three components of sustainability – environment, economy and society, in order to stay competent in this volatile market. The next chapter touches upon some of the aspects of product and process sustainability that can be derived from the attained achievement of increased tool-life in machining of powder metal steel products using PCBN and carbide tools.

CHAPTER 6

SUMMARY AND CONCLUSIONS

6.1. Summary of Present Work

This thesis work focused on developing an optimization method for maximizing tool-life in machining of powder metal automotive components. This new methodology was applied to plunge cutting and boring of ferrous powder metals using PCBN and carbide tools under flood-cooling conditions. The process considered in this study is a niche application, but the methodology developed through the investigation can be applied to broader range of applications. A systematic approach to optimizing the cutting conditions for machining operations has been carried out. The following major conclusions can be drawn from this research work:

1. The effects of cutting conditions (cutting speed and feed) on tool-life performance measure were established for both PCBN and carbide tools. Flank wear criterion was selected as the tool-wear criterion, since the change of tools was governed by the dimensional change in the width of the critical, 45° surface. Increased feed rate is found to have a positive impact on the life of the PCBN tools, as suggested also by Young (2002) and Šalack et al. (2005). Increased feed rate improves stability of the process (Knight, 1972). Whereas, for carbide tools reducing the feed rate led to an improvement in the tool-life performance. However, the optimized feed rate was found to be higher than the current feed rate, owing to the

cycle time constraint. Reduced cutting speed was found to be favorable to improved tool-life, both for PCBN and carbide tools.

2. Given the very small window of cycle time to work within, the achieved improvement in the tool-life, in the range of 5-27%, is dramatic.
3. The technique for assessing the tool-life is unique and can be applied for tools that have longer tool-life with a linear wear progression curve. This methodology can be useful for tools that require large quantity of parts to be machined in order to obtain the relation between the tool-wear and number of parts machined. The tool-life tests in such cases can require insurmountable amount of time and resources. This is usually true in the cases where a tool-life analysis is to be conducted for the components with higher tool-life and which are machined in a production environment. With the methodology presented in this thesis work, offline tests can be simulated in a lab environment, giving manufacturers (project sponsors) an opportunity to take advantage of offline lab facilities without disrupting their production lines.
4. Although a limited number of tests were conducted due to the limitation of time and resources, these tests give a good idea of the effect of cutting conditions on tool-life performance of PCBN and carbide tools. Due to the tight cycle time constraint, the improvement gained in tool-life is quantitatively less. However, qualitatively this work provides a fair idea of the behavior of PCBN and carbide tools for a lesser known work material, which is fast gaining popularity in the automotive and manufacturing industries. The work presented here can serve as a good foundation for future research work involving machining of powder metals.

5. A baseline for the current production practice was established through this work, serving as a reference to judge any future improvements made on the powder metal machining station.
6. The production line machining operation was successfully simulated in the lab environment, encouraging the industry groups to work closely with the university research labs and promote research activities, mutually beneficial to both the parties.

6.2. Product and Process Sustainability Contributions from the Current Work

Although the major objective of this work was to improve the tool-life of PCBN and carbide tools, other benefits that accompanied the accomplishment of the primary objective were:

(a) reduced tooling cost,

(b) reduced manufactured product cost,

(c) increased productivity,

(d) reduced labor,

(e) improved operator satisfaction/morale,

(f) improved product quality, and

(g) reduced scrap generation.

These benefits gained, can be looked at from the sustainability perspective of economy, environment and society. These benefits will improve the product and process sustainability by contributing to these three components of sustainability at varying levels.

It would be interesting to take a step further and consider the cutting tool as a product, which is an integral part of the machining process, and observe closely to see if any improvement in the performance of this product can directly, or indirectly benefit the performance of the machining process as a whole.

Wanigarathne et al. (2004) and de Silva et al. (2006) identified the six process and the six product related sustainability elements. These are shown in Figures 6.1 and 6.2.

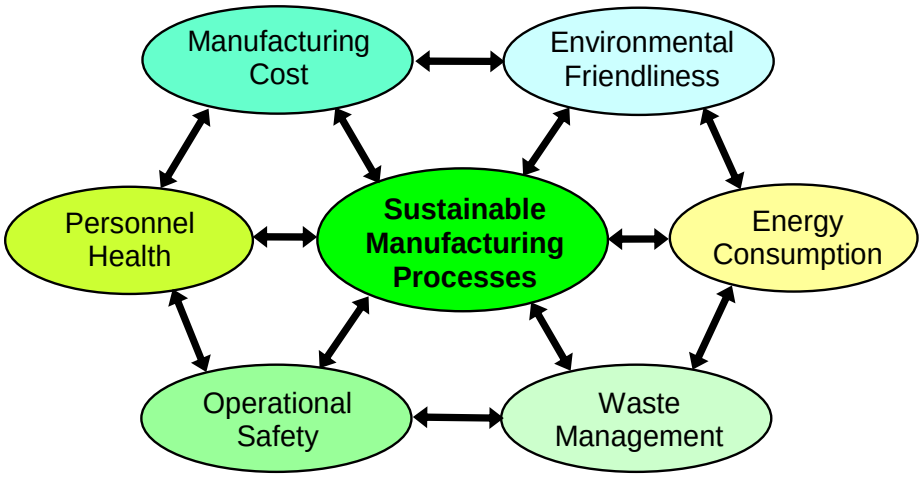


Figure 6.1: Six Major Process Sustainability Elements (Wanigarathne et al., 2004).

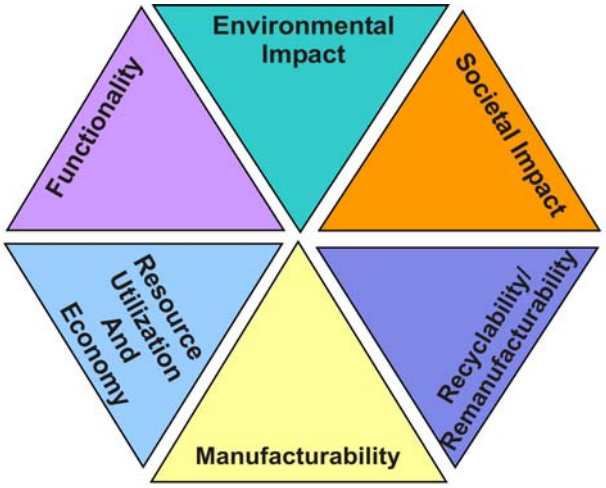


Figure 6.2: Six Major Product Sustainability Elements (de Silva et al., 2006).

Considering these product and process sustainability elements in relation to the current investigation, there seems to be an interrelationship between these elements and it would be interesting to draw conclusions as to how the product sustainability elements can affect the process sustainability elements.

Further work would be needed to quantitatively evaluate the effects of all associated benefits listed above (i.e., from (a) to (g)).

6.3. Suggestions for Future Work

Machining of powder metals is an emerging field and there is a bright future to it. With the large number of variables simultaneously involved in machining of powder metals, the scope of the research work is endless. With the new advancements in the manufacturing technology and the peer pressure from the competitors, the manufacturers need to be at the forefront of technology with the sole objective of providing cheaper, timely and sustainable products to their customers.

Further research work in machining of powder metals could include the effects of tool grades and coatings on tool-life and other machining performance measures, effect of lubricants/coolants (including cryogenic cooling) on machinability of powder metals and machining performance measures, surface integrity analysis of the machined product for sustainable functional performance of the product, etc.

APPENDIX

Sample Matlab (Version 7.0 - R14) Code for Optimization of Cutting Conditions in Machining of Powder Metal Steels

```
% Intake 75
clear all
clc
close

Part_Num=[200 300 350 400];
part_N=[200 250 300 600 900 1200 1500 1800];
Flank_wear_75=[
1       0.0298 0.0327 0.0379 0.043
2       0.02423        0.0275 0.0305 0.035
3       0.02073        0.0231 0.0287 0.0345
4       0.02102        0.0245 0.0267 0.0305
5       0.02608        0.0324 0.035   0.0403
6       0.02511        0.0272 0.029   0.0345
7       0.02213        0.0268 0.0303 0.0334
8       0.0133 0.0265 0.0292 0.032
9       0.0307 0.0349 0.0372 0.041
10      0.01767        0.0225 0.0272 0.0325
11      0.02197        0.0287 0.0301 0.0355
12      0.02236        0.0265 0.0311 0.0355
13      0.02504        0.029   0.0333 0.0375
14      0.02112        0.027   0.0336 0.0365
15      0.0201 0.0267 0.0315 0.035
16      0.02771        0.03285        0.0353 0.039];

toyota_parts_num=[      300     600      900   1200     1500     1800];
prog_tmmk_75=[  0.0391      0.0570 0.0782 0.0826 0.0913 0.1021
            0.0434      0.0608 0.0721 0.0831 0.0913 0.0987
            0.0478      0.0592 0.0652 0.0782 0.0913 0.1043];
highest=[];
lowest=[];
for i=1:6
   high=max(prog_tmmk_75(:,i));
   low=min(prog_tmmk_75(:,i));
   highest=[highest high];
   lowest=[lowest low];
end
```

```
highest;
lowest;

toyota_flank_wear=[mean(prog_tmmk_75)];
wear_cri=max(toyota_flank_wear);

figure(1)
plot(toyota_parts_num, prog_tmmk_75, '.')
hold

lower_error_limit=(toyota_flank_wear-lowest);
upper_error_limit=(highest-toyota_flank_wear);

errorbar(toyota_parts_num,toyota_flank_wear,lower_error_limit,upper_error_limit,'m*')
xlabel('Number of Parts','fontweight','bold','fontsize',16)
ylabel('Flank Wear (mm)','fontweight','bold','fontsize',16)
axis([0 1950 0 0.12 ])
title('PCBN 75° Insert - Progressive Wear Scatter Plot','fontweight','bold','fontsize',16)
grid on

toyota_slope_coeff=polyfit(toyota_parts_num,toyota_flank_wear,1);
toyota_parts=(wear_cri-toyota_slope_coeff(2))/(toyota_slope_coeff(1));

[p1,s,mu] = polyfit(toyota_parts_num,toyota_flank_wear,1);
pop1 = polyval(p1,part_N,s,mu);
plot(part_N,pop1,'m-')

parts_uk=[300 450 600];
wear_uk_baseline=[0.04 0.049 0.057];

uk_slope_coeff=polyfit(parts_uk,wear_uk_baseline,1);
uk_baseline_parts=(wear_cri-uk_slope_coeff(2))/(uk_slope_coeff(1));

plot(parts_uk, wear_uk_baseline,'b*')
[p1,s,mu] = polyfit(parts_uk, wear_uk_baseline,1);
pop1 = polyval(p1,part_N,s,mu);
plot(part_N,pop1,'b-')
xlabel('Number of Parts','fontweight','bold','fontsize',16)
ylabel('Flank Wear (mm)','fontweight','bold','fontsize',16)
axis([0 1950 0 0.12 ])
title('PCBN 75° Insert - Comparison of Tool-wear between OEM Shop Floor and Lab
Conditions','fontweight','bold','fontsize',14)
grid on

hold on
la=line([0,1900],[wear_cri,wear_cri],'linewidth', 2);
```

```
set(la,'color','black','linestyle','--');
lb=line([1800,1800],[0,wear_cri+0.01],'linewidth', 2);
set(lb,'color','black','linestyle','--');
gtext('OEM','fontweight','bold','fontsize',16);
gtext('Lab','fontweight','bold','fontsize',16);
gtext('Tool-wear Criterion','fontweight','bold','fontsize',16);

temp1=[];
temp2=[];

for i=1:16
   [p1,s] = polyfit(Part_Num,Flank_wear_75(i,2:5),1);
   temp1=[temp1 p1(1)];
   temp2=[temp2 p1(2)];
end

temp1';
temp2';

parts_exp=[];
for i=1:16
x=(wear_cri - temp2(i))/ (temp1(i));
parts_exp=[parts_exp x];
end

parts_exp';

compensation=[(toyota_parts-uk_baseline_parts)/toyota_parts];
compensated_parts_exp=(parts_exp') + (parts_exp'*compensation);
log_compensated_parts_exp=log(compensated_parts_exp);
diff=compensated_parts_exp-parts_exp';

speed=[1296
1296
1296
1296
1368
1368
1368
1368
1512
1512
1512
1512
1584
1584
```

```
1584
1584];
feed=[0.063
0.066
0.073
0.076
0.063
0.066
0.073
0.076
0.063
0.066
0.073
0.076
0.063
0.066
0.073
0.076];

speed_feed=[speed feed];
log_speed_feed=log(speed_feed);

regression_coeff=regstats(log_compensated_parts_exp,log_speed_feed,'linear','beta');

regression_coeff.beta(1)
regression_coeff.beta(2)
regression_coeff.beta(3)

hold off

pred_parts=exp(regression_coeff.beta(1))*(1440^regression_coeff.beta(2))*(0.06944^reg
ression_coeff.beta(3))
%-----------------------------------------------------------------------------------------------------

N1=linspace(1200,1650,300);   % rotational speed (rpm)
f1=linspace(0.055,0.085,300);  % feed (mm/rev)

N=linspace(1296,1584,300);   % rotational speed (rpm)
f=linspace(0.063,0.076,300);  % feed (mm/rev)

cycle_time=(5.3/((1440)*(0.06944)))*60;
tstar = 0;
pstar = 0;
nstar = [];
fstar = [];
```

```
for i=1:300
  for j=1:300
     % calculate the number of parts based on the flank wear prediction model

P(i,j)=exp(regression_coeff.beta(1))*(N(i).^regression_coeff.beta(2))*(f(j).^regression_c
oeff.beta(3));

P1(i,j)=exp(regression_coeff.beta(1))*(N1(i).^regression_coeff.beta(2))*(f1(j).^regressio
n_coeff.beta(3));
     % calculate time
     t(i,j)=(5.3/((N(i)*f(j))))*60;
     t1(i,j)=(5.3/((N1(i)*f1(j))))*60;

     if ((t(i,j) <= 3.5) & (P(i,j) >= pstar))
       tstar = t(i,j);
       pstar = P(i,j);
       nstar = N(i);
       fstar = f(j);
     end
  end
end

fprintf('Maximum parts : '),disp(pstar)
fprintf('Optimal speed : '),disp(nstar)
fprintf('Optimal feed : '),disp(fstar)
fprintf('Constraint cycle time : '),disp(tstar)

% show the results as contour plots
figure(2)
meshc(N,f,P);
xlabel('Speed (rpm)','fontweight','bold','fontsize',16);
ylabel('Feed (mm/rev)','fontweight','bold','fontsize',16);
zlabel('Parts','fontweight','bold','fontsize',16);
grid on;
hold on
colorbar('vert')

figure(3)
[C,h]=contour(N1,f1,P1');
hold
xlabel('Speed (rpm)','fontweight','bold','fontsize',16);
ylabel('Feed (mm/rev)','fontweight','bold','fontsize',16);
plot(nstar,fstar, 'marker','o','MarkerFaceColor','g','Markersize',10);
grid on;
hold on
clabel(C,h,'labelspacing',50)
```

```
[Ct,ht]=contour(N1,f1,t1',[(5.3/((1440)*(0.06944)))*60,(5.3/((1440)*(0.06944)))*60],'m-
');
set(ht,'linewidth',1);

[Ct2,ht2]=contour(N1,f1,t1',[((5.3/((1440)*(0.06944)))*60)+(0.1*((5.3/((1440)*(0.06944
)))*60)),((5.3/((1440)*(0.06944)))*60)+(0.1*((5.3/((1440)*(0.06944)))*60))],'m-');
set(ht2,'linewidth',2,'linestyle','--')

l1=line([1440,1440],[.055,.06944], 'linewidth',2);
set(l1,'color','red','linestyle','--');
l2=line([1200,1440],[.06944,.06944], 'linewidth',2);
set(l2,'color','red','linestyle','--');
plot(1440,0.06944,'o','MarkerFaceColor','b','Markersize',6)

l3=line([1296,1296],[.063,.076], 'linewidth',2);
set(l3,'color','black','linestyle','--');
l4=line([1296,1584],[.063,.063], 'linewidth',2);
set(l4,'color','black','linestyle','--');
l5=line([1584,1584],[.063,.076], 'linewidth',2);
set(l5,'color','black','linestyle','--');
l6=line([1584,1296],[.076,.076], 'linewidth',2);
set(l6,'color','black','linestyle','--');
colorbar('vert')

gtext('(N_c, f_c)','fontweight','bold','fontsize',16);
gtext('(N^*, f^*)','fontweight','bold','fontsize',16);
%-----------------------------------------------------------------------------------------------------------
```

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