UNIVERSITÀ DEGLI STUDI DI NAPOLI FEDERICO II

FACOLTÀ DI INGEGNERIA

SCUOLA DI DOTTORATO IN INGEGNERIA INDUSTRIALE

PHD PROGRAMME IN
PRODUCTION TECHNOLOGY AND SYSTEMS
COORDINATOR: PROF. GIUSEPPE GIORLEO
XXIV CYCLE

PHD THESIS

Advanced Techniques for Monitoring, Simulation and Optimization of Machining Processes

TUTOR
PROF. ROBERTO TETI

PHD CANDIDATE
ANUPAM KESHARI

ACADEMIC YEAR 2010-2011

Table of Contents

Abstract

Chapter 1: Advanced Technologies for Monitoring, Simulation and Optimization

1.1 Introduction 2

1.1.1 Machining Techniques 4

1.1.2 Material Flow and Deformation 10

1.1.3 Machine Tool 32

1.1.4 Milling Machine 33

1.1.5 Milling Machine Classification and Advancements 33

1.1.6 Turning Machine 35

1.1.7 Turning Machine Classification and Advancements 36

1.2 Decision Support System in Machining Process Monitoring and Control 38

1.2.1 Defining the Concept 38

1.3 Contexts of Problem Scenarios and Applied Techniques 40

1.3.1 Chip Formation Monitoring during Turning Operation 40

1.3.2 Process Condition Monitoring during Turning Operation 41

1.3.3 Real Time Tool Wear Detection & Measurement during Turning Operation 41

1.3.4 Machining Process Simulation and Process Verification and Optimization 42

1.4 Motivation and Scope 43

1.5 Objectives 44

References 46

Chapter 2: Classification and Clustering of Sensor Data to Build a Decision Support System for Chip Form Monitoring

2.1 Introduction 48

2.2 Materials and Experimental Procedures 51

2.3 Signal Analysis of Cutting Force Signal Specimens 52

2.4 Data Clustering and Classification using SOM Neural Network 52

2.4.1 Case study 54

2.5 Results and Discussion 55

References 61

Chapter 3: Classification and Clustering of Sensor Data to Build a Decision Support System for Process Condition Monitoring

3.1 Introduction 64

3.2 Materials and Experimental Procedures 66

3.3 Signal Processing and Creation of Data set 67

3.3.1 Signal conditioning 67

3.3.2 Signal analysis 68

3.4 SOM NN Data Processing 68

3.5 Identification of Ambiguous Data and Refinement 69

3.6 Results and Discussion 70

References 72

Chapter 4: Automatic Tool Wear Detection to Build a Decision Support System for Tool Wear Monitoring

4.1 Introduction 74

4.1.1 Theory of Tool Wear 74

4.1.1.1 Tool Wear Definition 74

4.1.1.2 Gradual Wear and its Characteristics 75

4.1.2 Scope of the Research 77

4.2 Experimental Setup and Tool Wear Image Collection 79

4.3 Automatic Tool Wear Detection Procedure 81

4.3.1 Standardization of Tool Image 81

4.3.2 Adjustment of Pixel Contrast and Brightness 81

4.3.3 Clear Crater Wear Identification and Filtering Out Unrelated Spots 82

4.3.4 Projection Lines Drawing 83

4.3.5 Measurement of Tool Wear Characteristics 83

4.3.6 Standardizing the Images with Matlab 84

4.4 Results and Discussion 85

References 90

Chapter 5: Machining Operation Simulation as a Decision Support System for Machining Process Verification

5.1 Introduction 92

5.2 Cam Software Features & Facilities to Create Machining Process Simulation 96

5.2.1 Esprit® Software 96

5.2.1.1 Esprit® Software Features 97

5.2.1.2 Turning Processes in Esprit® 98

5.2.1.3 Milling Process in Esprit® 100

5.2.2 Mastercam® Software 102

5.3 Development of Machining Operation Simulation 107

5.4 Case Studies Presenting Verification of Machining Operations 111

5.4.1 First Milling Process Simulation 111

5.4.2 Turning Operation Simulation on Aircraft Engine Components 124

5.4.2.1 Support Shroud 124

5.4.2.2 Operation and Tooling 125

5.4.2.3 Simulation Output 134

5.4.3 Second Milling Process Simulation in Mastercam® 137

5.4.4 Turning Process Simulation in Mastercam® 145

5.5 Machining Process Simulation Support in Teaching Programs 156

5.6 Results and Discussions 159

References 160

Bibliography 162

Abstract

In today's manufacturing industry, pressure for productivity, higher quality and cost saving is heavier than ever. Surviving in today's highly competitive world is not an easy task, contemporary technology updates and heavy investments are needed in state of the art machinery and modern cutting tool systems. If the machining resources are underutilized, feasible techniques are needed to utilize resources efficiently.

The new enhancements in the machine tools sector have enabled opportunities for rapid growth in production rate and high varieties in products in minimum time. But they also raised questions concerning sustainability of exiting manufacturing resources. Buying new machines and tooling lead to huge investments. However, buying new machines and tooling doesn't solve production profitability problems if they are underutilized. In order to find the answer for sustainability of existing manufacturing resources and enhancement of the machining efficiency, researchers are working on finding possible supplementary computer supports. In recent years, the indirect computer supported techniques such as sensor base monitoring and control and virtual machining process simulation have been greatly accepted for real-time decision making, sustainable development and efficient use of machining resources.

This thesis work is focused on the development of advanced techniques for monitoring, simulation and optimization of machining processes. The thesis presents the contributions to the development and application of decision support systems for three fundamental aspects of machining processes:

1) Chip form monitoring and process condition monitoring through sensor data clustering and classification.

2) Real time tool wear measurement through tool wear image processing.

3) Machining operation verification and optimization using machining process simulation.

CHAPTER 1

Advanced Technologies for Monitoring, Simulation and Optimization

1.1 Introduction

The new enhancements in the machine tools sector have enabled opportunities for rapid growth in production rate and high varieties in products in minimum time. On the other hand they also raised questions concerning sustainability of exiting manufacturing resources. Buying new machines and tooling lead to huge investments. However, buying new machines and tooling doesn't solve production profitability problems if they are underutilized.

Except for automated regulatory systems, most of these systems include a human interpretation and analysis of measurement data and decision making on control actions. Based on the information from the monitoring system, combined with other information about the process and a suitable process control strategy, decisions on necessary control actions are generated. The control strategies depends the on knowledge and experience of operators and engineers.

In recent year, development of indirect control and monitoring system has been a burning issue to enhance machining efficiency. The indirect control and decision making is concerned with either sensor based real time control or offline decision making in a virtual environment. In general, in direct control system can be classified in two types.

(1) Real- time monitoring and decision making system
(2) Off-line simulation and decision making system

Real- time control and decision making system:

The real-time control and monitoring is concerned with sensor application during the machining processes. Sensors are devices which convert physical properties (e.g. force, power, temperature, acceleration etc.) into electrical signals [2].

The application of sensors can be twofold, either for measurement or for process monitoring of a property. Process monitoring can be based on the quantitative measurement of a property, but does not necessarily need to do so. While measurement has the aim of quantitatively identifying a certain property, process monitoring is often based on defining a threshold or an operating range determining whether some condition is acceptable or not.

Off-line simulation and decision making system:

Off-line simulation has concerned with the realistic simulation modeling of machining operation in virtual environment. The realistic simulation allows us to realize machining process virtually as exactly performed on real machine.

Offline simulation benefits

- Cost savings by reducing programming time, scrap and costly rework
- Enabled rapid development of process planning and verification
- Set up the sequence of operations
- Facilitated realistic 3D simulation in virtual environment
- Better working conditions with increased programmer safety

This thesis research is focused on the development of advanced techniques for monitoring, simulation and optimization of machining processes. The thesis presents the contributions to develop and apply decision support systems for fundamental aspects of machining processes: chip form monitoring, process condition monitoring, real time tool wear detection and machining process verification. The objectives are to enhance productivity trough decreased downtime and minimized quality losses as well as decreased tooling and consumables costs.

Machining Technology and Advancements

Problems such as the geometric complexity and dimensions make hard to use foundry and plastic deformation techniques to shape metal parts.

In fact, foundry cannot assure a proper accuracy of the surface finish and material properties, while deformation is limited by size (bigger pieces requires bigger forces, hence bigger machineries) and material type (it could be hard to deform). Moreover the geometry complexity can create even more severe difficulties.

Most of this problems are overcame thanks to metal cutting, a technique that makes possible the removal of the material in excess creating chips by using a cutting tool.

Analysing the cutting zone some specific zones can be highlighted.

1.1.1 Machining Techniques

Shaping and Planing

In this case, a plane surface is achieved. During shaping, the tool (shaper) has a seesaw motion and after each cutting the tool moves perpendicularly to have another part to cut (feed – "*avanzamento*" in the picture). The cutting in this case is said to be intermittent (as it is not continuous). Figure 1.1 illustrates the shaping process.

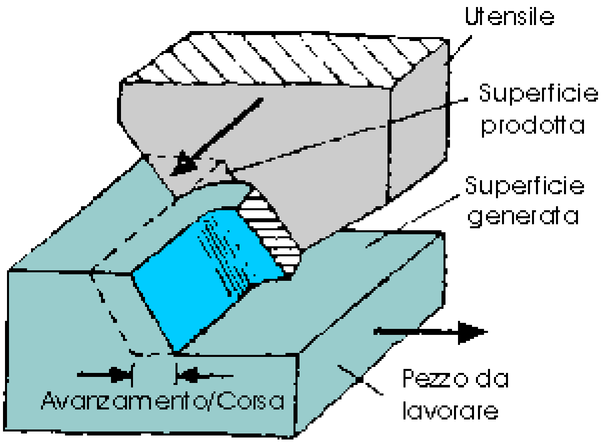


Figure 1.1: Shaping

If the length of the piece is bigger, the cutting with the shaper becomes difficult, hence the planer is used.

The planer is geometrically very similar to the shaper (linear relative motion between the workpiece and a single-point cutting tool to machine a linear toolpath), but it is larger and with the entire workpiece moving on a table beneath the cutter, instead of the cutter riding a ram that moves above a stationary workpiece. The table is moved back and forth on the bed beneath the cutting head either by mechanical means or by a hydraulic cylinder.

Turning

This operation is used to achieve cylindrical shapes. Also plain surfaces can be obtained by turning (i.e. a plain base at the beginning and/or at the end of the shaft). The cutting machine used for this operation is said lathe.

In the picture a typical turning operation is shown, the piece is rotating around its axis while the cutting tool moves in a direction parallel to the axis of the piece; hence it has a helicoidal motion respect to the piece.

To obtain a plain surface, the tool moves along the base, in a radial direction and this causes a reduction in the length of the piece.

Figure 1.2 illustrates the turning process.

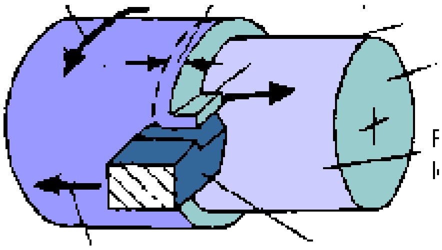


Figure 1.2: Turning

Drilling

It is an operation that is used to make a hole in a solid. The cutting is achieved through the rotation and an axial movement of the drilling tool. Obviously the hole has a cylindrical shape. In the figure a draft is shown.

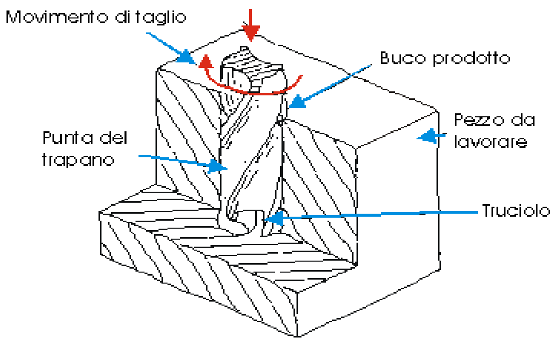


Figure 1.3: Drilling

Milling

This is a versatile operation that can be used to achieve different surfaces. In the picture the operation is used to obtain a plane surface: the cutting tool, with several cutting edges has a rotational movement while the piece advances creating a continuous cutting.

Grinding

In this case the cutting tools are the abrasive grains of the rotating wheel. The wheel has on its surface a huge number of grains with random direction. Evidently, in this case the chip dimension is extremely small.

Figure 1.4 illustrates both the milling (on the left) and the turning (on the right) processes.

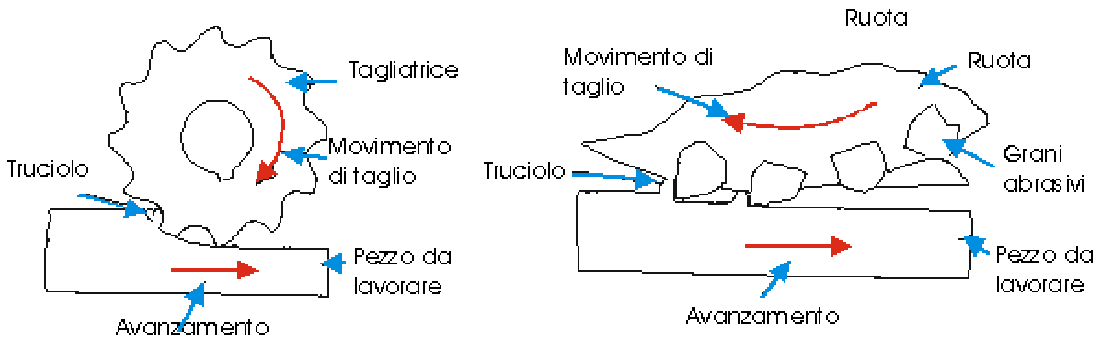


Figure 1.4: Milling (left), Grinding (right)

Turning

The three most widely used machining operations are turning, milling and drilling. In this study we will focus on turning.

To machine metals the workpiece is held in the chuck of a lathe and rotated, and then a rigidly held tool is moved at a constant rate along the axis of the rotating work piece, cutting away a layer of the material. The metal layer that is cut away and flows over the tool is called a chip. The tools surface over which the chip flows is called the *rake face*. The other side of the tool that is also facing uncut material is called the *flank* or *clearance face* of the tool and the intersection of these two sides form the cutting edge. The flank is positioned with a *clearance angle* so there is no contact with the newly cut metal surface. The third side of the tool that is facing the center of the work piece is the *end clearance face* which all so is positioned at such an angle that as little friction as possible takes place.

The intersection of the three faces that are facing the work material is called the *nose* of the tool and has often a radius between the two clearance faces named the *nose radius*. The nose radius makes the tool more rigid and prevents failure which would be expected with a shape-nosed tool.

The angle between the work piece's axis of rotation and rake face can be adjusted to give better cutting performance and is called the *rake angle*, α, and is shown in figure 1.6.

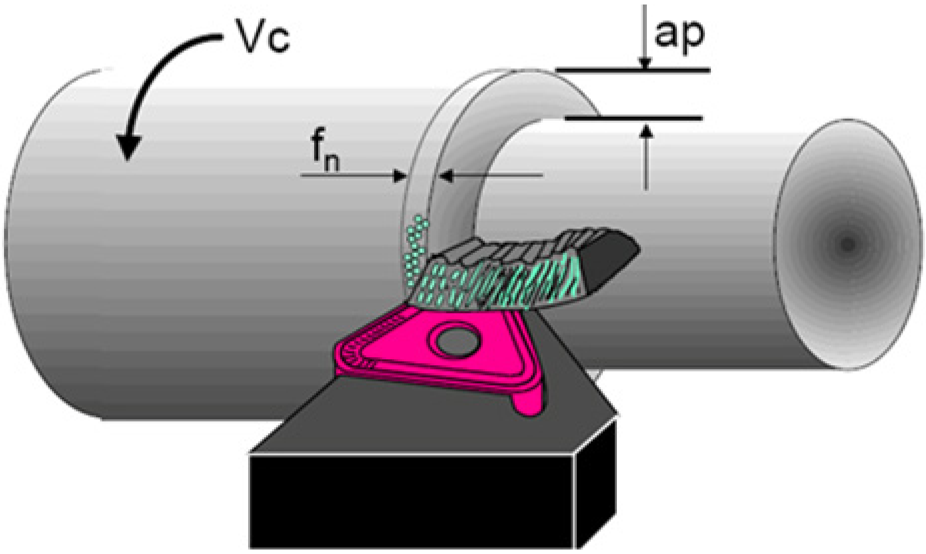


Figure 1.5: Turning Process

Here the most important cutting parameters are shown, in the table below (Table 1.1) they are listed according to the ISO nomenclature:

	Parameter	Unit of Measurement
v_c	Cutting Velocity	m/min
n	Revolution per minute	Revolution/min
D	Diameter	mm
f_n	Feed rate	mm/revolution
a_p	Depth of cut	mm
Q	Chip Volume	cm^3/min
h	Chiip Width	mm
P_c	Power required	kW
k_c	Specific Cutting Force	N/mm^2

Table 1.1: Machining Paremeters

- Cutting Velocity (v_c):
  - It is defined as *Peripheral Constant Velocity (m/min)*;
  - Vc is not a diameter function, while n (rpm) is;
  - $v_c = \frac{n \cdot \emptyset \cdot \pi}{1000}$; $n = \frac{v_c \cdot 1000}{\emptyset \cdot \pi}$;

- Feed **(f_n)**:

It indicates the movement of the tool in each revolution or unit of time. Usually its measure is revolution per minute (rpm);

- Depth of cut **(a_p)**:

It is the distance (usually in mm) between the original surface and the new surface after the cutting.

Changing this set of parameters the life of the tool can be changed, as well as the volume of the removed chip.

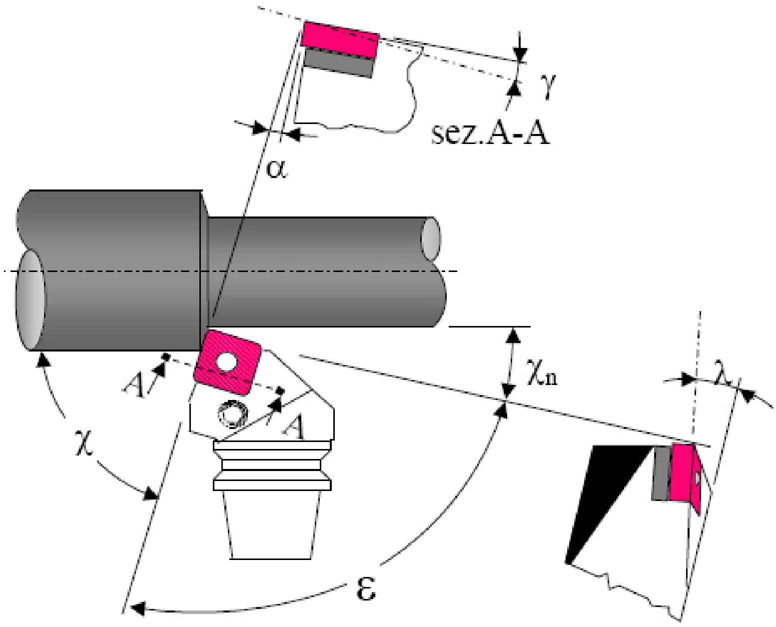


Figure 1.6: Turning of cylindrical shafts with the principal parameters

γ	Rake Angle	χ_n	Back rake angle
α	Clearance Angle	ε	Nose Angle
χ	Entering Angle, in orthogonal cutting it is 90°.	λ	Inclination angle, in orthogonal cutting it is zero

As said the metal removed by the tool is called chip. The tool has different surfaces and its orientation is defined by some angles.

The tool surface over which the chip flows is called the rake face. The other side of the tool that is also facing uncut material is called flank or clearance face, finally the intersection of these two sides forms the cutting edge.

The most important angles to define the tool are:

- Rake angle (γ) – The angle between a line parallel to the workpiece rotational axis and the rake face of the cutting insert, see figure 3b and figure 4. A negative rake angle provides a stronger cutting edge but also leads to higher cutting forces.

- Inclination angle (λ) – The angle at which the cutting insert is mounted in the tool holder.

- Entering angle (χ) – The entering angle is defined as the angle between the cutting edge and the feed direction. The entering angle controls the length of the cutting edge and also affects the cutting forces. A small entering angle gives a large cutting edge length for a given depth of cut and thereby increases the passive (or radial) force component.

  A small entering angle promotes longer tool life in a number of ways:

  - A gradual build-up of forces as the cutting edge length is increased gradually.

  - Initial contact with the workpiece is made further from the relatively weaker tip of the insert.

  - The surface layer, which often is harder, perhaps by scales from the previous forming process, heat treatment or work-hardening from the previous cutting pass, is spread over a larger length of the cutting edge. This reduces notch wear.

  - The greater contact length promotes better heat conduction into the workpiece and more even heat distribution in the cutting insert.

- Clearance angle (α) – The angle between the tangent to the workpiece surface and the flank face of the insert. The clearance angle is often on the order of 6-10° to avoid rubbing the flank face against the workpiece.

Finally there is the nose radius. The purpose of the nose radius is to provide strength to the tip (nose) of the insert and it is essential in determining the surface finish. A small nose radius is useful for small cutting depths and reduces vibrations but suffers from lower strength while a larger nose radius is desirable for higher depths of cut and feed rates, as this result in higher forces, demanding a stronger cutting edge.

A special case of turning is orthogonal cutting (Figure 1.7). In orthogonal cutting a straight tool edge is used and it is normal to both the direction of cutting and to the feed. This can be achieved by cutting in tubes or flanges, where flanges have the advantage of having a constant cutting speed over the cutting edge. The disadvantage is that the rotational speed has to be increased gradually as the diameter decreases in order to have a constant cutting speed.

In order to have a purely orthogonal setup, the nose radius of the tool should not be used for cutting; otherwise the condition is known as "semi-orthogonal" cutting.

1.1.2 Material Flow & Deformation

In the process of machining, a metal layer is removed. The resulting chips are plastically deformed and large quantities of energy are needed to deform and move the chip on the rake face.

The idealized deformation is shown in the figure. The chip is generated at the shear plane (OD), defined as the line connecting the tip of the tool with the uncut surface.

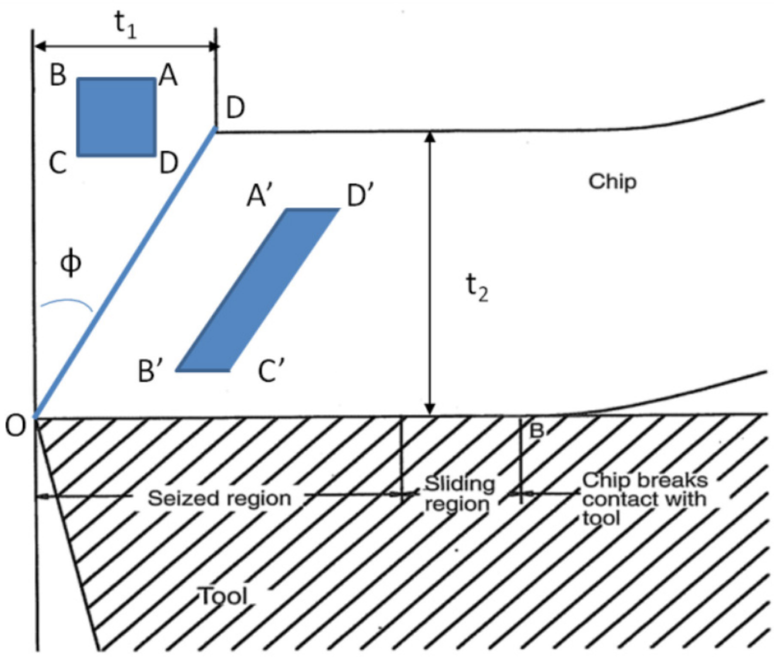


Figure 1.7: Orthogonal Cutting

The shear plane angle can be found by a simple goniometric relation:

$$\phi = arctan\frac{t_1}{t_2}$$

where t1 and t2 are the undeformed chip thickness and the chip thickness, respectively.

The volume of the metal ABCD is plastically deformed to the new shape (A'B'C'D').

The chip size and shape depends on cutting conditions and material used, but it is usually work-hardened.

During machining the chip tends to spread sideways, so that the width becomes greater than the depth of cut. Soft materials tends to spread more than harder ones. The chip thickness is not constrained by tooling and may be much greater than the feed, usually largest at the middle followed by a slight decrease towards the sides.

The lower surface of the chip, facing the rake face, is usually smooth compared to the upper surface which is always rough with a serrated shape. Periodic cracks often occur in the chip, breaking up the outer edge into segments. Due to the complex shape of the chip it is usually simplified to a rectangular cross section, whose height is the measured mean thickness of the chip and whose width is the depth of cut.

Actually the formation process of chips is pretty complex even if it can be simply visualised imagining the work material as a deck of cards standing on the long side and moving towards the tool (figure 1.8). Each card represents the thickness of a shear plane. Hence the shearing takes place between the "cards" at intervals and little or no deformation takes place in the bulk of the card.

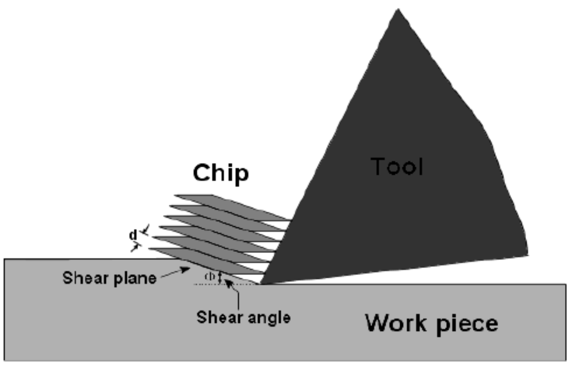
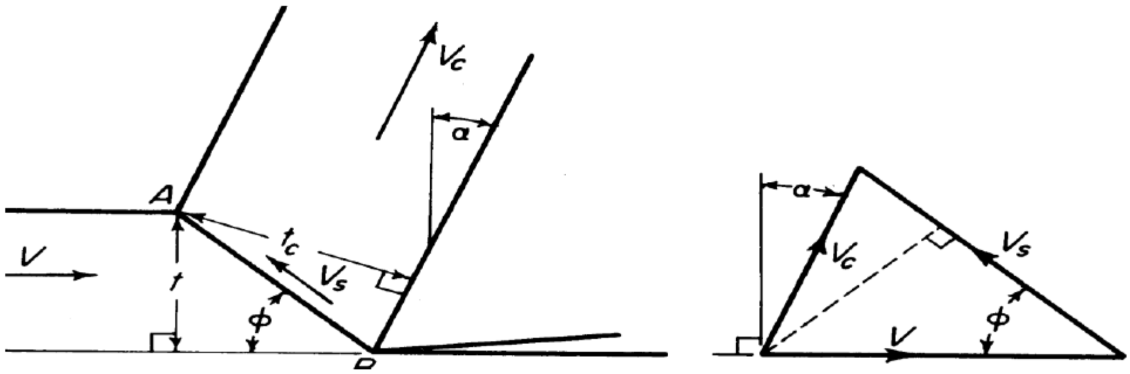


Figure 1.8: Chip Formation



$$Vc = \frac{\sin\phi}{\cos(\phi-\alpha)}V \qquad Vs = \frac{\cos\alpha}{\cos(\phi-\alpha)}V \qquad \gamma = \frac{Vs}{V * \sin\phi}$$

Figure 1.9: Relationships between shear angle, chip thickness and velocities

To fully understand machinability, it is essential have a clear view of the physics of the problem. In the figure 1.9, the principal relations are highlighted and 3 equations for the velocity in chip formation and velocity of shearing are presented.

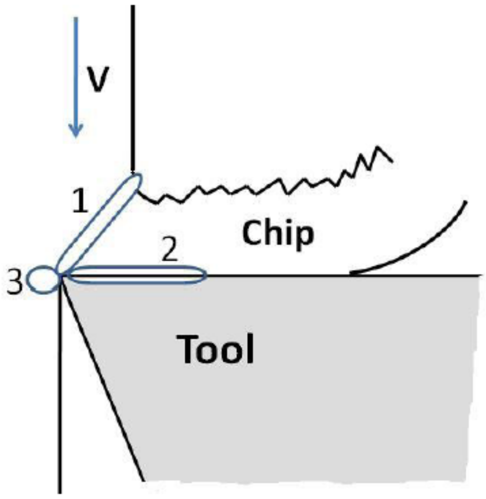


Figure 1.10: The three shear zones

Three zones can be defined in cutting, regarding the material flow and deformation, this are showed in figure 1.10:

- ***Primary Shear Zone (1)***

  It is actually the shear plane, even if in reality is not a plane (it has a thickness), for simplification it is considered to be a plane defined by an angle φ. This angle together with the rake angle influences the deformation of the chip, hence its thickness.

- ***Secondary Shear Zone (2)***

  Here the chip shears against the tool rake face and receives additional deformation through shearing and sliding. The process in the primary and secondary shear zones depends on each other, as the material that flows against the rake face has been plastically deformed and heated in the primary shear zone.

Here the chip can be in condition of sliding or in condition of seizure. The latter is favoured by surface free from contaminations (greases, oxide films) and plastic deformation of the surfaces. Long cutting time, high cutting speeds and little difference in hardness between tool and workpiece also promote seizure.

Thanks to the quick stop technique and modelling, it has been possible to draw flow lines and measuring the contact length between the tool and the material. In figure 1.11 is highlighted the secondary shear zone, and it shows how the shear stress is less intense between O and Q. This behaviour explains that the wear on the rake face of the tool is found to be localised in a small zone between Q and M.

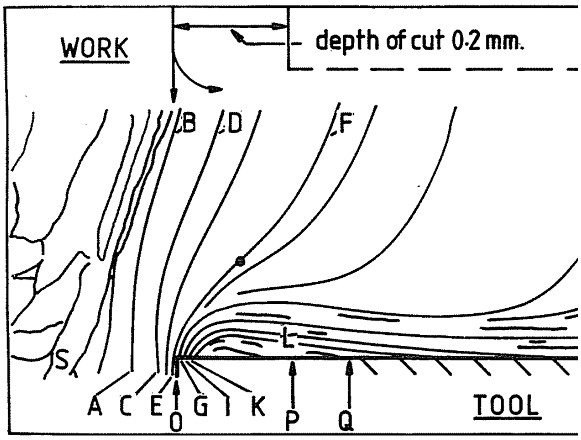


Figure 1.11: Flow lines and formation of a chip by coming across the rake face of the tool

- ***Tertiary Shear Zone (3)***

  In this zone, the tool moves over the newly cut surface and introduce a friction force resulting in deformation on the flank. Of course, also this newly created surface is plastically strained. The depth and amount of strain under the machined surface depends on the cutting parameters and on the materials used (workpiece and cutting tool). The tool is not infinitely sharp and moving on the new surface it wears. The integrity and sharpness of the tool edge is of great importance since a less sharp edge due to wear, increases the imposed strain on the machined surface.

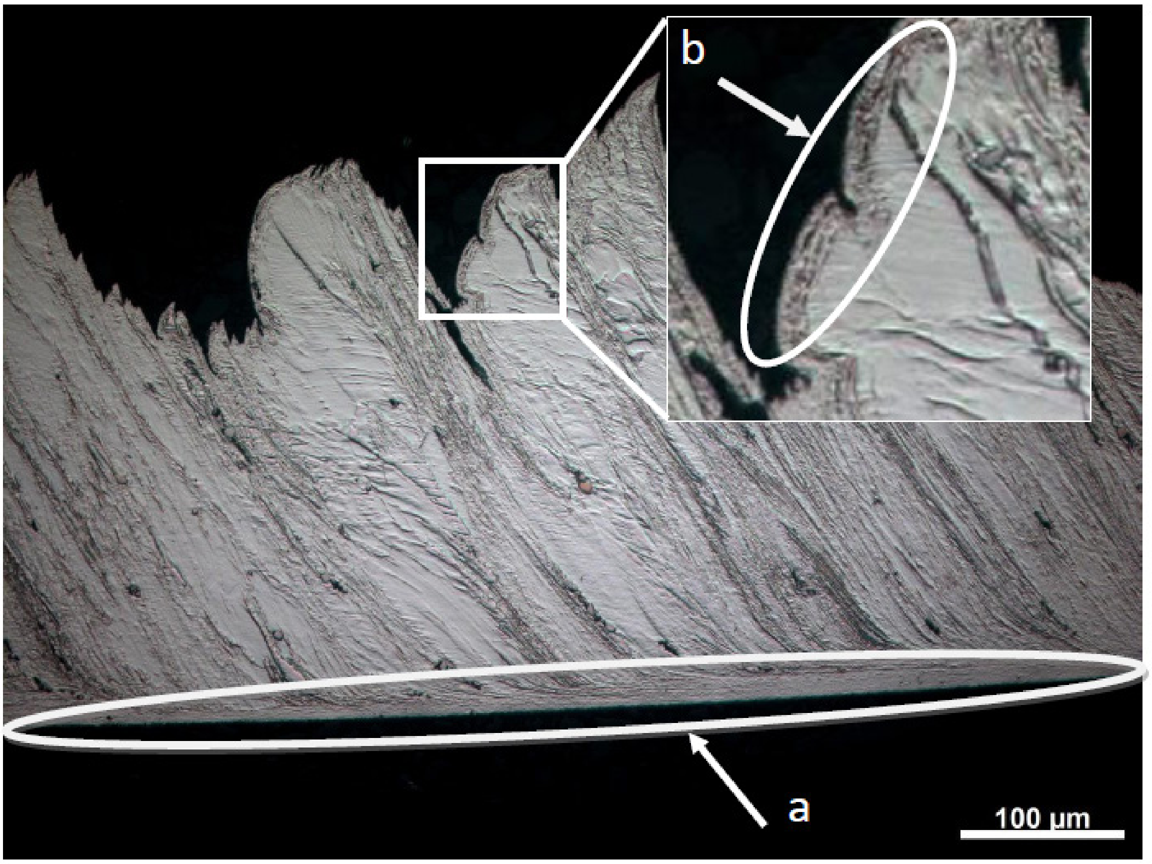


Figure 1.12: Impact of secondary (a) and tertiary (b) shear zones on the chip.

Figure 1.12 shows the impact of secondary and tertiary shear zones on the chip.

The Chip

Chips formed during the machining of workpieces can have different characteristics. The side of the chip in contact with the cutting tool is normally shiny, flat and smooth while the other side, which is the free workpiece surface, is jagged due to shear.

It is important to study the formation of chips during the machining process as the former affects the surface finish, cutting forces, temperature, tool life and dimensional tolerance. Understanding the chip formation during the machining process for the specific materials will allow determining the machining speeds, feed rates and depth of cuts for efficient machining and increased tool life in the specific actual machining operation.

The chips can be divided in three groups according to their characteristics and appearance: continuous chip, discontinuous chip and serrated chip (figure 1.13).

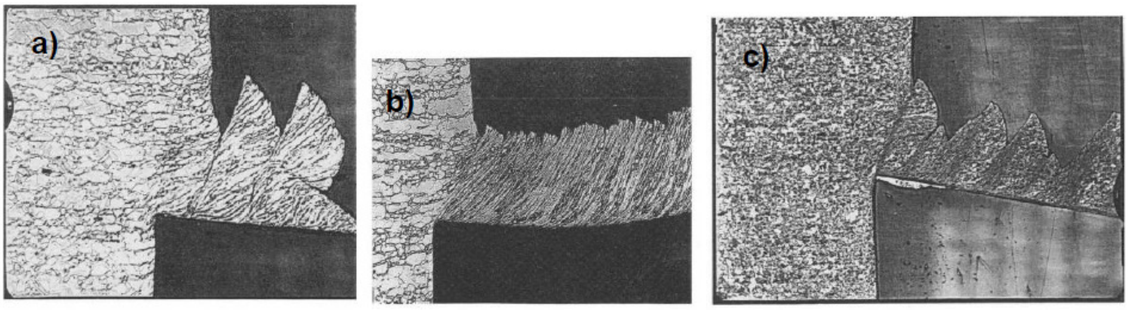


Figure 1.13: Chip morphologies. a) discontinuous chip b) continuous chip c) serrated chip

The continuous chip is usually observed when machining soft or ductile materials such as copper or aluminium. During continuous chip formation, a continuous "ribbon" of metal flows up the chip-tool zone. This is considered too be the idea condition for cutting action.

Sometimes, especially when machining at low-to-medium speeds soft non-ferrous metals, work-hardened metals or ductile metals a Built-Up-Edge (BUE) can result. Condition of seizure does not always result in a flow-zone at the interface: material may accumulate layer by layer on the rake face and around the cutting edge of the tool, displacing the chip from the tool; this is the *built-up edge*. The BUE and the work material are one continuous body of metal where the layer of shearing has been transferred from the interface of tool/material to the top of the built-up edge; hence the BUE changes the geometry of the cutting and can be considered as an extension to the cutting tool. The built-up edge is unstable, growing until fragments breaks off which creates a typical feature on the machined surface and on the bottom of the chip.

Common problems are the built-up edge breaking off and being embedded in the workpiece during machining, decrease in tool life and final poor surface finish of the workpiece.

To reduce built-up edges, improving the lubrication conditions, use sharp tools and better surface finish tool but also apply ultrasonic vibration during machining process may help.

The discontinuous chip is usually formed when cutting hard, brittle materials, partly because these materials cannot withstand high shear forces and therefore the chips formed shear cleanly away. However, the chips formed may be firmly or loosely attached to each other or may leave the cutting area in a fine shower (e.g. when cutting hard brass). When discontinuous chips are formed there is a greater possibility of tool chatter (unless the tool, tool-holder and workpiece are held very rigidly) due to pressure at the tool tip increasing during chip formation and then releasing suddenly as the chip shears.

This chip is typical of brittle materials, low cutting speeds, large feed and depth of cut, high tool-chip friction.

Finally the serrated chips are semicontinuous chips, with a saw-tooth appearance. Sometimes these chips are referred as cyclical, as they alternate high shear strain zones with low shear strain zones. Usually this type of chip is associated with difficult-to-machine metals at high cutting speeds.

They are produced very similarly to the discontinuous chips and the process can be explained by the stick-slip model, based on the friction between the chip being formed and the cutting tool. As the chip slides against the tool the friction force will grow as the surface increases leading to a point where the chip will stick to the tool. The material will then be pushed up along the shear plane making the chip thicker. However this will increase the force on the chip which will overcome the friction force holding it back and the chip will slip away. At this point the thickness of the chip will decrease thanks to the increased speed of the chip. As this cycle repeats itself a serrated chip will be formed.

The Tool

As seen before, metal cutting is a deformation process caused by a force applied on the material.

The choice of the tool is essential and it relies especially on the capability of it of retaining its form despite the high forces and the high temperatures.

First requirement to meet is that the tool is harder of 30 – 50 % than the workpiece (not more than 50%, otherwise the heat production due to attrition would be excessive and would decrease the properties both of the workpiece and the tool).

Actually during machining (hence during dynamic condition) the increase in temperature is more critical for the tool than the workpiece, this is because the workpiece undergoes a severe plastic deformation, therefore the work-hardening balances at least partially the softening due to the increasing of temperature.

According to T.N. Loladze, the requirement to satisfy is the following:

$$1{,}35 < \left(\frac{H_{tool}}{H_{work}}\right)_{MOD} < 1{,}50$$

where H indicates the hardness and MOD dynamic conditions with high velocity and temperature.

Therefore the most important characteristics of the tool material are the following:

- Hardness (H) must be higher than the hardness of the workpiece and this must be valid also at high temperatures ($H_{tool} > H_{work}$ about 30 – 50%);
- The resilience must be high and the tool must not be brittle;
- Wear resistance must be high;
- Thermal conductibility, ***k***, must be high as well as the specific heat, ***c***;
- The attrition coefficient $\boldsymbol{\mu}$ between tool and workpiece must be low.

Of course it is extremely hard to find a material that has all this features at once, but the materials which better fit all these are the following, and for this they are usually used for cutting tool:

- High Carbon Steel (0.6-0.9% of Carbon);
- High Speed Steel (HSS);
- Sintered Carbide;
- Ceramic material.

Different are the abrasive materials such as silica carbide, aluminum oxide, diamond powder and so on, used for grinding.

The figure 1.14 shows how the hardness (Brinnel) of the different materials decreases with the increasing temperature. It is clear that the High carbon steels do not have a good resistance over temperature, better do the HSS, thanks to the high amount of tungsten, and the most stable ones are the Tungsten Carbides (WC), but they are the most brittle.

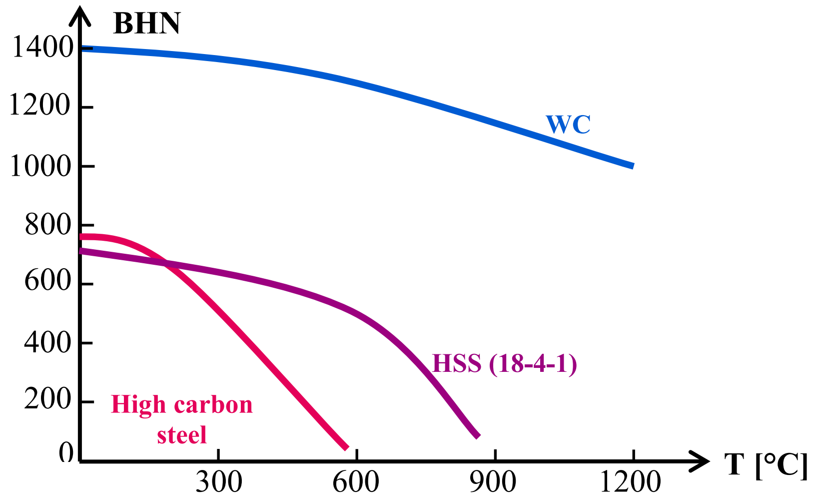


Figure 1.14: Hardness vs. Temperature

A typical composition for High Carbon Steels and HHS is listed in the table below (table 1.2):

MATERIAL	C	W	CR	V	M_n	Fe
High Carbon Steel	0.9	-	-	-	0.6	remaining
HSS	0.75	18.0	4.0	1.0	0.6	remaining

Table 1.2: Composition for steel tool

These steels are heat treated to improve the resistance and the hardness.

The sintered carbide, instead, are obtained by sintered powders, hence they are pressed at high temperatures and pressures. This treatment is necessary for the difficulty of processing such a hard material. The powder grains are sintered together also thanks to a binder (e.g. cobalt) that helps to reduce porosity. Other components (e.g. TaC and TiC) are added to achieve a more uniform surface finish.

This processing techniques allows to obtain just small tools (about 10cm), because the bigger are the dimensions, the higher the required forces to press the powders during sintering.

The table 1.3 shows a typical composition for tool made of metal carbides:

WC	Co	TaC	TiC	USO
94.0	6.0	-	-	Acciaio fuso
70.7	4.5	12.2	12.6	Acciai
72.0	8.5	11.5	8.0	Leghe al nichel

Table 1.3: Composition for Metal Carbide cutting tools

Recent is the use of coated carbide tools. The most used materials are TiC, TiN, CBN (nitride of boron and carbon), Al_2O_3. The layers of these materials are really thin (~5µm) and take advantage of the toughness of the carbide and the hardness and wear resistance of the coating.

These particular tools are very used to cut the superalloys (especially nickel based and titanium based), as these have a very high resistance to high temperatures and hence have an important application as material for aerospace engines. The average life of these tools is between 5 and 10 minutes, a normal tool with hard-to-machine materials would have a life well under 1 minute of continuous cutting.

Ceramic materials such as Al_2O_3 are very resistant to wear and high temperatures, but are quite brittle and hence are used only in very particular machining operations with:

- High cutting velocities (at low speeds the probability of failure increases);
- Continuous cutting for smooth surfaces;
- Cutting conditions creating to small chips.

The following table (table 1.4) reports the maximum cutting speed for the different tools cutting of soft steel:

TOOL MATERIAL	CUTTING SPEED (m/min)
High Carbon Steel	5
HSS	30
Sintered Carbide	150
Coated Carbide	350
Ceramics	600

Table 1.4: Cutting Speeds for different tool materials

According to the ISO-513 classification, we can have:

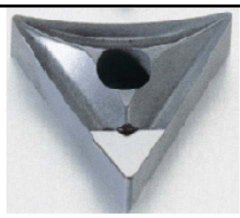
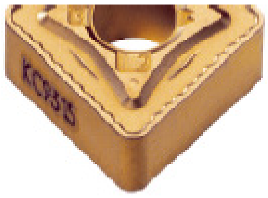
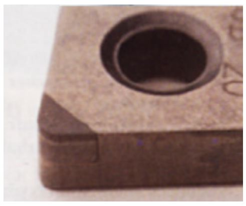
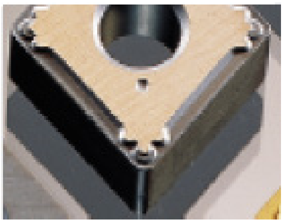
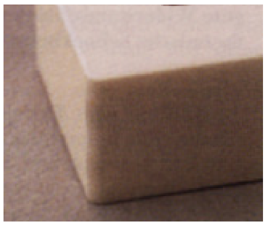
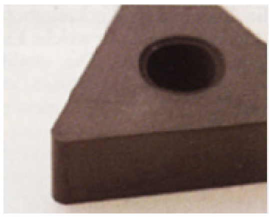
HW Hard Metal without coating		DP Policristalline Diamond	
HC Coated Hard Metal		BL Nitrite of Cubic Boron	
HT Cermets		CA Ceramic Oxide	
HF Hard Metal with fine grains		MC Composite Ceramics	
HSS High Speed Steels		CN Nitride of Ceramic Silicon	

Table 1.5: Cutting material classification according to ISO-513

- ***Tungsten Carbide***

The tungsten carbide is a cutting material that can withstand high temperatures extremely well, even more than HSS and HSS/Co. However is not very resilient and is sensible to sudden temperature changes. The grades are made up by Tungsten, Titanium, Tantalum, Molybdenum and as binder the cobalt is used.

Nowadays, the tungsten carbide (WC) is produced only by sintering and in the figure the basic steps of the process are shown.

Figure 1.15 shows the sintering process of HW cutting tools.

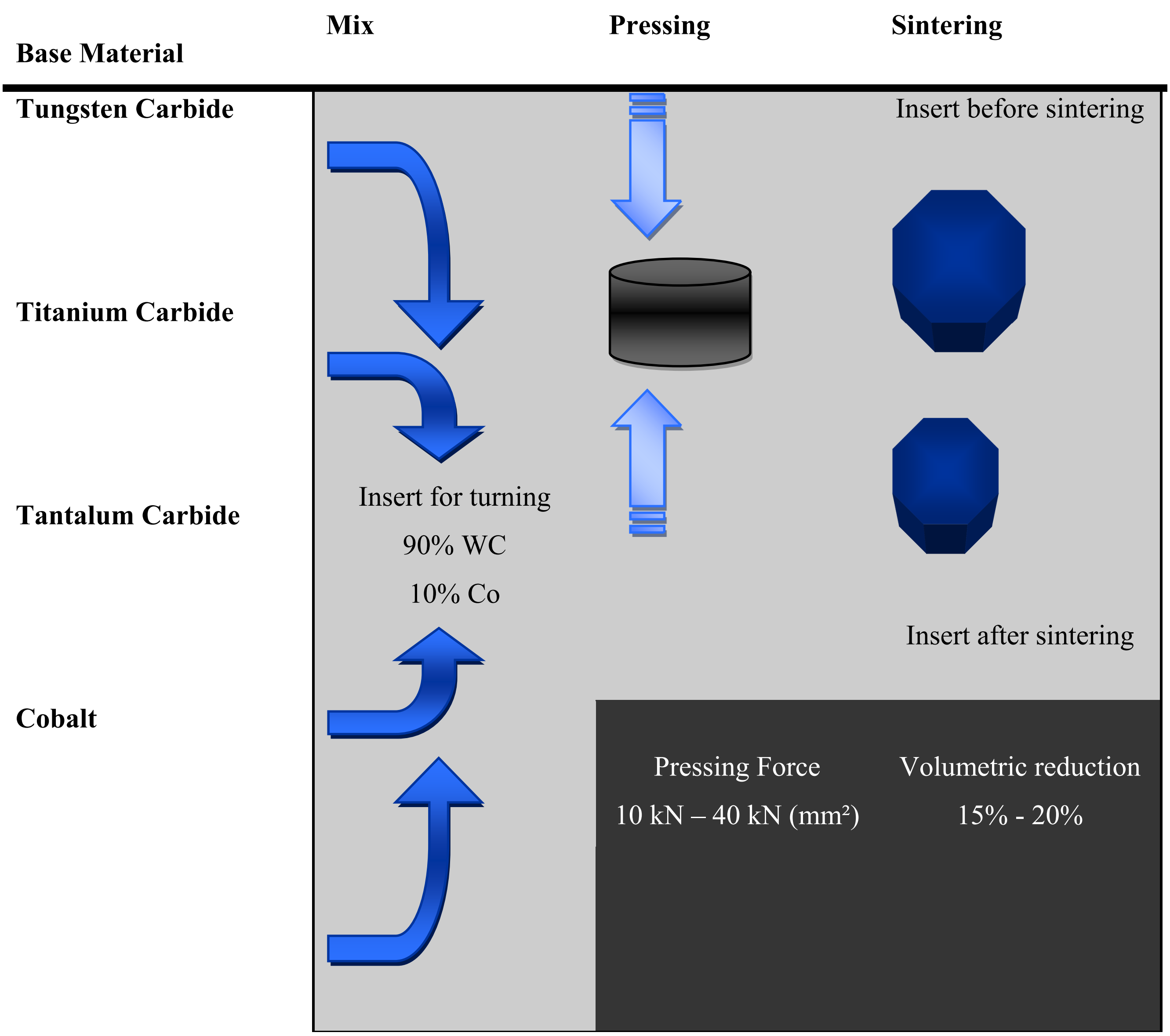


Figure 1.15: Sintering Process for HW cutting tools

The ISO classification uses also colours:

P = Blu e. g. **P 40** **M = Yellow** e. g. **M 20** **K = Red** e. g. **K 10**

N = green e. g. **N 10** **S = Orange** e. g. **S 20** **H = Grey** e. g. **H 10**

The letters refer to the materials that are worked by the tool, while the number refers to the wear resistance / toughness.

Table 1.6 shows the ISO classification for the cutting tools.

MATERIAL	ISO GROUP	TiC+TaC+NbC	% Co %	CUTTING CONDITIONS
P Acciai, getti in acciaio, materiali a truciolo lungo	**01**	30/40%	4/8%	Turning and drilling with high speed velocities and little chips, good surface finish, extremely precise tolerances, no vibrations and chatters.
	10	20/30%	5/8%	Turning, threading, milling with high speed and small/medium chip thickness.
	20	12/15%	6/9%	Turning, milling with medium velocities and lo-to-medium chip thickness.
	30	5/8%	7/10%	Turning, milling, planing with low-to-medium velocities, medium-to-high chip thickness, usually used in non-favorable cutting conditions.
	40	3/5%	8/11%	Turning, Planing, milling, truncation with slow speeds, thick chips, use also with high rake angles. Usually non-favorable cutting conditions.
	50	2/4%	11/12%	Turning, planing, truncation at slow speeds. It allows thick chip formation, high rake angle. Used for interrupted cutting.

Table 1.6: ISO Classification for the Cutting Tools

As already mentioned, the coating is a small layer (about 5 micron) covering the core material of the tool. The advantages are essentially less wear (flank and crater wear), hence a longer tool life that improves the machining time and helps in cost savings.

The coating processes are:

- CVD Chemical Vapour Deposition (gaseous atmosphere at 1000-1100°C)
- MT-CVD Medium Temperature – CVD (about 600-700° C)
- PVD Physical Vapour Deposition (ionic atmosphere at 450-500°C)
- CVD / PVC Combination of the two processes.

The ISO classification uses several parameters to differentiate the tools.

They are all reported on the packaging of the tool. In fact on the packaging there is a tag similar to the table shown below (table 1.7).

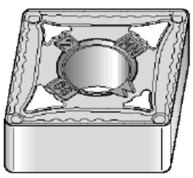
W	N	M	G	08	04	08	FN	KC9125
Form	Clearence Angle	Tollerance	Type	Edge	Thickness	Nose Radius	Chipbreaker	Quality

Table 1.7: Parameters used for the Tool Classification

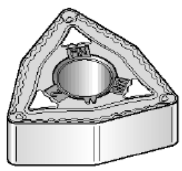
- **Form**

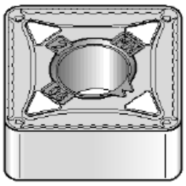
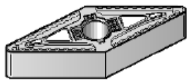
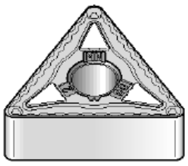
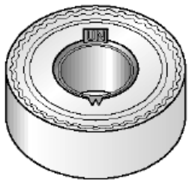
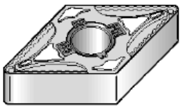
Here the different forms are reported.

- **C** rhomboid 80°



- **W** trigon 80°



- **S**quare 90° 
- **V** rhomboid 35° 
- **T** riangle 60° 
- **R**ound 
- **D**rhomboid 55° 

- **Clearance Angle**

According to the width of this angle, a letter is used to indicate the type of the tool as shown in table 1.8. Figure 1.16 shows some examples of clearance angles.

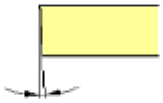
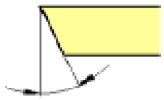
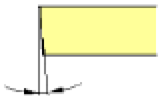
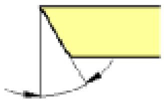
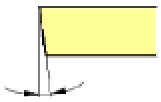
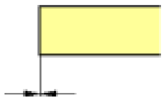
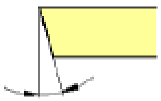
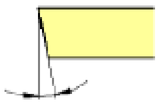
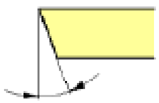
Classification of the Clearence Angle					
A	3°		**F**	25°	
B	5°		**G**	30°	
C	7°		**N**	0°	
D	15°		**P**	11°	
E	20°		**O**	Special angle, it requires always a description	

Table 1.8: Classification of clearance angles

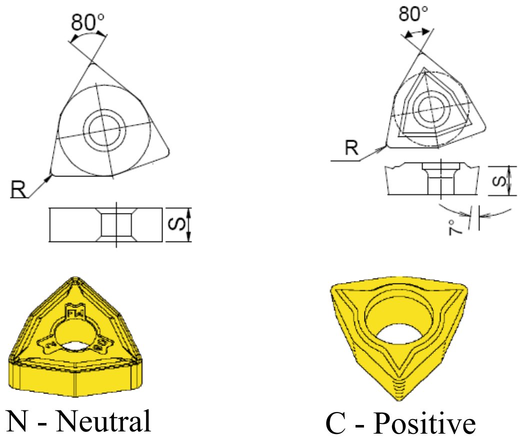


Figure 1.16: Examples of Clearance Angles

- **Tolerance**

This value is strictly related on the processing technique used in the production (usually or sintering or grinding). Also in this case there are some classes, each of these, has a tolerance value, also related to the geometrical value shown in table 1.9.

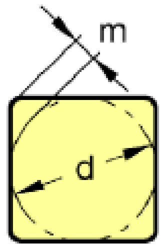
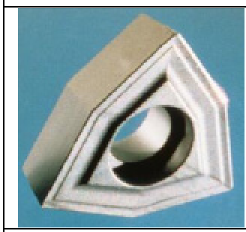
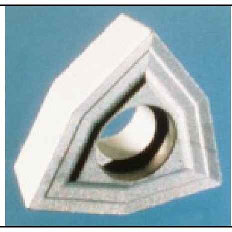
<table>
<tr><td>WNMG
Sintered</td><td>WNGG
Grinded</td><td rowspan="2"></td></tr>
<tr><td></td><td></td></tr>
<tr><td colspan="3">Versions:
H - O - P - S - T - C - E - M - W – R
Tolerance for “d”</td></tr>
<tr><td>Inscribed circle “d”</td><td>Class of tolerance</td><td>Value of tolerance</td></tr>
<tr><td></td><td>A-C-E
G-F-H</td><td>± 0.025
± 0.013</td></tr>
<tr><td>3.9-10</td><td rowspan="5">J-K-L-M-N</td><td>0.05</td></tr>
<tr><td>10-15</td><td>0.08</td></tr>
<tr><td>15-20</td><td>0.10</td></tr>
<tr><td>20-26</td><td>0.13</td></tr>
<tr><td>26-32</td><td>0.15</td></tr>
</table>

Table 1.9: Tool Tolerances

Forces

Different tool angles influence the cutting forces. For semi-orthogonal cutting the force can be divided in to three components met in different directions. The one acting in the rake face normal to the cutting edge is usually the largest and is called the cutting force, F_c. The cutting force acts on the tool and generate a compressive stress on the contact area on the rake face.

The second one is named the feed force, F_f, and acts parallel to the feed direction. The feed force induces a shearing stress on the contact area and is normally a smaller stress than the first one.

The third one normal to the other two forces pushing the tool away from the work material is called passive force (F_p), it is the smallest and it is usually not considered because of its low influence.

The force needed to form the chip is dependent on the area of the shear plane and the yield strength of the material under working conditions. An increase in either shear plane area or yield strength of working material results in an increase of the cutting force, with the shear plane area having a dominant influence in practice. Due to the thin layer removed in machining the forces needed are usually small, however the contact area is small generating high stresses (F/Area). An increase of the operator parameters feed and depth of cut leads to a direct proportional increase of the forces i.e. an increase of area.

The tool forces are also influenced by the rake angle and an increase here would lower both feed force and cutting force. The shear plane angle greatly influences the shearing force but is not as easily controlled.

Ductile metals may generate a large contact area on the rake face and a small shear plane angle and thus, increasing the forces. Increasing the cutting speed decreases the thickness of the chip in most metals and decreases the forces. A lubricant may also lower the forces acting on the tool and are most affective at low cutting speeds.

Figure 1.17 is a diagram of cutting forces in the cutting process.

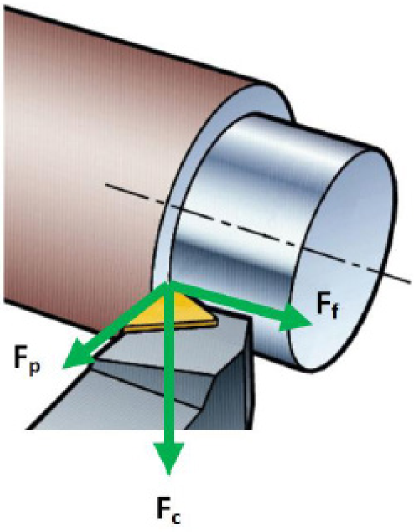


Figure 1.17: Cutting forces diagram

Heat

The power consumed in metal cutting is in large part converted into heat near the tool. Most of the heat generated on the shear plane is transferred into the chip and from there only a small proportion is conducted into the work material.

M. Trent and K. Wright states:

"The work done in (1) deforming the bar to form the chip and (2) moving the chip and freshly cut work surface over the tool is nearly all converted into heat. Because of the very large amount of plastic strain, it is unlikely that more than 1% of the work done is stored as elastic energy, the remaining 99% going to heat the chip, the tool and the work material."

Temperatures at the material/tool interface increase with cutting speed. For high metal removal rates of work materials, with high melting point, the tools are heated to high temperatures. These high temperatures combined with stress may cause the tools to fail after short cutting times. Most of the heat raising the tool's temperature is generated in the flow-zone under condition of seizure.

Cutting Fluids

Usually the use of a cutting fluid improves the quality of the cutting operation. However sometimes dry cutting is used, especially for the negative impact cutting fluids have on the environment.

Sometimes also some chemical active cutting fluids are used. For example to cut steels a chlorine fluid is used, the chlorine combines with the steel creating ferrous chlorine, that acts as lubricant and prevent the formation of a BUE.

Cutting fluids has few major benefits:

1. Reduce friction working as lubricant reducing the contact length between the tool and the workpiece. This leads to lower forces (and hence also power saving), prevent the BUE formation assuring a better surface finish.

2. Help the cutting tool to better dissipate the heat, improving tool life. Of course this action is more pronounced at lower cutting speed, as usually when the velocity is high most of the heat is taken away from the chip.

3. Help to keep the cutting zone clean pushing away the chips (useful especially when the chips are very little such as in grinding).

4. They can protect the surface from the corrosion.

Therefore a good cutting fluid should have the following features:

- High thermal conductivity and specific heat to absorb and dissipate the heat;
- Low viscosity and little molecular dimensions to penetrate the interface tool-workpiece;
- Being chemically active to create a chemical product that helps to lower the forces and the attrition on the tool tip;
- Being economical and highly available;
- Not being corrosive, but helping to prevent corrosion;
- Being eco-friendly.

Wear

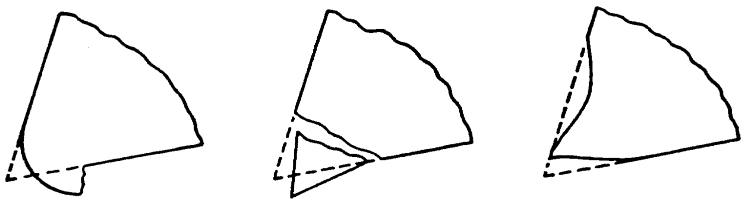
Of course the efficiency and the quality of a cutting process depend mainly from the tool conditions as the geometry integrity.

During machining the tool is under extreme conditions with high temperatures and extensive stresses and thus, the tool is worn down.

The tool life is defined on the wear extension and a tool is said to be worn when it cannot achieve a cutting with reasonable power consumption or with an acceptable surface finish.

The tool life can expire for the following reasons:

- The tool can plastically deform due to the high forces and the high temperatures generated (it should be noted that only metals and alloys can undergo to this process, while carbide and oxides cannot). In fact, at high temperatures and stresses the yield limit of the tool may be exceeded casing a plastic deformation of the tool tip and chipping occurs if small cracks are initiated by cyclic loadingThis situation is represented in figure 1.18 (a).
- The forces lead to a tool failure (figure 1.18 (b));
  - The tool can be gradually worn down due to the cutting process itself (figure 1.18 (c)).



(a) (b) (c)

Figure 1.18: Different tool failures

Once the tool life expired, if the insert is made of steel it is sharpened, if made of carbide or ceramics it needs to be replaced.

While the first two points can be prevented with a proper choice of tool material, tool geometry and cutting parameters, the third point is unavoidable and can only be slowed down and it is called wear.

Wear mechanisms can be divided into abrasion, adhesion, diffusion, and oxidation.

Abrasion

Abrasive wear comes from metal removal by hard particles such as carbides that are harder than the tool material. As the hard particles come in contact with the tool they cut away small amounts of material.

Adhesion

When the work materials surface comes close enough to the tool surface atomic bonds may be formed. The tendency for such bonds comes from attractive forces between the surface atoms of the two materials. If these bonds are stronger than the internal strength, particles may transfer from tool to the work material and generates wear.

Diffusion

At high surface temperatures solid state diffusion may take place between work material and tool. Elements from the work piece can diffuse into the cemented carbide tool and weakens the binder phase of cobalt due to similar atom radius of nickel and cobalt. This results in the carbide particles being pulled out under the influence of high shear stress at the chip-tool interface.

Oxidation

At very high temperatures the tool reacts with the atmospheric oxygen and weakens the tool binder. Subsequently carbides are pulled out of the tool generating wear.

Figure 1.19 shows the wear geometry:

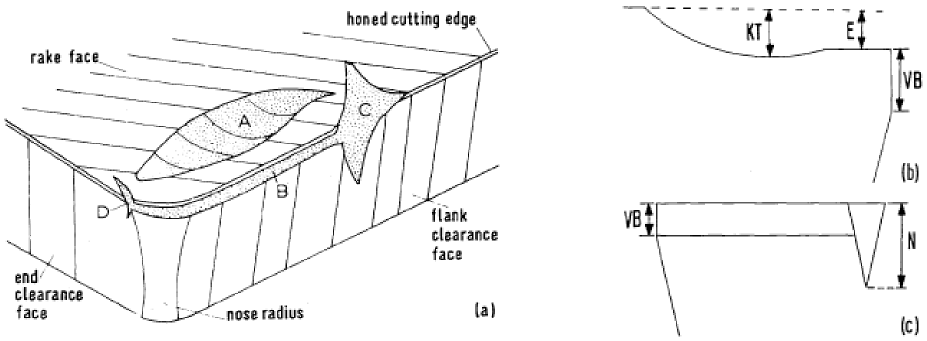


Figure 1.19: In figure (a): zone A crater wear on the rake face; zone B flank wear, zone C and D notch wear. (b) section parallel to the end clearance face, KT is the maximum crater depth, E is the edge depression, VB flank wear land; (c) view of flank clearance face with N notch depth flank face.

- ***Flank wear***

The flank face of the machining tool is subjected to flank wear due to rubbing of the tool along the freshly machined surface. The mechanism causing the flank wear is Adhesive and/or abrasive wear and it is strongly influenced by the cutting speed.

- ***Notch wear***

The notch wear appears at the depth of cut line when machining alloys with a significant strain hardening such as Inconel 718. Notch wear normally appears outside the area of physical contact between work material and tool i.e. outside the depth of cut, DOC. Several possible explanations for this exist:

- Steep temperature gradients at DOC.

- Work hardened layer from the previously cut surface.
- Abrasive oxide on the previously cut surface.
- Chip side flow and localized shearing in the notch region.
- Oxidation.
- Stress concentration due to stress gradient on the free surface.

- ***Crater wear***

The chip moves over the rake face under high temperature and pressure causing friction and adhesion. The result is crater wear on the rake face of the tool due to diffusion and with an increasing wear as temperature increases.

Measuring this type of wear is not simple; hence usually it is condensed in one parameter, defined as:

$$VB = \frac{e}{\frac{1}{2} + f}$$

Where e is the depth of the crater (distance from the lowest point to the height of the surface) and f is the distance between the crater and the flank wear. If the crater is particularly irregular, usually is not calculated the mean VB, but the VB_{max}.

All these wear mechanisms are present in each cutting, but usually only some of them predominates determining the tool life.

Both the crater wear and the flank wear follow the trend showed in the graph with an *initial wear* zone where the wear increases pretty rapidly but VB stays little, followed by a *plateau zone* of almost uniform deformation, ending in a *rapid wear zone*, where the wear has a steep increase.

Figure 1.20 illustrates the typical tool wear trend and tool life.

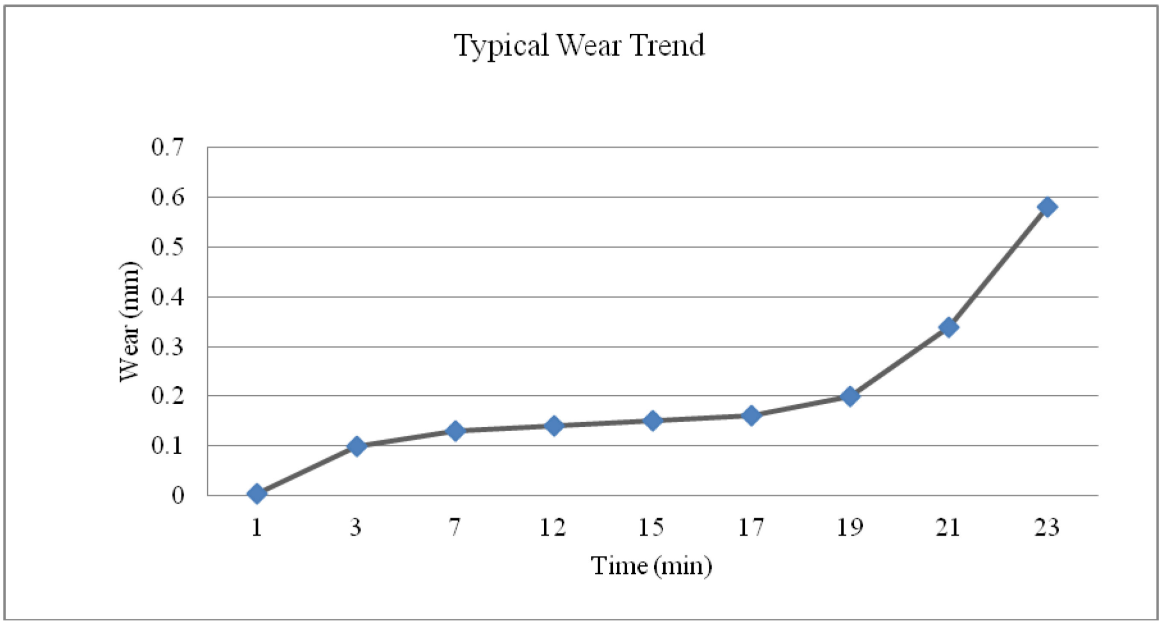


Figure 1.20: Typical Wear Trend and Tool Life

Among the different cutting parameters the one which mostly affect the tool wear is the cutting speed.

To sum up, the tool life can be expressed through different according to:

- Tolerance limits for the specific workpiece;
- Tolerance limits for the surface finish (e.g. roughness);
- Maximum wear value for the flank wear;
- Maximum wear value for crater wear.

Depending on the type of cutting and operation one or more of these limits can be considered. All of them, however, indicate the result of a wear mechanism.

1.1.3 Machine Tool

A machine tool can be defined as an electrically powered machine, equipped with cutting tools which is used to remove material, usually metal. A machine tool has facilities to control the metal removal rate and achieve a desired shape or finish. A machine tool typically holds the workpiece and a cutting tool, and moves the workpiece, tool or both to provide a means of machining the material to the desired shape. Machining is a metal-cutting operation, which is performed by shaving away the metal in small pieces called chips. With use of machining operation, the original workpiece can be reduced by approximately half of its weight. The modern machine tool enables facilities to achieve high accuracy and precision, if is utilized efficiently. The major operations performed by machine tools are milling, turning, boring, planning, shaping, drilling, power sawing, and grinding.

The main problem for today's industry is not the availability of machines, tools or methods. All of these are readily available. What industry is confronted with is a lack to utilize them effectively. The effective use of the machines depends on the availability of either experienced operators or the user friendly supports such as addition computer support and virtual machining process simulation that can make easy understanding of process monitoring and control for everyone.

1.1.4 Milling Machine

Milling is the process of machining flat, curved or irregular surfaces by feeding the workpiece against the rotating cutter containing a number of cutting edges. The milling machine consists basically of a motor driven spindle, which mounts and revolves the milling cutter. The workpiece is usually held in vises, special holding fixtures, or clamped directly to the machine table and fed at right angles to the axis of the milling cutter to produce flat, recessed, or contoured surfaces.

1.1.5 Milling Machine Classification and Advancements

According to the orientation of the spindle, milling machines can generally be classified as vertical or horizontal. Vertical milling machines can also have what is called "multiaxis" capability where the vertical axis can tilt and swivel to enable the machining of closed angles and contoured surfaces. Vertical milling machines are extremely versatile and can machine horizontal surfaces, vertical surfaces, angular surfaces, shoulders, grooves, fillets, keyways, T-slots, dovetails, and precision holes. Milling machines comprise one of the largest categories of machine tools with many different varieties and configurations available. Examples of vertical and horizontal milling machine are shown in figure 1.21.

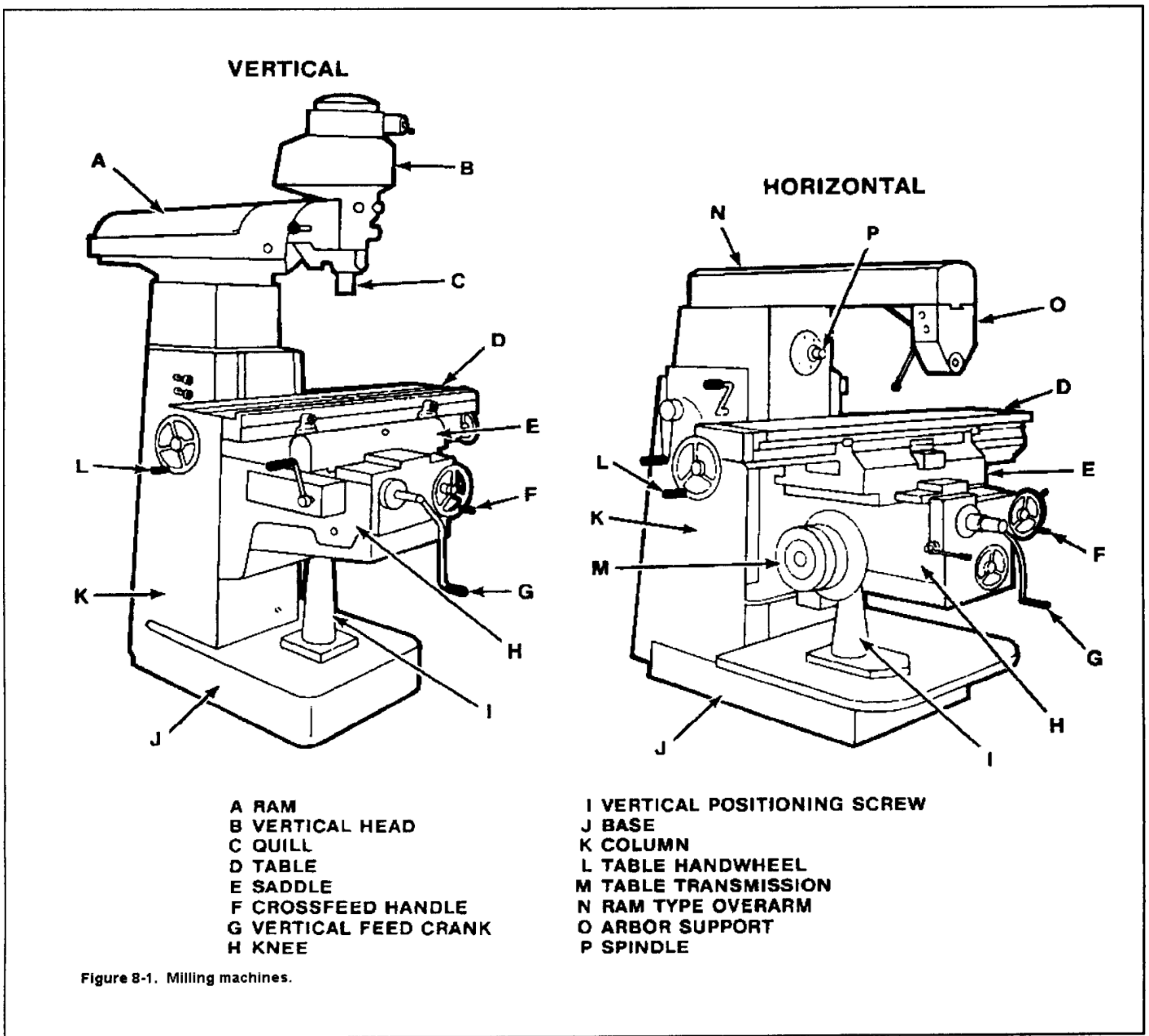


Figure 8-1. Milling machines.

Figure 1.21: Milling machine (Vertical and Horizontal).

Horizontal milling machines are available in plain and universal types. Plain milling machines have tables which are fixed at right angles to the knee. Universal milling machines have a table which can be pivoted in a horizontal plane. This allows the machine table to be swiveled to different angles for milling helical grooves.

The universal milling machine is widely used by maintenance machinists and toolmakers because of its versatility. Computer numerically controlled (CNC) mills or "machining centers" are available in vertical and horizontal configurations and come with automatic tool changers which can store many different tools in "carousels." The major components of a typical milling machine include the following: base, column, knee, elevating screw, saddle, machine table, ram, head, and spindle. The base is the heavy foundation member of the machine which can also be used as a reservoir for coolant or cutting lubricant often used in machining operations. The base is a massive casting which helps to absorb and dampen vibration from the machining process. The column, which is either, cast with the base or keyed and bolted on, supports the functioning members of the machine. Horizontal "ways" on top of the column support the ram and head while vertical "ways" on the column front face support the knee, saddle, and machine table. The knee moves along the vertical ways of the column and is the basic work-supporting member. The knee is equipped with ways on top to allow horizontal movement of the saddle to and from the column face. The elevating screw provides additional support for the knee and allows the knee to be raised and lowered. The saddle mounts on the ways of the knee and has horizontal ways at right angles to the knee ways to support the machine table. The machine table moves longitudinally on the ways of the saddle and supports the workpiece. Combined movements of the knee, saddle, and machine table allow for precise positioning and feeding of the workpiece left and right, in and out, and up and down. This is called "3-axis" movement (X = left and right movement, Y = in and out movement, and Z = up and down movement). A rotary table can be added to a 3-axis mill to give it 4-axis capabilities (typically rotation is about the longitudinal or X-axis), while 5-axis mills are able to tilt and swivel about the vertical axis. The ram is mounted on the horizontal ways at the top of the column and supports the head and provides horizontal movement and positioning of the head at varying distances from the column face. The head includes the motor, stepped pulley, belt drive (or in the case of heavier duty mills, the gear drive), and the spindle. The head assembly provides for rotation of the spindle and spindle feeding along the vertical axis using a quill. The spindle contains the tool-holding mount and drives the cutter.

1.1.6 Turning Machine

Lathes are considered to be one of the oldest machine tools in existence. Lathes were typically foot-powered until water and steam power was harnessed. One of the first machines driven by Watt's steam engine was a lathe which is how it came to be known as an "engine lathe." The lathe operates by holding the workpiece in a rotating holder, usually a chuck or collet, and then a single-point cutting tool is fed into the workpiece. If the tool is fed along the axis of rotation of the workpiece, it is considered to be a "turning" operation and any desired cylindrical contour can be made. If the cylindrical contour is produced on the inside of the workpiece, the operation is called "boring." In addition to turning and boring, the lathe is also used for threading, tapping, facing, tapering, drilling, reaming, polishing, and knurling. Some typical parts a lathe may produce are pins, bolts, screws, shafts, discs, pulleys, and gear blanks. Different attachments allow a lathe to perform milling, grinding, and broaching operations. With the right combination of attachments, it is said that the lathe is the only machine tool capable of reproducing itself. The size of a lathe is given in terms of the maximum "swing" and length of bed. The swing refers to the maximum diameter of work which can be rotated in the lathe. The length of the lathe bed refers to the maximum length of the lathe ways, not the maximum distance between centers of the chuck and tailstock. Many different varieties of lathes are available ranging from the small precision lathe used for making watch parts to the extremely large lathes used in producing mill rolls and rocket casings.

1.1.7 Turning Machine Classification and Advancements

Lathes can generally be classified in one of the following five basic groups: engine lathes, speed lathes, turret lathes, vertical lathes, and automatics. The engine lathe, sometimes referred to as a "geared-head" lathe, is the most commonly found lathe model. Speed lathes are used where the workpiece is polished or formed (e.g., spinning) rather than cut. Turret lathes have a "turret" tool changer which rotates to permit a number of different tools to be used in a certain sequence. Vertical lathes have a vertical axis of workpiece rotation rather than horizontal. Automatic lathes consist of high production turning machines such as screw machines and single or multiple spindle chucking and bar fed machines. All of the five basic lathe groups can also be found in a computer numerically controlled version, sometimes called a "turning center." The main components of a typical engine lathe include the following: bed, headstock, feedbox, tailstock, and carriage. The bed is the base of the lathe that supports the other components. The precision ways are the part of the bed on which the carriage travels. The bed is a massive casting in order to absorb and dampen vibration from the machining process. The headstock is mounted rigidly on the bed and houses all the gearing and mechanism for the spindle drive and power takeoff source for the feedbox. Controls for selecting and changing spindle speeds are also part of the headstock. The feedbox, which may be an integral part of the headstock or a separate unit, drives both the feed rod and the lead screw for the feed rate or thread lead required. Figure 1.22 shows some examples of turning machines and figure 1.23 illustrates the lathe components.

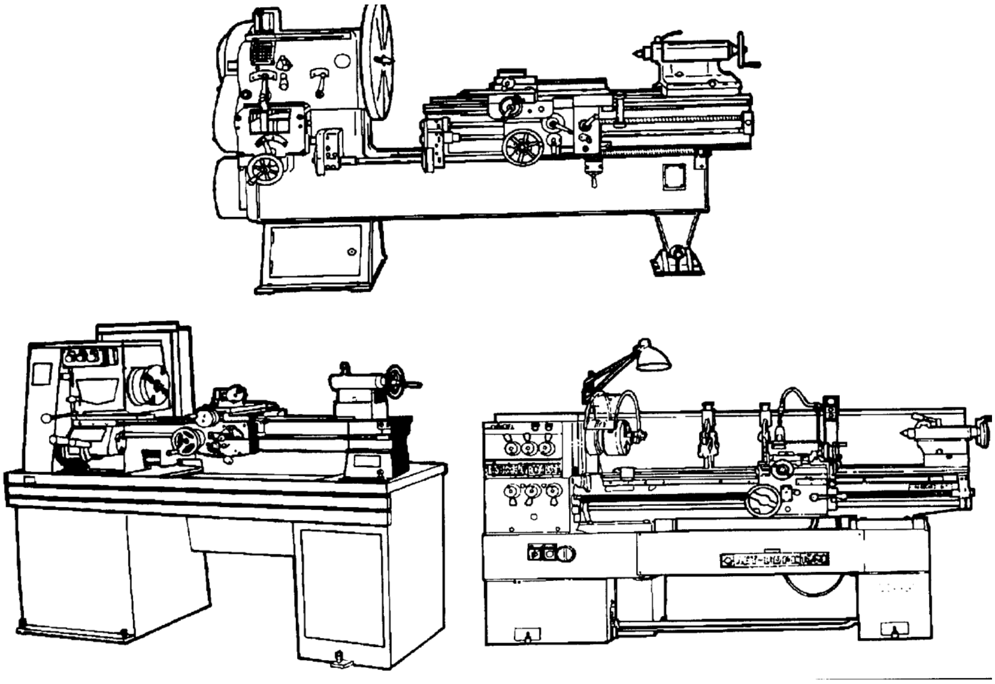


Figure 1.22: Examples of turning machines

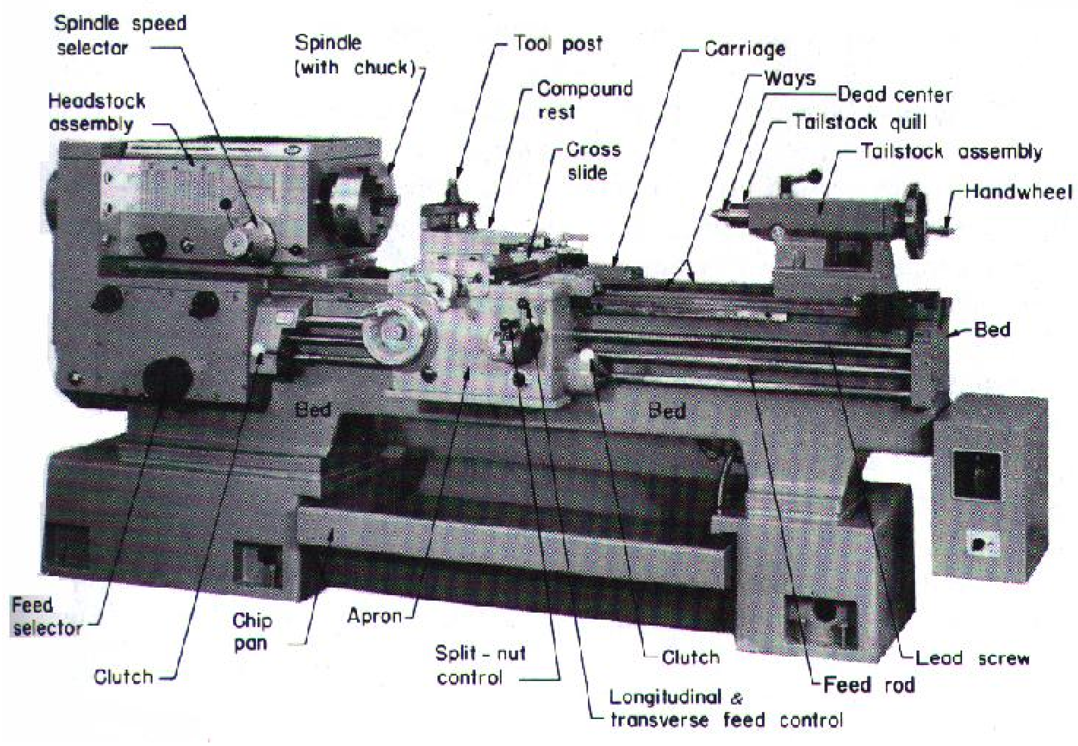


Figure 1.23: Lathe components.

A direct mechanical connection with the spindle drive is required to provide the proper relationship for feeding or threading operations. The lead screw is a precision part and is usually only used for threading operations to avoid unnecessary wear.

Most engine lathes incorporate a feed rod which is used to drive the carriage for operations other than threading. The headstock spindle supports a faceplate, chuck, or collet, which in turn holds and drives the workpiece. There are four types of standard spindles, all identified by the type of nose: threaded nose, cam lock, taper nose key drive, or flanged nose. The threaded nose spindle is usually only found on smaller and less expensive lathes. The cam lock type allows faster changing of faceplates or chucks. The taper nose key drive type provides greater support to the workpiece while the flanged spindle nose permits mounting of special chucks or power operated equipment and can be found on turret lathes and automatics.

The tailstock is mounted on the bed ways and may be positioned and clamped to support work for turning. It may also use a tool mounted in place of the tailstock center so that boring, drilling, or reaming can be done. The tailstock must be perfectly aligned with the headstock spindle in order to produce good parts. The carriage is the tool platform of the machine and supports and feeds the cutting tool over the work. The carriage consists of the cross slide, which bridges the ways to support the compound and tool post, or tool holder, and the apron. The lead screw and the feed rod pass through the apron and transmit feeding power to the carriage. The main controls for positioning and feeding the tool are also located on the apron.

1.2 Decision Support System in Machining Process Monitoring and Control

Although many manufacturing systems technology and data management communities are very familiar with the term "decision support system", machining process control still needs a robust implementation and support of online decision making. The presented research can provide better understanding of decision support systems: how they are configured, how they operate, and how they can be implemented in machining process planning.

1.2.1 Defining the Concept

A "decision support system" may be defined in many ways. Some definitions emphasize hardware and software components; others focus primarily on function (i.e., fulfilling the information needs of decision makers); while a few even describe user interfaces, job functions, and data flow. Definitions of decision support systems include:

1. An interactive software-based computerized information system intended to help decision makers compile useful information from raw data, documents, personal knowledge, and business models to identify and solve problems and to make decisions.

2. An interactive computerized system that gathers and presents data from a wide range of sources to help people make decisions. Applications are not single information resources, such as a database or a graphics program, but rather the combination of integrated resources working together.
3. A cohesive and integrated set of programs that shares data and information and provides the ability to query computers on an ad-hoc basis, analyzes information, and predicts the impact of possible decisions.

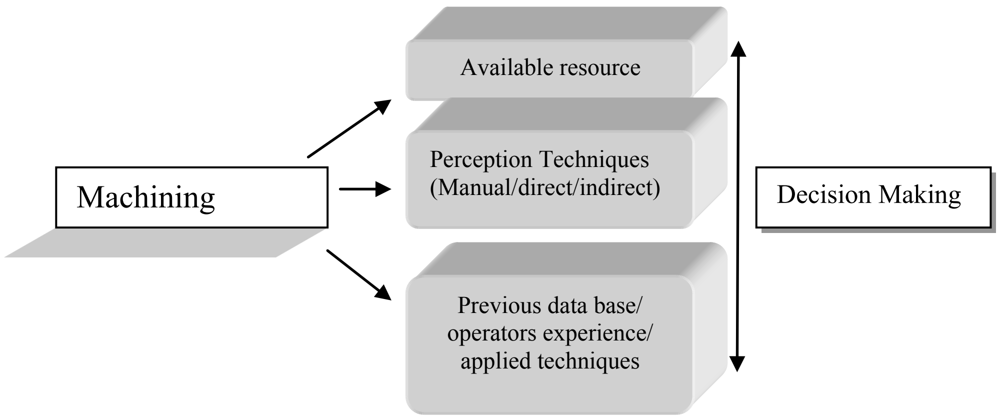


Figure 1.24: Block diagram decision making for machining processes.

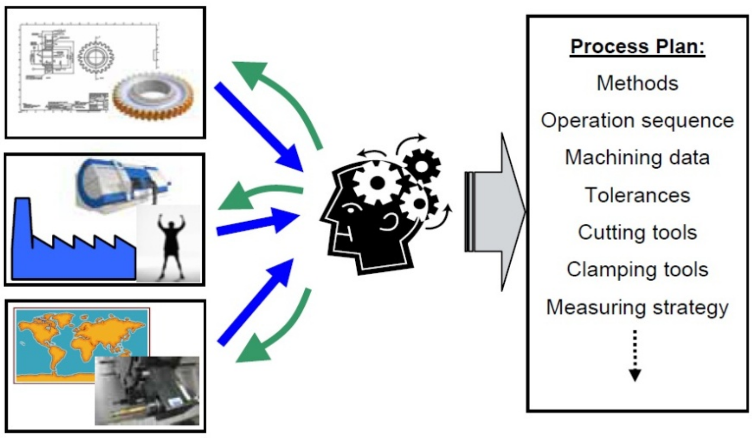


Figure 1.25: Decision making and process planning.

This research presents four different aspects of machining process decision making, where three of them (Chip-form detection and monitoring, Tool wear detection and measurement, Process condition monitoring) can provide real-time decision making and the other (Machining process simulation) provides an off-line decision making supports.

1.3 Problem Scenarios and Applied Techniques

Computerization simplifies the technological preparation in every stream of technology. A computer provides easy support to process the data collected by contact or non-contact measuring means. Therefore, development of a computer supported decision making system for machining processes has been a great interest of research in manufacturing era. The system aims to provide real-time/offline control and monitoring on machining processes.

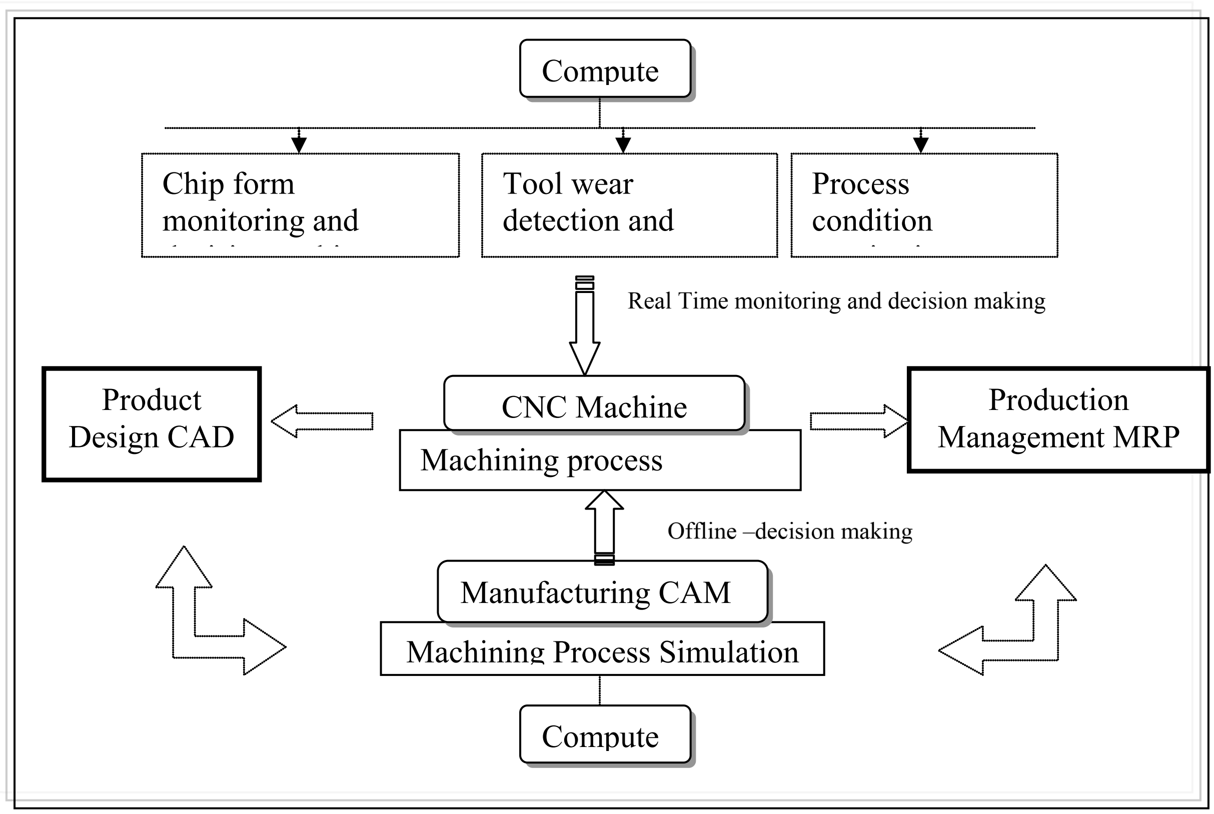


Figure 1.26: Block diagram machine processes and decision making supports.

1.3.1 Chip formation monitoring during turning operation

The monitoring and control of the chip form is a notable aspect affecting the efficiency of machining processes. The normal variations of process conditions, due to the inherent variation of work material properties, thermal expansion, tool wear development, etc., can produce changes of the chip form during a machining operation. Problems in surface finishing, work-piece accuracy and tool life can be caused by even minor changes in chip forms. Moreover, unacceptable chip shapes can cause injuries to operators and damage to cutting tools, work-pieces and machines.

This decision making system presents the contributions to the development and application of decision support systems for chip form monitoring aimed to identify the chip form in real time using cutting force sensor signals. A SOM NN (Self-Organizing Map Neural Networks) based approach was utilized for classification and identification of chip form using cutting force sensor data.

1.3.2 Process Condition monitoring during turning operation

Sensor monitoring systems for process optimization and control is notable aspect affection the machining process efficiency. With the purpose of process optimization, sensor signals are correlated to process conditions so that the effects of process parameter changes can be realized on the basis of sensor signal features rather than empirically based on skilled operators' experience.

This research work presents the contributions to the development and application of sensor monitoring of machining processes with the aim of process optimization. Decision making on process conditions acceptability was performed through clustering and classification of vibration sensor data. The vibration sensor signals were detected during turning test of Ti alloy (TiAl6V4). Self Organizing Map Neural Networks (SOM NN) were utilized for clustering and classification. SOM NN following an unsupervised learning methodology is an effective tool to visualize multi-dimensional clustered data.

Moreover, SOM NN can be utilized as a valuable tool to identify ambiguous sensor data. Ambiguous data can be defined as a data vector that lies in more than one cluster causing problems in creating clearly separate clusters. Identification of ambiguous data vectors plays a crucial role in the refinement and analysis of data sets.

1.3.3 Real time tool wear detection and measurement during turning operation

The necessity for appropriate tool wear control becomes more important especially in modern machining systems in which many numerically controlled and computerized numerically controlled machines are operated in a more flexible and unmanned manner.

Tool wear detection and monitoring is one of the fundamental aspects to be dealt with for machining process enhancement. As the quality of the tool is directly related to the quality of the product, the amount of tool wear should be kept under control during machining operations. In order to build computer applications for real time detection of tool wear development, real time digital images of the cutting tool were detected by an optical sensor (video camera). These digital images were processed through image processing techniques to measure the tool wear development. With this approach, tool wear development can be regularly analyzed and controlled. In particular, the research work was focused on procedures for the standardisation of tool images and the application of image processing techniques to obtain tool wear characterisation. The goal of this research work is the development of automatic (software) techniques for the detection of on-time tool wear development, based on imaging methods. The technique allows faster and highly dynamic measurements of tool wear and it is totally non-contact and non-invasive.

The decision making system describes a procedure to standardize tool wear images, detected during quasi-orthogonal cutting tests for **Automatic Tool Wear Detection** (ATWD). The ATWD procedure was applied for the detection of crater wear area and maximum crater width development with cutting time. The ATWD procedure was tested for four different cutting conditions and the results of the automatic image processing procedure are compared with the values measured through a tool maker's microscope. Accurate ATWD results could be obtained preferably in the case of less severe cutting conditions and for very clear standardized tool wear image.

1.3.4 Machining Process Simulation and process verification and optimization

High machine utilization depends on work queued for immediate processing. Efficient resource management is aimed to improve the productivity. Whether a part is cut in five minutes or five hours, it may take days to create the part geometry, and days to create the tool-path. Moreover, the machining process verification and the tool-path NC code generation become more complicated when machining operations are performed on multi-axis computerized numerical control (CNC) machines.

Collision-avoidance and geometric-error detection are critical issues for multi-axis CNC machining. Simulation of tool paths and machine operations is desirable for cost and time savings. Machining process simulation provides off-line full range machine tool facility to verify the machining operations, generation of NC code, rapid adaptation of new changes in processes, collision-error detection and geometric error detection.

Moreover, machining process simulation can provide a crucial support to realize the 3D view of the machining processes and complex machine system in a virtual environment. The wide growth of CNC application in industries encourages strengthening of student knowledge in CNC programming and process management. The CNC practices in industries are relatively more complicated than real applications as is taught during academic theory classes. It is essential to facilitate practical experience by working with CNC machines. Because of limitation of CNC facilities and environment, it has always been difficult to implement intense practical classes in universities. Virtual CNC machine and process simulation environment provides an alternative way to support CNC knowledge extension programs.

1.4 Motivation and scope

The most expensive, non-value-added process in most shops is part inspection. Inspecting good parts - parts that match all quality requirements is much time consuming. Advances in machine accuracy, on-machine touch probing technology and noncontact tool setting, provide powerful tools for automating and speeding machining. Rather than back-end detection, attention is shifting to front-end prevention (Real time monitoring system/ off-line supporting techniques). The front-end prevention can be easily implemented by buying new advanced machines, which requires huge investments. In case the existing machines are not able to reach required level of excellence in machining, it raises a matter of sustainability of the existing machines.

In order to find the answer to sustainability of existing manufacturing resources and enhancement of the machining efficiency, researchers are working on finding possible supplementary computer supports. In recent years, the indirect computer supported techniques such as sensor base monitoring and control and virtual machining process simulation have been greatly accepted for real-time decision making, sustainable development and efficient use of machining resources.

Industries' aim is to perfectly produce parts, right at the first time, with severe tolerances in the lowest total processing time. Under that mantra, a variety of practices and technologies are being applied to machine tools to achieve a better process control.

Indirect real-time monitoring systems can keep process and parts in control, while minimizing downtime for operator intervention. Front-end prevention takes three forms:

- identifying and maintaining machine capability;
- in-process probing (testing);
- automated tool monitoring.

The machining process on CNC machines demands a high-level of accuracy in NC program to produce the part. Inaccurate NC program files can lead to expensive consequences related to cutting tool cost and tool management. CNC operators or machinists must verify and optimize the process condition before the machining process begins. Machining process simulation has presented a decision supporting platform where machining processes are verified and machining technologies can be correlated each other in order to achieve an optimized process. Moreover, to avoid unwelcome machining planning errors, machining technological knowledge can be collected, managed and appropriately shared among personnel.

The machining process simulation based offline support can make machining process setup faster, with greater geometric and dimensional accuracy, and less operator intervention, rework or manual finishing.

Machining process simulation can include the following facilities

- Geometrical feature recognition;
- Machine operation selection;
- Cutting tool selection;
- Sequencing operation and time estimation;
- Collision error and tool path error detection;
- Calibration and comparison between actual and machined part;

- Improved accuracy - Better fit - Superior finish - Better life - Produce more work in less time - Improving the accuracy and finish - Reducing polishing and fitting time - Tools simply last longer because their chip load is more consistent.

1.5 Objectives

The objective of this thesis work is to develop computer support systems for machining processes which can incorporate decision making for real-time monitoring. The decision systems aim to recognize the process irregularities and to estimate the corrective action in unattended machining operations.

By exploring the advantages of SOM Neural Networks data clustering, classification and multi-dimensional visualization facilities, decision making systems was build to deal with chip-form monitoring and process condition monitoring.

A computer support system for automatic tool wear detection and measurement has been presented. An automatic tool wear measurement technique is developed, and it can be adopted for CNC lathes for automatic inter-process monitoring of tool wear. Using the real-time tool wear development information, tool compensation can be performed by adjusting position over time. Tool wear digital information will be portable, in order to be transferred to CNC controller, allowing tool wear compensation if any reliable adaptive control algorithm is available.

Effective management of machining knowledge is a critical issue in getting and maintaining the advantages of machine tool utilities. Machining process simulation deals with the objective presenting a decision support virtual platform where machining processes are verified precisely. Machining technological knowledge can be collected, managed and shared appropriately among industrial personnel, as well as it can be useful to extend and support CNC related teaching programs.

References

[1] Teti, R., Jemileniak, K.,O‟Donnel, G., Dornfeld D., 2010, Advanced monitoring of machining operations, Annals of the CIRP Vol 59/2 pp 717-739.

[2] Byrne, G., Dornfeld, D., Inasaki, I., Ketteler, G., König, W., Teti, R., 1995, Tool Condition Monitoring (TCM) – The Status of Research and Industrial Application, Annals of the CIRP Vol. 44/2 pp. 441 – 567.

[3] Jemielniak, K., 1999, Commercial Tool Condition Monitoring Systems, The International Journal of Advanced Manufacturing Technology, 15 pp. 711-721.

[4] Allchin, D. 2001. "Error Types". Perspectives on Science 9 (1): 38–58.

[5] Hon, K.K.B., 2005, Performance and Evaluation of Manufacturing Systems, CIRP Annals 54/2, pp 139-154.

[6] Munzinger, C., Fleischer, J., Broos, A., Hennrich, H., Wieser, J., Ochs, A., Schopp, M., 2009, Development and implementation of smart maintenance activities for machine tools, CIRP Journal of Manufacturing Science and Technology, Volume 1, Issue 4, 2009, Pages 237-246.

[7] Martinsen, K., Holtskogb, H., 2011, Social aspects of Process Monitoring in Manufacturing Systems, CIRP Annals Manufacturing Technology, Annals 2011 - Vol. 60/1.

[8] Wikan Sakarinto, Hiroshi Narazaki, and Keiichi Shirase, 2011, A decision support system for capturing CNC operator knowledge, International Journal of Automation Technology, Vol.5. No.5.

CHAPTER 2

Classification and Clustering of Sensor Data to Build a Decision Support System for Chip Form Monitoring

2.1 Introduction

The present tendency in machining is towards achieving higher material removal rates with high degrees of automation in truly untended manufacturing systems. This requires the development of very reliable machining processes. One of the aspects notably affecting the efficiency of machining processes is the monitoring and control of the chip form [1]. The normal variations of process conditions, due to the inherent variation of work material properties, thermal expansion, tool wear development, etc., can produce changes of the chip form or shape during a machining operation.

Problems in surface finish, workpiece accuracy and tool life can be caused by even minor changes in chip forms [2, 3]. Moreover, unacceptable chip shapes can cause injuries to operators and damage to cutting tools, workpieces and machines. All these negative effects can lead to additional costs due to scrap parts, lost machining time, and delays in part delivery.

Efficient chip form monitoring and control is therefore needed to allow for the formation of favorable chip shapes (Table 2.1, Figure 2.1) that can be easily and reliably evacuated from the working zone [4]. This would contribute to the improvement of machining process reliability, the production of high quality machined surfaces, the increase of productivity, and the enhancement of operation safety (including operator safety) and tools and machines protection [1].

In order to provide for real time chip form monitoring and control, sensor based approaches have been widely accepted as promising solutions [5, 6]. Sensors are utilised to detect real time information on cutting force, acceleration, acoustic emission and vibration [7, 8]. These real time sensorial data play a significant role in explicit observation and controlling over machining operations. Thus, knowledge extraction and getting insight details and inferences from the sensorial data have been considered useful and challenging tasks. A key issue to obtain inferences from sensor signals is the achievement of a clear classification and clustering of the characteristic parameters of the sensorial signals [9].

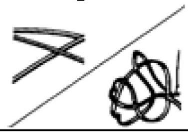
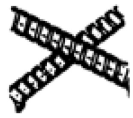
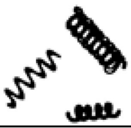
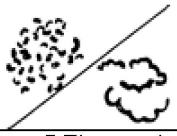
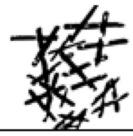
Cutting		Favourable	Unfavourable	
Straight	1 Ribbon Chips	1.2 Short 		1.1 Long/1.3 Snarled 
Mainly up curling	2 Tubular Chips	2.2 Short 	2.1 Long 	2.3 Snarled 
	3 Spiral Chips		3.1 Flat/3.2 Conical 	
Mainly Side curling	4 Washer type Chips	4.2 Short 	4.1 Long 	4.3 Snarled 
Up and Side Curling	5 Conical Helical Chips	5.2 Short 	5.1 Long 	5.3 Snarled 
	6 Arc Chips	6.2 Loose/6.1 Conn 		
	7-8 Natural Broken Chips	7 Elemental 		8 Needle 

Table 2.1: Chip form classification ISO 3685

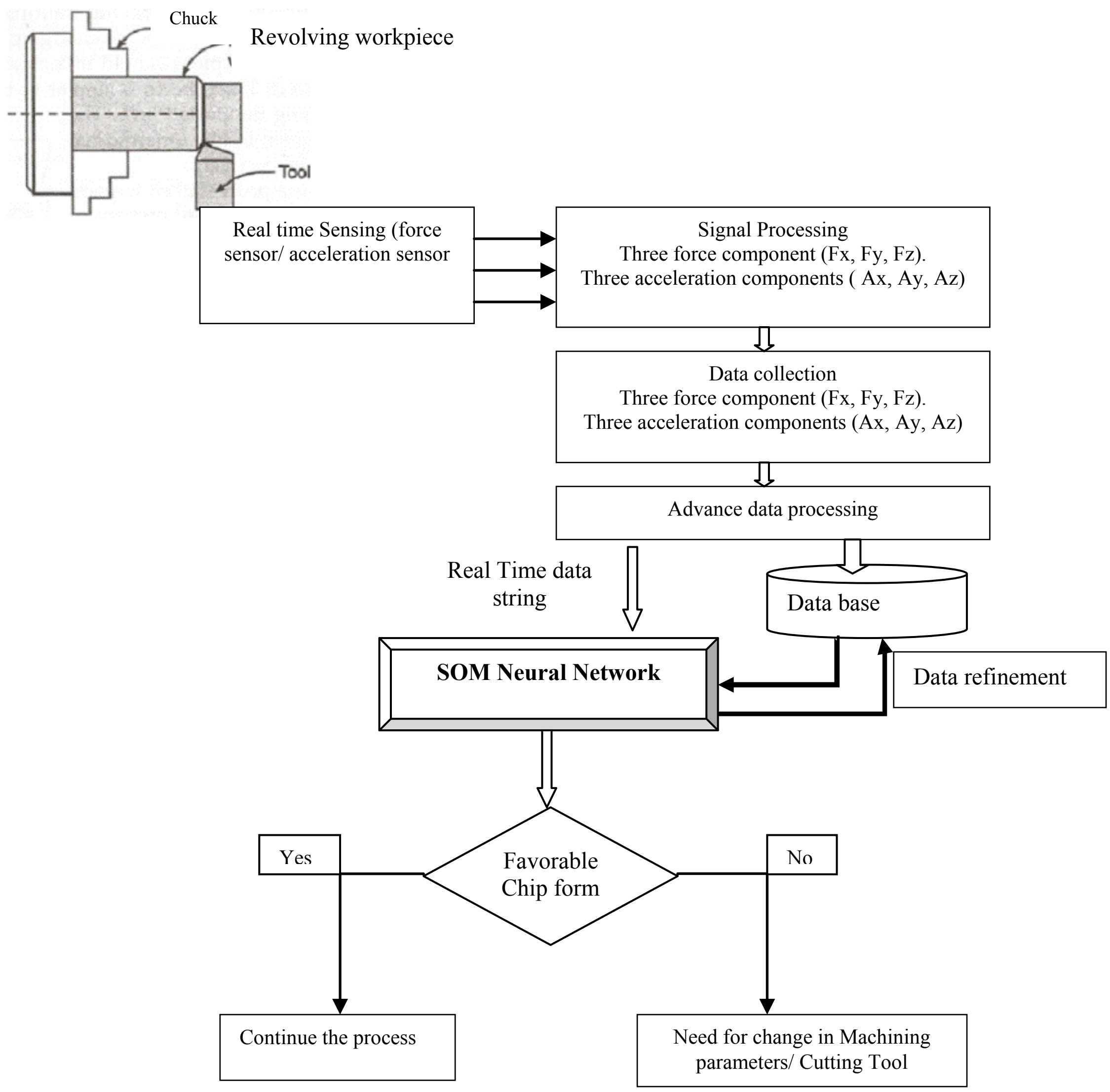


Figure 2.1: Block diagram for on-line chip form monitoring for turning operation

This chapter thesis reports on a SOM (Self-Organizing Map) based approach for classification and identification of chip form using cutting force sensor data collected through experimental sensor monitoring during longitudinal turning operation. The SOM methodology facilitates the visualization of multidimensional numerical data [10]. Characteristic features of the cutting force signals are used to construct patterns vectors which help in the identification of chip form. The SOM paradigm has shown a great potential for this application: in [11] a chip form classification was presented along with a comparative study of a 2D visualization technique and a SOM based data representation technique.

Four case studies were considered in this paper: in the first three case studies (Case 1, Case 2, and Case 3) single cutting force components Fc, Ff, and Fp are utilized separately. In the last case study (Case 4), all three cutting force components are used jointly.

A comparative study of chip form identification for all four case studies along with data refinement procedures have been carried out. Moreover, the SOM maps were utilized as a powerful tool to identify ambiguous data vectors lying in two or more chip form clusters. Identification of ambiguous data samples plays a crucial role in refinement and analysis of data sets by providing additional inferences about sensitive points of cluster overlapping. Simulation results indicate that the SOM technique performs better when using all three cutting force components together. Moreover, after refinement of ambiguous data vectors, an extremely successful result for chip form identification was achieved.

2.2 Materials and Experimental Procedures

Cutting force sensor signals were obtained as an issue of the activities of STC-C CIRP Co-Operative Work on “Round Robin on Sensor Monitoring of Chip Form during Machining” [12]. In particular, cutting process was a longitudinal turning of C45 (AISI 1045) steel with coated carbide tool inserts (TNMG 332 or grade 4025) and variable cutting conditions, yielding different chip forms classified according to ISO 3685 standard (Table 2.1) as: snarled, short, and short spiral [13].

Chip form types classified according to the ISO standard 3685:

- **Snarled (2.3.1)**
- **Short (6.2.6)**
- **Short spiral (5.2.1)**

The cutting parameters utilized for the experimental tests were:

- **Cutting speed = 150, 250 m/min**
- **Feed rate = 0.10, 0.20, 0.30, 0.35 mm/rev**
- **Depth of cut = 1.0, 1.2, 1.3, 1.4 mm.**

During turning tests, three cutting force components:

- **F_c - cutting force**
- **F_f - feed force**
- **F_p - radial force**

were measured using a 3-channel piezoelectric Kistler dynamometer 9257A. Cutting force component signals were digitized at 2500 Hz for 3 s providing a data sequence of 7500 points.

2.3 Signal Analysis of Cutting Force Signal Specimens

The analysis of cutting force signal (CFS) specimens is carried out by achieving spectral estimation through a parametric method [14]. In this procedure, the signal spectrum is assumed to take on a specific functional form, the parameters of which are unknown. The spectral estimation problem, therefore, becomes one of estimating these unknown parameters of the spectrum model rather than the spectrum itself. For each CFS specimen, a four elements feature vector {a1, a2, a3, a4}, characteristic of the spectrum model, was obtained through linear predictive analysis (LPA). Feature extraction was executed through the application of the Durbin algorithm [14].

2.4 Data Clustering and Classification using SOM Neural Network

Numerical, statistical or artificial intelligence methods of data classification are attractive for in-process, real time monitoring of manufacturing processes. Neural Network (NN) sensor data analysis under unsupervised training based on self-organising maps (SOM) was utilised to carry out a clustering procedure.

A SOM can be considered as a two-dimensional scene in which the case features are classified so that those which share related characteristics are located in the same zone of the map. A SOM map is formed by a grid of neurons, also called nodes or units, which govern the placing of stimuli vectors. A stimulus is a vector of dimension d which describes the case to be classified.

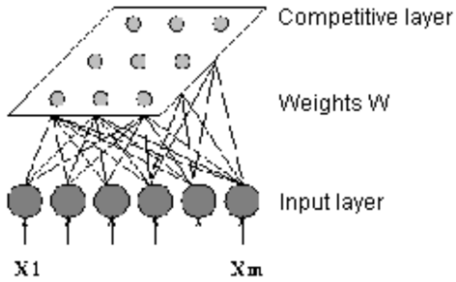


Figure 2.2: SOM architecture.

Each unit of the grid is linked to the input vector (stimulus) by means of m synapses of weight w. Thus, each unit is associated with a vector of dimension m which contains the weights w.

Like any other NN, the use of the Kohonen map follows two steps: the training step and the testing step. While training, the input vectors are sequentially presented to the NN and every time the weights of the connections are changed. The input data are repeatedly used until the NN converges. While testing, the weights don't change and the output of the NN is used as its response to the given input data.

At the beginning of the training process, the weights of the connections from the input layer to the competitive layer are initialized with random values in a certain interval. For each input vector, the winner neuron is determined and the weights of the connections to this neuron and to its neighboring neurons are adapted. In the course of time, the learning rate as well as the neighborhood radius (and thus the set of neurons that are adapted apart from the winner neuron) is reduced. Finally, the network reaches a more or less stable state, in which the weight changes almost cease.

After the training phase is over, the map should be topologically ordered; this means that input vectors judged topologically close on the basis of some distance measure (e.g. Euclidean distance) are located in adjacent map neurons or even in the same single map neuron.

The Unified Distance Matrix, or U-matrix, is the most popular method to visualize a SOM: the distances of each map unit from each of its immediate neighbours are calculated and visualised using some representation for the matrix, e.g. a colour or gray-level image. The colours in the map can be selected so that, for example, the more similar the colour of two neurons, the smaller their relative distance [15].

2.4.1 Case study

In the first three case studies of this thesis, SOM training and testing was carried out by using the single cutting force components separately. Since one cutting force component signal is characterised by a 4 elements feature vector, a stimulus is a 4 dimensional input vector labelled with an encoded chip form label.

In the forth case study, where all three cutting force components are considered together, the stimuli are made of 12 elements vectors comprising all 4 features associated with each of the 3 cutting force components: Fc, Ff and Fp.

The input data set is configured as an ASCII file; some lines of the file utilised for the forth case study are shown in Table 2.2.

a1Fc	**a2Fc**	**a3Fc**	**a4Fc**	**a1Ff**	**a2Ff**	**a3Ff**	**a4Ff**	**a1Fp**	**a2Fp**	**a3Fp**	**a4Fp**	**Label**
0.72	0.22	0.069	0.12	0.563	0.234	0.325	0.124	0.39	0.30	0.169	0.129	**Sna**
0.69	0.24	0.084	0.14	0.56	0.135	0.167	0.13	0.58	0.10	0.178	0.342	**Sho**
…	…	…	…	…	…	…	…	…	…	…	…	**…**
0.76	0.05	0.024	0.03	0.535	-0.243	0.839	-0.134	0.193	0.17	0.539	0.092	**Sh.Sp**

Table 2.2: 12 elements input vectors comprising all 4 features associated with each of the 3 cutting force components. Each input vector is labeled according to the generated chip form:
Sna = Snarled*; Sho* = Short*; Sh.Sp* = Short Spiral.

The first row contains the names of the variables and each of the following rows reports the numeric values of each single data sample and ends with the associated chip form label. The sequence of 210 input vectors (210 rows) make up a data set of 210 stimuli to be applied to the SOM NN for training and testing [16, 17]. The MATLAB SOM Tool Box was utilized to construct the SOM NN [18]. The SOM NN was trained with all input vectors in the training set except for the test vector which was set aside to be used later for classification performance.

2.5 Results and Discussion

The training phase provides an optimally configured SOM NN with representation of the Unified Distance Matrix (U-matrix) and the associated map unit labels [18]. The U-matrix visualises the distances of each map unit from each of its immediate neighbours, calculated as Euclidean Distance, using colour variations. The colours and colour tones in the map are selected so that the more similar the colour of two neurons, the smaller the relative distance [16]. The map unit labels in the SOM neurons identify the different chip forms. Another visualization tool in data analysis using SOM is the hit histogram. A hit histogram is formed by taking a data set, finding the Best-Matching Unit (BMU) in the map for each data sample in the data set, and increasing the counter in the corresponding map unit. The hit histogram shows the distribution of the data set on the map.

In this thesis, the hit histogram for the whole input data set is calculated and visualized on the U-matrix where the hittings corresponding to Snarled (Sna), Short (Sho) and Short-Spiral (Sh.Sp) chip forms are shown in red, green and blue colours, respectively.

After training, it is important to verify whether the SOM NN has properly adapted itself to the training data set. The SOM NN is checked through the test data samples: if a test data sample is placed in the unit of the map containing the correct label, a successful test occurs. On other hand, an unsuccessful test is defined when the test data sample is placed in a wrongly labelled or in an unlabelled map unit.

Testing failures are of two types: Type1 occurs when the test data sample is placed in a blank map unit (no label) and Type2 happens when the test data is placed in a wrongly labelled map unit. In Type1 failure, the test data sample is assigned in a U-matrix area where there are similarly labelled map units in the neighbourhood. The neighbourhood map units can identify the chip form cluster even if the test data sample lies in an unlabelled map unit. However, in Type2 failure, the test data sample is assigned in a wrong map unit and this clearly misguides in the identification of the right chip form. Both types of unsuccessful results reduce the reliability of chip form identification, but Type2 failures create a high ambiguity in the classification. Thus, it is worth identifying the inherent reasons and/or the specific data vectors that cause the unclear classification of chip form types.

By looking at the hit histogram map units in the U-matrix for cutting force component Fc (Case 1, Figure 2.3), it can be observed that several data samples associated with different chip forms hit on same map unit (map unit overlapped with two or more colours). This means that the data vectors hitting on the same map unit present hardly any difference though they belong to different chip form clusters. These data vectors represent a critical problem for chip form identification and, to improve data classification accuracy, the SOM NN training data set should be refined by removing such ambiguous data vectors. The overlapped map units in Figures 2.4 and 3 show ambiguous data vectors also for cutting force components Ff (Case 2) and Fp (Case 3), respectively. Figure 2.5 shows that for Case 4, when all three cutting force components (Fc, Ff, Fp) are used, less overlapped map units are observed in comparison with the other case studies.

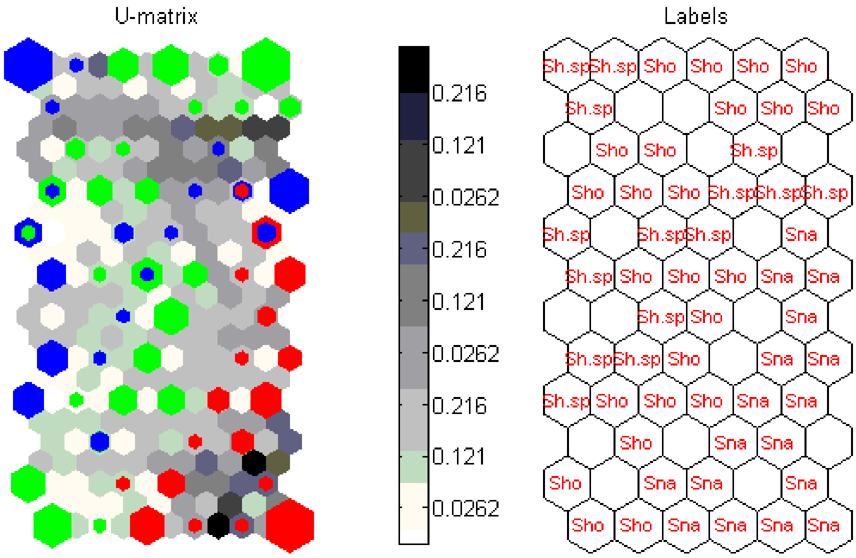


Figure 2.3: Hit histograms visualized on the U-matrix for Case 1 (Fc) representing the distribution of the whole data set on the map (before refinement).

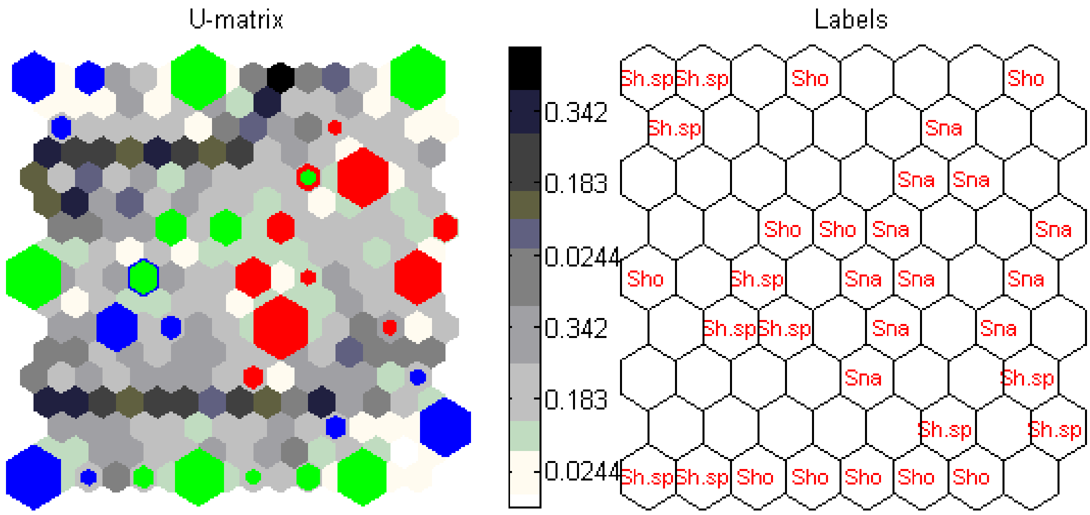


Figure 2.4: Hit histograms visualized on the U-matrix for Case 2 (Ff) representing the distribution of the whole data set on the map (before refinement).

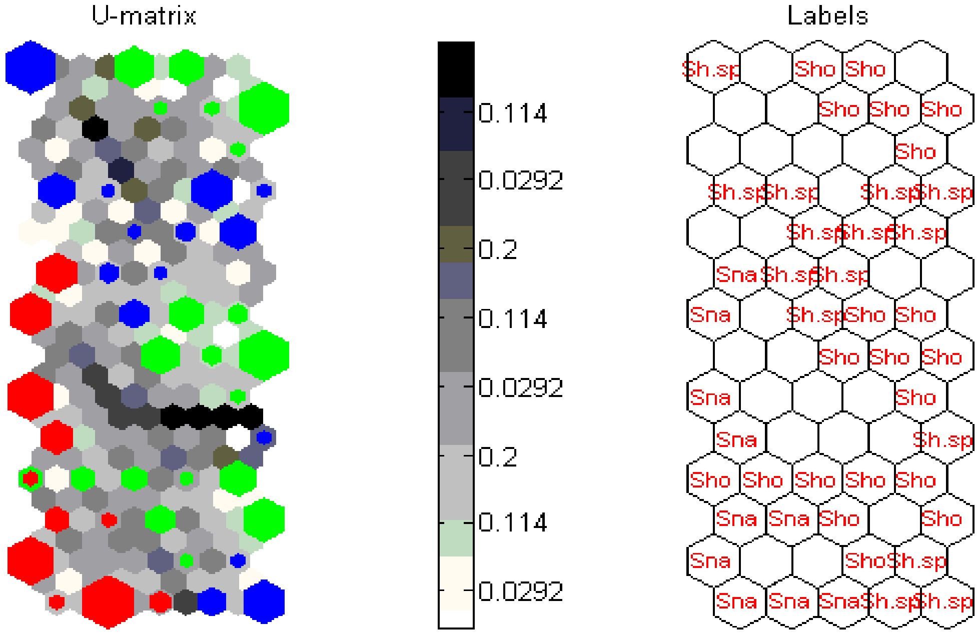


Figure 2.5: Hit histograms visualized on the U-matrix for Case 3 (Fp).representing the distribution of the whole data set on the map (before refinement).

Also the success rate for Case 4 is higher than for Cases 1, 2 and 3 (Table 2.3): the former achieves a value of over 97%, significantly higher than for the other case studies.

In Cases 1, 2 and 3, where single cutting force components are considered, only four data features are used to distinguish the data vectors. On other hand, in Case 4 twelve data features cooperate in data vectors discrimination. Data vectors with four features have a higher probability of being similar than data vectors with twelve features. For this reason, Case 4 has a lower number of ambiguous data vectors.

Although by increasing the number of data vector features a higher success rate is obtained, there are still ambiguous data vectors responsible for misclassifications.

Case Study	Utilised Cutting Force Component(s)	No. of Input Variables	Successful Tests / Total Tests	Unsuccessful Tests / Total Tests		Success Rate (%)
				Type 1	Type 2	
Case 1	Fc	4	185/210	16/210	9/210	88.10
Case 2	Ff	4	194/210	5/210	11/210	92.38
Case 3	Fp	4	195/210	12/210	3/210	92.86
Case 4	Fc, Ff and Fp	12	205/210	3/210	2/210	97.62
Case 4 (with refined data set)	Fc, Ff and Fp	12	204/208	4/208	0/208	98.08

Table 2.3: Result outcomes of all case studies reporting successful/unsuccessful SOM NN classifications.

These data vectors can be identified by observing the overlapped hit histogram map unit such as the one indicated by a circle in Figure 2.6. The overlapped map unit is characterised by a given vector value obtained during SOM NN training. It can be seen that there are data samples in the data set that, although they belong to different chip form clusters, have values similar to this vector value and thus hit on this same map unit (*Sna* and *Sho* chip form data samples in Figure 2.5).

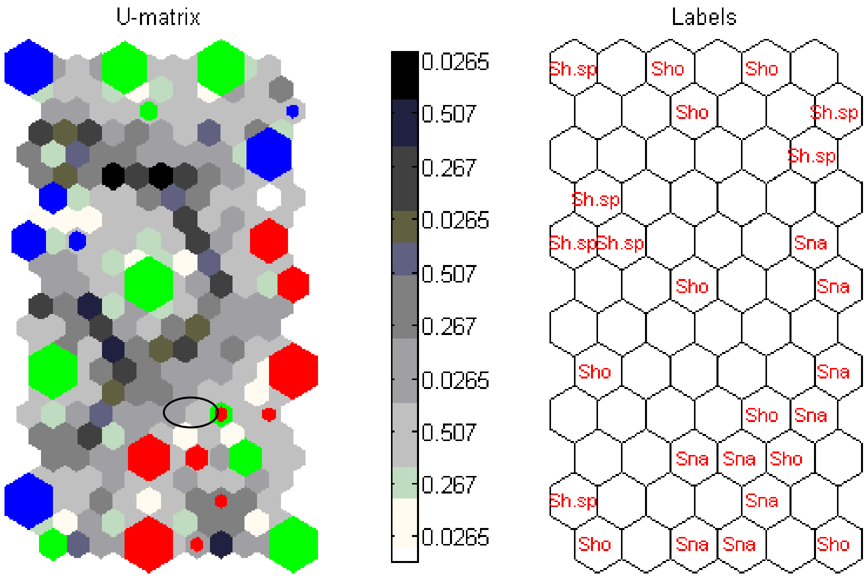


Figure 2.6: Hit histograms visualized on the U-matrix for Case 4 (Fc, Ff, Fp) representing the distribution of the whole data set on the map (before refinement).

The data vectors lying in the overlapped map unit have very close values for all twelve features, as shown in Figure 2.7. Among the data vectors in Figure 2.7, two data vectors belong to *Sna* chip form and the others correspond to *Sho* chip form. To remove the ambiguity generated by these data vectors, data samples 41 and 42 were eliminated from the input data set. SOM NN training was carried out again with the refined data set. The newly learned SOM NN provided a better hit histogram map (Figure 2.8) where no single map unit presents an overlapping, showing clearly separate chip form map units.

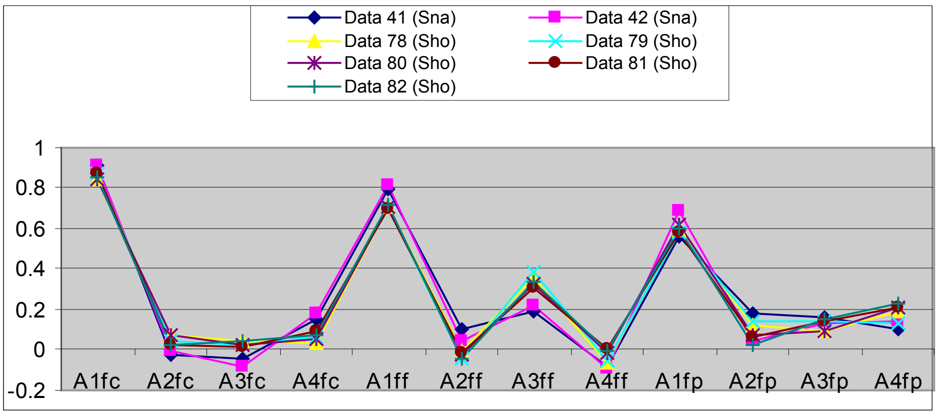


Figure 2.7: Seven ambiguous data vectors with very close feature values in all 12 dimensions

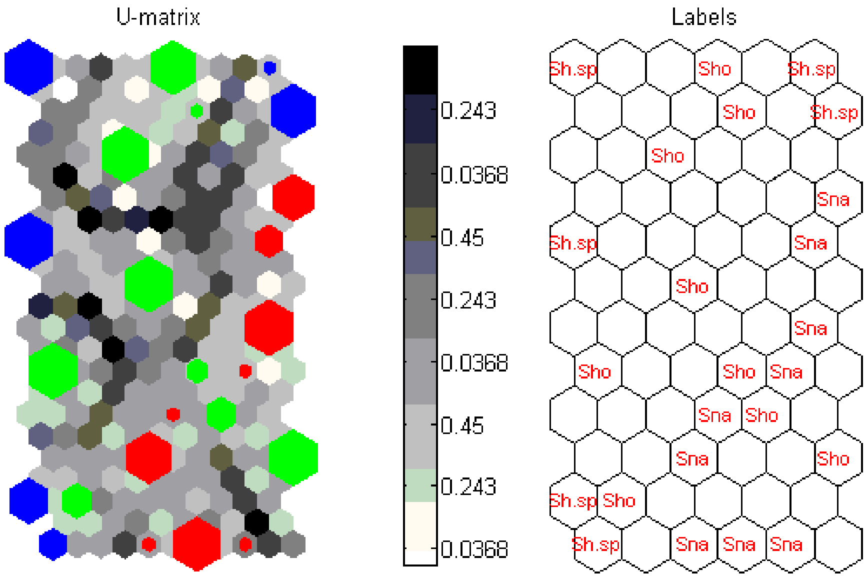


Figure 2.8: Hit histograms visualized on the U-matrix for Case 4 (Fc, Ff, Fp) representing the distribution of the whole data set on the map (after refinement)

In order to check the SOM NN constructed with the refined data set, testing was carried out for all 208 input data vectors one by one and 204 successful results were obtained.

It is interesting to observe that the 4 unsuccessful classifications are Type1 failures and no Type2 failure is verified (Table 2.3). Thus, the result outcomes justify that refinement of data set is 100% successful in the elimination of Type2 failures.

References

[1] Jawahir, I.S., van Luttervelt, C.A., 1993, Recent Developments in Chip Control Research and Applications, Annals of CIRP, 42/2, pp. 659-693.

[2] Spaans, C., 1970, A Systematic Approach to Three Dimensional Chip Curl, Chip Breaking and Chip Control, SME Paper, MR 70-241.

[3] Sukvittayong, S., Inasaki, I., 1991, Identification of Chip Form in Turning Process, ISME Series III, 34 (4), pp. 553-560.

[4] Nakayama, K, 1984, Chip Control in Metal Cutting, Bulletin JSPE, 18 (2), pp. 97-103.

[5] Moriwaki, T., Mori, Y., 1992, Sensor Fusion for In-process Identification of Cutting Process Based on Neural Network Approach, IMACS/SICE Int. Symp. on Robotics, Mechatronics and Manufacturing Systems, Kobe, Japan, pp. 245-250.

[6] Andreasen, J.L., De Chiffre, L., 1993, Automatic Chip-Breaking Detection in Turning by Frequency Analysis of Cutting Force, Annals of CIRP, 42/1, pp. 45-48.

[7] Dornfeld, D.A., Pan, C.S., 1985, A Study of Continous/Discontinus Chip Formation Using Acoustic Emission, J. Applied Metalwork, 4 (1), pp. 18-29.

[8] Segreto, T., Teti, R., Applications of Intelligent Sensor Monitoring for Machining Processes, 8th Int. Conf. and Exhibition on Laser Metrology, Machine Tool, CMM & Robotic Performance, 25-28 June 2007, Cardiff, Wales, pp. 388-399.

[9] Teti, R., Buonadonna, P., D'Addona, D., 2001, Chip Form Monitoring via Cutting Force Signal Processing, V AITeM Conf., Bari, 18-20 Sept., pp. 21-30.

[10] Kohonen, T., 1999, Self-Organizing Maps, Springer, Berlin, Heidelberg.

[11] D'Addona, D., Keshari, A., Teti, R., 2008, Spectrum estimation and processing of cutting force sensor signals for chip form monitoring and classification, 4th I*PROMS NoE Virtual International Conference on Innovative Production Machines and Systems - IPROMS 2008, 1-14 July, pp.555-560.

[12] Minutes of the STC-O CIRP Co-Operative Work Meeting, CIRP Jan. Meeting, Paris, 24-26 Jan. 2001.

[13] ISO 3685, 1993, Tool-Life Testing with Single-Point Turning Tools, Annex G: 41.

[14] Teti, R., Jawahir, I.S., Jemielniak, K., Segreto, T., Chen, S., Kossakowska, J., 2006, Chip Form Monitoring through Advanced Processing of Cutting Force Sensor Signals, Annals of CIRP, 55/1, ISBN 0080450490, ISSN 007-8506 (CIRP Annals), ISSN 1660-2773 (CD Rom): pp 75-80

[15] Merkl, D., Rauber, A., 1997, Alternative Ways for Cluster Visualization in Self-Organizing Maps, Workshop on Self-Organizing Maps – WSOM '97, Espoo, June 4-6: 106-111.

[16] Merkl and Rauber, 1997. Alternative ways for cluster visualization in self-organizing maps, Proc. of WSOM'97, Workshop on Self-Organizing Maps, Espoo, Finland, June 4-6, pp.106-111.

[17] Masters, T., 1993, Practical Neural Network Recipes in C++, Academic Press, San Diego, CA

[18] Vesanto, J., Himberg, J., Alhoniemi, J. Parhankangas, E., 2000, SOM Toolbox For Matlab5, http://www.cis.hut.fi/projects/somtoolbox/

CHAPTER 3

Classification and Clustering of Sensor Data to Build a Decision Support System for Process Condition Monitoring

3.1 Introduction

With the growing application of Ti alloys, the ability to produce parts with high productivity and good quality has become a critical issue in the research community [1, 2]. Ti alloys are known to be difficult-to-machine materials. Their material properties such as low weight, high strength and high temperature stability are crucially accepted for aircraft industry uses, on the other hand, their hardness and toughness cause challenging situations against machining operations.

During machining of Ti alloys, tool wear develops in a very rapid way reducing tool life down to few minutes; chip form is continuous and therefore difficult to remove from the machining area, and in order to fulfil the quality requirements of the product, process parameter values must be kept low against productivity [2]. However, tool wear is very fast and the experimenting specimen expenses are higher than the normal materials (steel, aluminium, etc.), determining additional burden on experimental expenses.

The optimization of these machining processes is decidedly important in industrial environments but, since reliable machining models are scarce for these materials, process parameters are selected in an empirical way on the basis of skilled operators' experience. However, sensor monitoring for process condition can be an alternative way to correlate skilled operators' experiences with the sensor signals during the machining process.

The utilisation of sensor monitoring systems for process conditions during machining represents an effective solution to the problem of their optimization and production cost reduction [3 - 6].

This chapter presents the utilization of acceleration sensor signals monitoring for process optimization. The concerned machining process is turning of Ti alloy, where the acceptable and not-acceptable process conditions are correlated with its real time sensor signal features. The sensor signal features are classified into acceptable and Not acceptable process conditions. The classification provides a decision support system to evaluate the process acceptability.

The main activities can be divided into:

1. Turning of Ti alloys with detection and conditioning of acceleration sensor signals
2. Advanced signal processing feature extraction and creation of data samples in correlation with various combinations of process parameters
3. Classification of process conditions into two acceptable and not-acceptable clusters
4. Refinement of ambiguous data to improve cluster classification

This research work is the continuation of a collaborative research activities [6], where two laboratories: the Machining Technology Laboratory at the Fraunhofer Institute for Machine Tools and Forming Technology (IWU), Chemnitz, Germany, and the Laboratory for Advanced Production Technology (LAPT) at the Department of Materials and Production Engineering, University of Naples Federico II, Italy were contributed in development and application of sensor monitoring of machining process with the aim of process optimization. The block diagram for process condition selection and decision making has been shown in Figure 3.1, where decision making is performed by SOM Neural Networks.

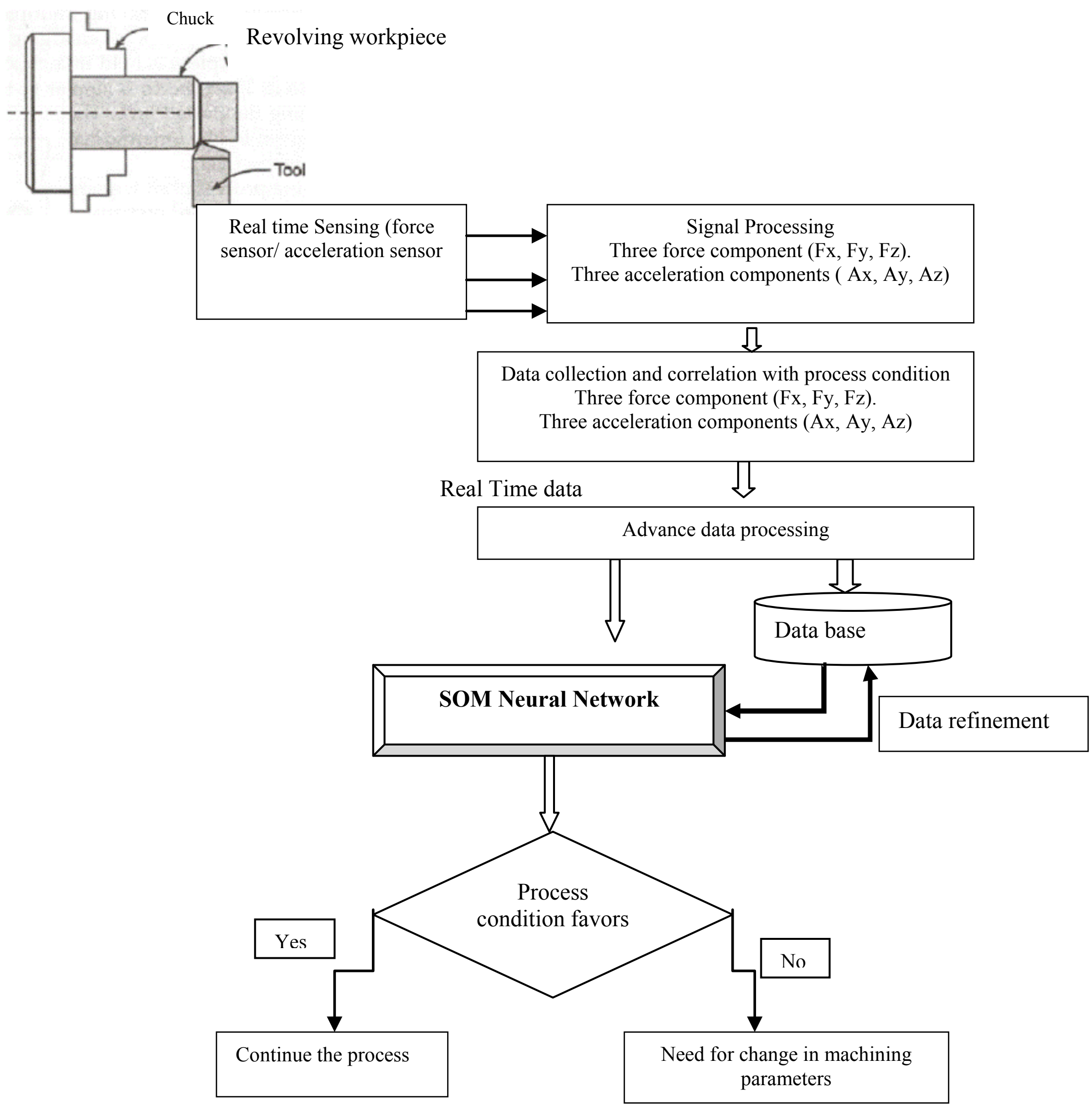


Figure 3.1: Block diagram for on-line process condition monitoring for turning operation

3.2 Materials and Experimental Procedures

Turning tests were performed at the IWU Lab on a CNC lathe (ZMM CU500) during dry cutting of a difficult-to-machine Ti alloy (TiAl6V4) under the following process conditions (see Table 3.1):

- cutting speed: v_c = 85, 110, 145, 185 m/min
- feed rate: f = 0.1, 0.15, 0.20 mm/rev
- depth of cut: d = 0.4 mm

The cutting tool had these characteristics:

- coated carbide insert: Kendex TPGN160308
- coating: KC5010 (PVD TiAlN)
- rake angle: $\gamma = 0°$
- clearance angle: $\alpha = 11°$
- no chip breaker

During the cutting tests, the following measurements were carried out (Figure 3.2):

- three acceleration components a_x, a_y, and a_z using a 3D vibration sensor (ICP 604A61 SN 183) bolted onto the tool holder near the cutting insert.

Test ID	**v_c (m/min)**	**f (mm/rev)**	**d (mm)**
Ti-85-10	85	0.10	0.40
Ti-85-15	85	0.15	0.40
Ti-85-20	85	0.20	0.40
Ti-110-10	110	0.10	0.40
Ti-110-15	110	0.15	0.40
Ti-110-20	110	0.20	0.40
Ti-145-10	145	0.10	0.40
Ti-145-15	145	0.15	0.40
Ti-145-20	145	0.20	0.40
Ti-185-10	185	0.10	0.40
Ti-185-15	185	0.15	0.40
Ti-185-20	185	0.20	0.40

Table 3.1: Test programme: v_c = cutting speed, f = feed rate, d = depth-of-cut.

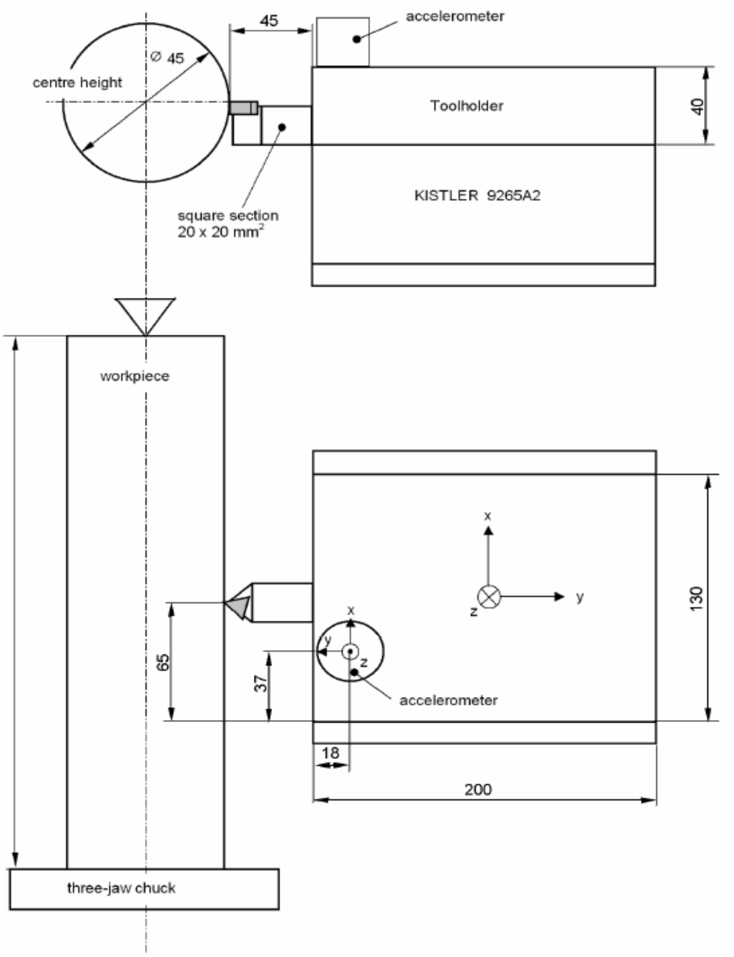


Figure 3.2: Sensor monitoring system.

3.3 Signal Processing and Creation of Data set

Sensor signal analysis procedures were carried out for the identification of the correlations between sensor data and process conditions during turning of Ti alloys.

The procedures adopted for the characterization of sensor signals detected during the experimental tests are based on frequency domain analysis.

3.3.1 Signal conditioning

The detected sensor signals are know as raw sensor signals. Some portions of the raw sensor signals were not related to the cutting test under regime conditions. In particular, their initial and final portions, connected with transient conditions at the beginning and the end of the cutting test, need to be removed as they may easily contain spurious information.

3.3.2. Signal analysis

The signal analysis can be divided into two parts:

(1) Sub-division of conditioned acceleration sensor signals into certain number of acceleration signal specimens,

(2) The extraction of sensor signal features from the acquired signal specimens [6].

The conditioned acceleration component signals were sub-divided into 5 equal parts of 62500/5 = 12500 samples (acceleration signal specimens). Therefore, out of 12 turning tests, total 60 signal specimens were obtained separately for each acceleration components (Ax, Ay and Az).

The extraction of sensor signal features was carried out through a parametric method. The signal specimen spectrum is assumed to take on a specific functional form, the parameters of which are unknown. The parameters, *p* are called sensor features or predictor coefficients $\{a_1, \ldots, a_p\}$, are obtained through linear predictive analysis (LPA). Feature extraction was implemented with p= 4, 8, 16. Accordingly, the obtained feature vector from each sensor signal specimen through this procedure consists of 4, 8, 16-vector coefficients.

For each acceleration components (Ax, Ay and Az), three data sets were created, where the data samples have four, eight or sixteen feature coefficients. Overall, nine data sets were created, each data set contains 60 data samples produced by 60 sensor signal specimens, which are labeled with correlated process condition. The forty data samples belong to acceptable and the rest 20 belong to not-acceptable process condition. Each data set has been utilized as a separate case study to realize/compare the classification performance of the acceleration components.

3.4 SOM NN Data Processing

SOM (Self Organizing Map) can be considered as a two-dimensional scene in which the case features are classified so that those which share related characteristics are located in the same zone of the map. A SOM map is formed by a grid of neurons, also called nodes or units, which govern the placing of stimuli vectors.

A stimulus is a vector of dimension d which describes the case to be classified. As example in case study 1, the acceleration component Ax signal is characterised by a 4 elements feature vector, a stimulus is a 4 dimensional input vector labelled with acceptable or not-acceptable encode (Table 3.2). The SOM NN was trained with all input vectors in the training set except for the test vector which was set aside to be used later for classification performance.

a1Ax	a2Ax	a3Ax	a4Ax	Label
0.2282	-0.048	0.0221	0.0013	*No*
0.2446	-0.0522	0.0359	-0.0045	*No*
…	…	…	…	…
0.1795	0.0595	-0.0025	0.0032	*Yes*

Table 3.2: 4 elements input vectors comprising 4 features associated with acceleration signal Ax, each input vector is labeled with process condition. *No*= acceptable and *Yes*= not-acceptable

3.5 Identification of Ambiguous Data and Refinement

The ambiguous data can be defined as a data vector that lies in more than one clusters causes problem to create clearly separate clusters. Identification of the ambiguous data vectors plays a crucial role to refinement and analysis of data sets by providing additional inferences about sensitive points of cluster overlapping. A visualization tool in data analysis using SOM is the hit histogram. A hit histogram is formed by taking a data set, finding the Best-Matching Unit (BMU) in the map for each data sample in the data set, and increasing the counter in the corresponding map unit. The hit histogram shows the distribution of the data set on the map. In this paper, the hit histogram for the whole input data set is calculated and visualized on the U-matrix where the hittings corresponding to acceptable and not-acceptable are shown in red and green colors, respectively. The hit histogram of first case study, identifying the ambiguous data vectors has been shown in Figure 3.3 (Overlapping points of the clusters are indicated by the circles).

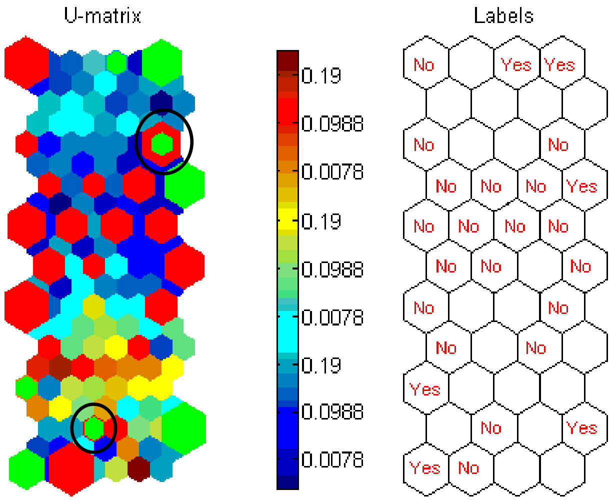


Figure 3.3: Hit histograms visualized on the U-matrix for Case 1 (Ax) representing the distribution of the whole data set on the map (before refinement).

In Figure 3.4, same hit histogram has been shown after the removal of the ambiguous data samples.

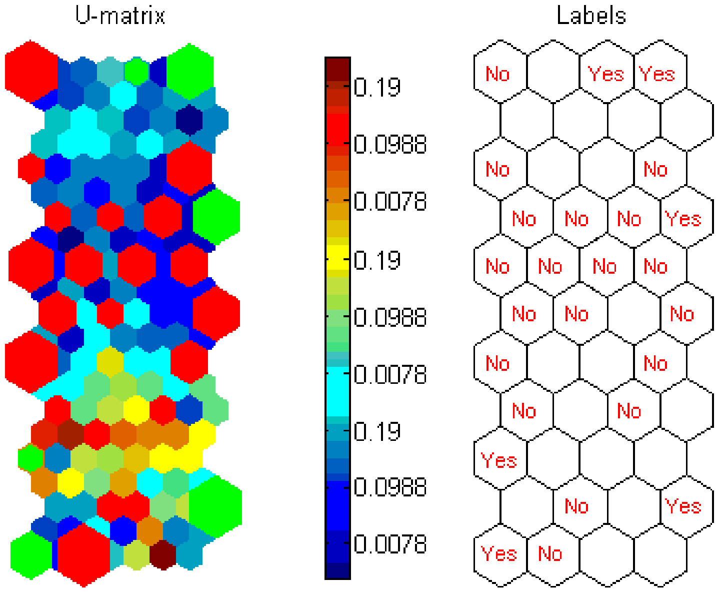


Figure 3. 4: Hit histograms visualized on the U-matrix for Case 1 (Ax) representing the distribution of the whole data set on the map (After refinement).

3.6 Results and Discussion

Nine case studies were considered: in the first three case studies (Case 1, Case 2, and Case 3) single cutting acceleration components Ax, Ay, and Az are utilized separately, where the sensor signals have four features (a1, a2, a3 and a4). Similarly, in the other case studies (case 4 to case 9) the first three cases have eight features and the last three cases consider sixteen features.

After training, it is important to verify whether the SOM NN has properly adapted itself to the training data set. The SOM NN is checked through the test data samples: if a test data sample is placed in the unit of the map containing the correct label, a successful test occurs. On other hand, an unsuccessful test is defined when the test data sample is placed in a wrongly labeled or in an unlabelled map unit. Testing failures are of two types: Type1 occurs when the test data sample is placed in a blank map unit (no label) and Type2 happens when the test data is placed in a wrongly labeled map unit. In Type1 failure, the test data sample is assigned in a U-matrix area where there are similarly labeled map units in the neighborhood. The neighborhood map units can identify the process condition cluster even if the test data sample lies in an unlabelled map unit. However, in Type2 failure, the test data sample is assigned in a wrong map unit and this clearly misguides in the identification of the right process condition. Analysis of the SOM based classification has been carried out for the all nine case studies. The success rate to identify process conditions is considerably high (Table 3.2). In the case 7, where acceleration component Ax concerned with 16 characteristics has achieved 85% of identification success rate (Table 3.2). It is worthwhile to notice that the utilization of Ax in the each case study with 4, 8 and 16 vector coefficients (case 1, case 4 and case 7) has shown better results than that Ay and Az. The Ax based classification is more successful to provide correct decision (Table 3.2). To cluster the acceptable and the not-acceptable process condition, x-component of the acceleration signals are more effective to find clearly separate clusters.

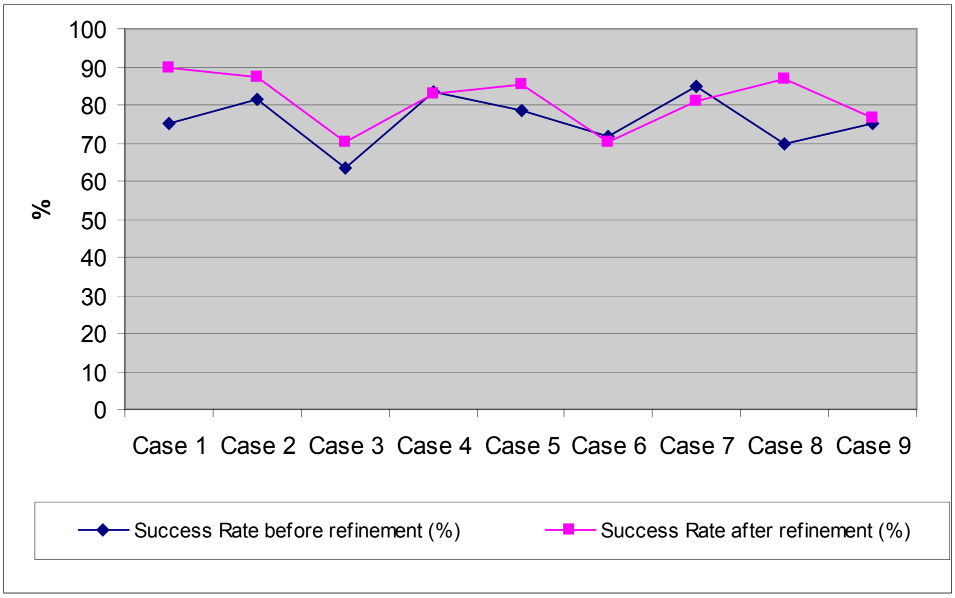


Figure 3. 5: Comparison of SOM NN Classification performance between the utilization of whole data set and refined data set

Moreover, in order to improve the classification clarity, all the data sets have refined by detection of overlapping regions between the clusters. The overlapped regions can be seen where more than one data samples belonging to different clusters hit into same neuron (Figure 3. 2). The neuron is actually the part of the cluster which dominates over it. The data samples belonging to the under-dominate cluster are detected and removed. For all nine cases, the data sets are refined by the same procedure, and SOM NN classification performance of the refined data sets has been re-examined (Table 3.2). A considerable improvement in classification performance was observed in almost every nine case studies (Figure 3. 5).

References

[1] Rahman, M., Wang Z.G., Wong, Y.S., 2006, A Review of High-Speed Machining of Titanium Alloys, JSME Int. J. Ser. C: Mech. Syst. Mach. Elem. Manuf., Vol. 49: 11-20.

[2] Teti, R., 2007, Difficult to Machine Materials, 2nd Mftg. Eng. Soc. Int. Conf. – CISIF/MESIC '07, 9-11 July, Madrid, CD ROM

[3] Segreto, T., Teti, R., 2007, Applications of Intelligent Sensor Monitoring for Machining Processes, 8th Int. Conf. on Lamdamap, 25-28 June, Cardiff: 388-399.

[4] Teti, R., Jawahir, I.S., Jemielniak, K., Segreto, T., Chen, S., Kossakowska, J., 2006, Chip Form Monitoring through Advanced Processing of Cutting Force Sensor Signals, Annals of CIRP, 55/1: 75-80.

[5] Rubio, E.M., Teti, R., Baciu, I.L., 2006, Advanced Signal Processing in Acoustic Emission Monitoring Systems for Machining Technology, 2nd Int. Virtual Conf. on IPROMS, 3-14 July: 189-192.

[6] Segreto, T., Teti, R., Neugebauer, R., Harzbecker, C., 2008, Sensor Monitoring Based Optimisation during Turning of Titanium Alloys, Proceedings of Virtual International Conf. on Innovative Production Machines and Systems - IPROMS2008, 1-14 July: 547-554.

CHAPTER 4

Automatic Tool Wear Detection to Build a Decision Support System for Tool Wear Monitoring

4.1 Introduction

With the existing knowledge of materials science and mechanical tools (finite elements techniques) engineers are able to predict the functional behavior of a component of a product or process with respect to strength, fatigue etc. with reasonable accuracy. However, the lifetime of a component depends on wear. Wear is difficult to measure for its dynamic and complex nature [1].

4.1.1 Theory of Tool Wear

In manufacturing science, cutting tool wear is of great importance. The introduction of this chapter will give a quick and general overview of cutting tool wear and its types.

4.1.1.1 Tool Wear Definition

Tool wear describes the gradual failure of cutting tools due to regular operation. It is characterized by the change of shape of the tool, during cutting, due to the gradual loss of the cutting material. [2, 3, 4].

During operation, cutting tools are subjected to an extremely severe rubbing process. They are in contact with both formed chips and the work piece, under conditions of high temperature and high stress. The situation is aggravated due to the existence of extreme stress and temperature gradients near the surface of the tool. [3, 4].

During machining, cutting tools remove material from the component to achieve the required shape, dimension and surface roughness (finish). However, wear occurs during the cutting action, and it will ultimately result in the failure of the cutting tool. When the tool wear reaches a certain extent, the tool or active edge has to be replaced to guarantee the desired cutting action. [3, 4].

The cutting tool can fail in three different modes:

1. ***Fracture failure*****:** This mode of failure occurs when the cutting force at the cutting point becomes excessive, causing to fail suddenly by gradual failure [5].
2. ***Temperature failure*****:** This failure occurs when the cutting temperature is too high for the tool material, causing the material at the tool point to soften, which leads to plastic deformation and loss of sharp edge [5].
3. ***Gradual wear*****:** Gradual wearing of the cutting edge causes loss of tool shape, reduction in cutting efficiency, an acceleration of wearing as the tool become heavily worn, and finally tool failure in a manner similar to temperature failure [5].

Fracture and temperature failure lead to a premature loss and failure of the tool. Gradual wear leads to the longest possible use of the tool, with the associated economic advantage of that longer use [6].

4.1.1.2 Gradual Wear and its Characteristics

Two types of gradual wear can be distinguished: flank wear, occurring on the flank of the cutting tool, and crater wear, occurring on the top rake face of the cutting tool. Figures 4.1, 4.2, and 4.3 illustrate the tool wears and their respective locations on the cutting tool.

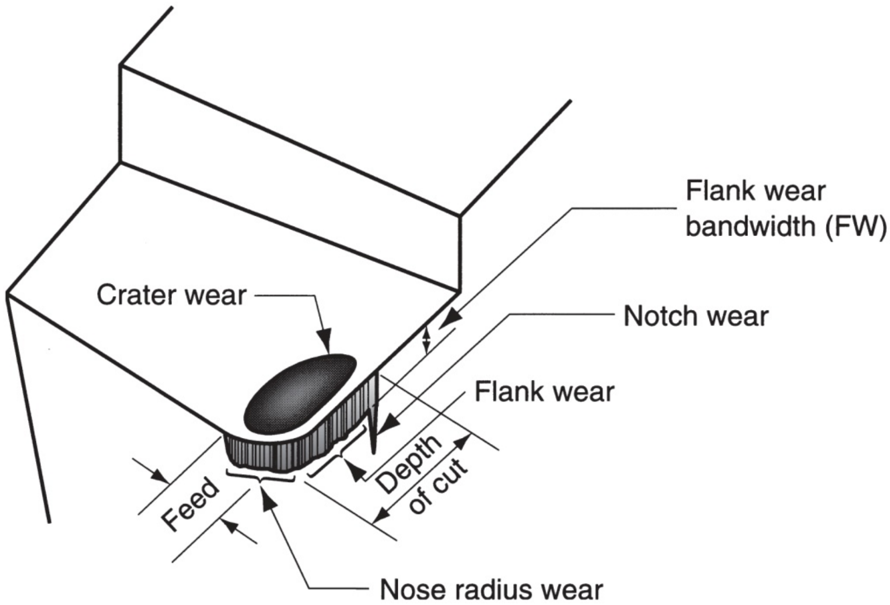


Figure 4.1: Worn cutting tool, showing the principal locations and types of wear [5].

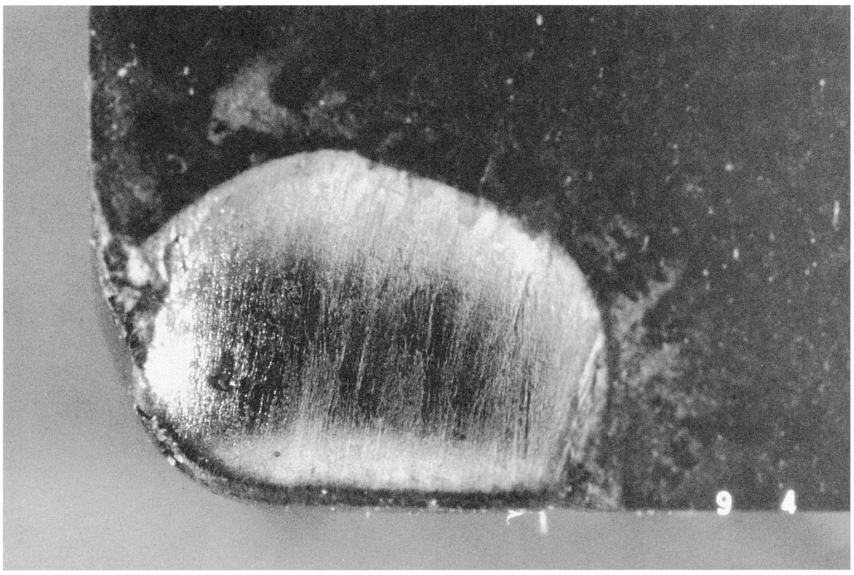


Figure 4.2: Crater wear on a cemented carbide tool [5].

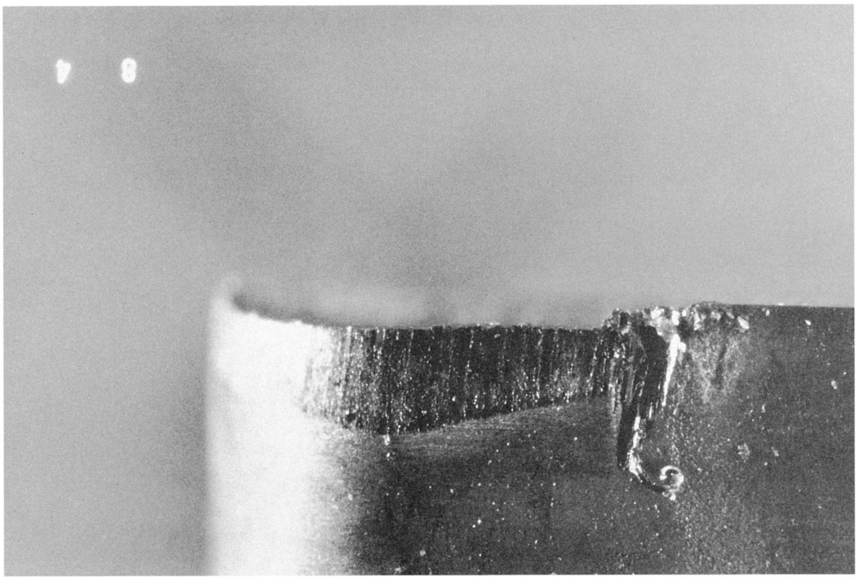
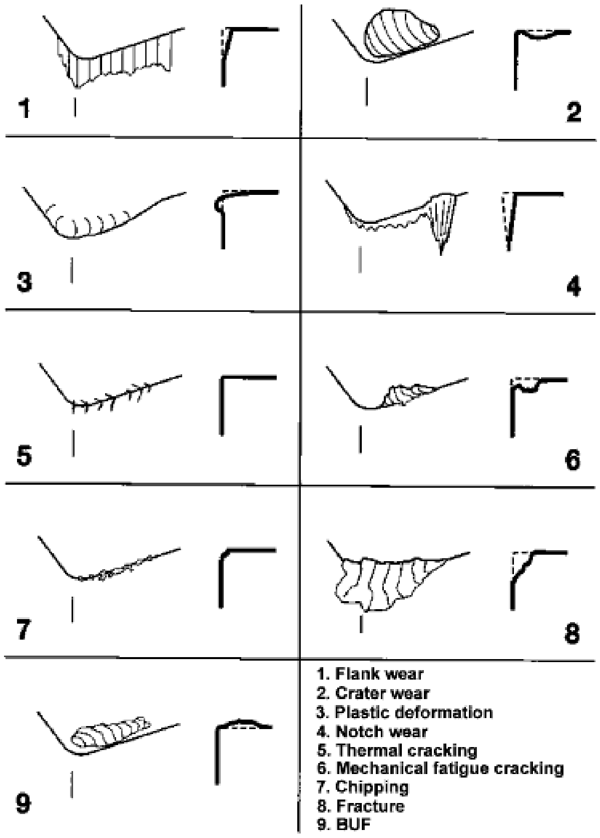


Figure 4.3: Flank wear on a cemented carbide tool [5].

Crater wear (Figure 4.2) consists of a concave section on the rake face of the tool, formed by the action of the chip sliding against the surface. High stresses and temperatures characterize the tool-chip contact interface, contributing to the wearing action [5].

Flank wear (Figure 4.3) occurs on the flank face, or the relief face, of the tool. It results from rubbing between the newly generated work surface and the flank face adjacent to the cutting edge [5].

Certain features of the flank wear can be identified. First, an extreme condition of flank wear often appears on the cutting edge at the location corresponding to the original surface of the work part. This is called ***notch wear***. It occurs because the original work surface is harder and/or more abrasive than the internal material, due to work hardening from cold drawing or previous machining, sand particles in the surface from casting, or other reasons. As a consequence of the harder surface, wear is accelerated at this location. A second region of flank wear that can be identified is ***nose radius wear***; this occurs on the nose radius leading into the end cutting edge [5].



Scheme 4.1: Types of wear on cutting tools [6].

4.1.2 Scope of the Research

Chapter 4 will mainly focus on the investigation of new methodology, techniques, and instrument suitable for detection and monitoring of cutting tool wear, particularly online and non-contact, using imaging methods.

In machining process enhancement research field, knowledge about the nature and development of tool wear is of growing importance, because of the ever increasing demand for better performance of tools and components/products. On the other hand, in manufacturing or engineering industry, inspection and control of the cutting, machining or coating process to guarantee surface quality, require suitable damage/wear detection techniques/tools.

The goal of this research is the development of measurement tools (hardware and software) for the detection of micro- and macro-wear of materials online, based on imaging methods. These techniques allow faster and hence dynamic measurements of wear, and are essentially non-contact.

Wear is a dynamic and complex process which involves not only surface and material properties but operating conditions as well. Most of the existing techniques for wear measurement are offline and they have intrinsic restrictions:

- During measurement the specimen needs to be taken away from the wear tester and be measured under some instrument periodically, which is cumbersome and time-consuming.
- During mounting and dismounting steps extra damage to the specimen's surface may be introduced.
- It is hard to measure the same location of the surface. Repositioning is a big challenge.
- During measurement the wear process is interrupted and the wearing environment is hardly kept the same.
- It usually needs a well-trained operator to do the measurement (especially for interference microscopy, AFM, STM, SEM etc.). Otherwise operating errors may be introduced.

Because of the above restrictions of the existing techniques new online wear monitoring methodology, which offers higher accuracy in the sense of neither interrupting the wear process nor changing the wearing environment, is demanded in cutting operation research.

As the quality of the cutting tool is directly related to the quality of the product, automatic tool wear monitoring is vital to ensure smooth automatic control of machining. In this paper, automatic tool wear detection (ATWD) procedure, based on image processing of sequences of cutting tool images captured during turning tests, is proposed.

The ATWD procedure can be divided into five steps: (1) standardization of tool images; (2) adjustment of pixel colour density and noise removal to obtain clear edges over tool wear region; (3) drawing the projection line to find the coordinates of the edge lines; (4) identifying the tool wear area; (5) evaluation of tool wear development characteristics. The tool wear characteristics are evaluated on the basis of the processed edge. The sequence images are processed through the ATWD procedure which automatically provides the growth of tool wear. The maximum width of the crater wear, KB, measured through the ATWD procedure is compared with KB values measured by a tool maker's microscope. The comparison of results confirms that the ATWD procedure can achieve a sufficient degree of accuracy to be used for the evaluation of tool wear development on an on-line basis.

Automatic tool wear detection is a vital aspect to monitor the tool life and/or product quality in unattended machining. Cutting tool life depends on service time under cutting conditions; it is difficult to estimate service time and cutting conditions in machining centres where a variety of tools are used [7]. Tool wear development monitoring can allow the identification of the correct moment to replace the tool, thus protecting the workpiece and/or increasing the tool life [8, 9]. In order to measure the tool wear development characteristics, digital pictures of the cutting tool detected during turning tests can be utilized [10]. This paper presents an image processing methodology based on an automatic procedure to measure the crater wear area and tool wear development characteristics. During the turning operation, cutting tool crater wear images were collected sequentially after each minute of machining until tool failure. An image overlapping technique was utilized to produce images with standard size and pixel density. The standardized pictures were sequentially processed one by one through the ATWD procedures to obtain the tool wear state and its development with cutting time.

4.2 Experimental Setup and Tool Wear Image Collection

The experimental turning tests consisted in quasi-orthogonal cutting operations on cylindrical bars made of AISI 1045 steel. Tungsten carbide inserts with rake angle 6°, relief angle 5°, side cutting edge angle 0°, and nose radius 0.8 mm were used.

The cutting parameters values are reported in Table 4.1. Out of 18 possible parameter combinations, 14 cutting conditions were selected and identified as “adh”, ”aeh”, “aei”, “afh”, “afi”, “bdi”, “beh”, “bfh”, “bfi”, “ldi”, “leh”, ”lei”, “lfh”, “lfi”. For every cutting condition, the quasi-orthogonal cutting test was performed with a new tool insert utilized until tool failure.

During each machining test, crater wear digital images were captured with a digital camera for each minute of cutting [11, 12]. Depending on the test duration, the number of sequence images varied between 3 and 60. The maximum number of images was detected for cutting conditions “beh”, where the test was interrupted after 60 minutes even thought the tool failure was not achieved. The minimum number of images was obtained for test “lfi” where only 3 images were detected before the fast tool failure (Table 4.2). The images were captured so that the crater wear characteristics could be identified as clearly as possible (Figure 4.4).

Crater wear was also measured with a tool maker's microscope: the selected crater wear parameter was the maximum width of the crater wear, KB.

Cutting Speed (mm/min)		**Feed Rate (mm/rev)**		**Depth of Cut (mm)**	
Level-id	Parameter Value	Level-id	Parameter Value	Level-id	Parameter Value
a	200	d	0.06	h	1.0
b	150	e	0.12	i	1.5
l	250	f	0.19		

Table 4.1: Cutting parameters for the quasi-orthogonal cutting tests.

Test id	Tool images	**Test id**	Tool images	**Test id**	Tool images
adh	51	**bdi**	57	**ldi**	29
aeh	27	**beh**	61	**leh**	15
aei	15	**bfh**	23	**lei**	8
afh	17	**bfi**	33	**lfh**	7
afi	11			**lfi**	3

Table 4.2: Number of tool images for the different cutting tests.

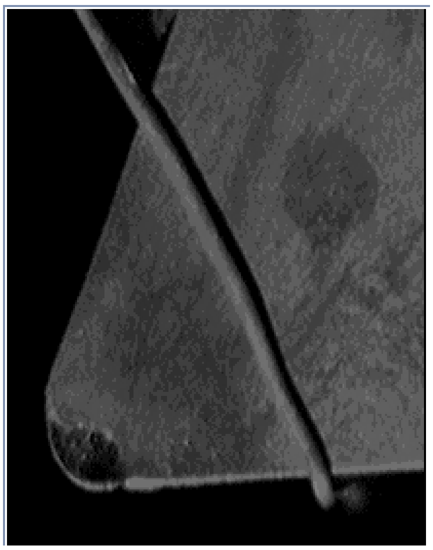


Figure 4.4: Raw crater wear image with $\Phi = 0.25$ mm reference copper wire.

4.3 Automatic Tool Wear Detection Procedure

4.3.1 Standardization of Tool Image

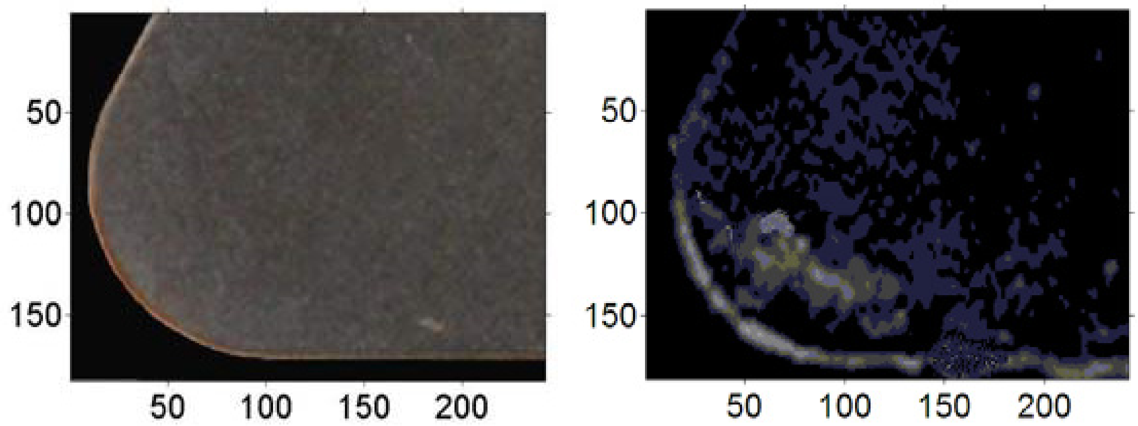
To automatically measure the tool wear development through image processing, all tool images should essentially have the same size and pixel density, i.e. images should be standardized. For this standardization, the fresh tool image was used as reference.

Each cutting tool image was overlapped onto the reference image and the image size and pixel density were adjusted to find the best fit with the reference image. This overlapping based standardization technique minimizes the original image capturing errors generated by variable camera to tool distance, focusing, and lighting conditions.

The standardization procedure provided homogenous pictures with respect to contrast definition, size, picture resolution and position of crater wear area. The standard image size is 242 pixels x 181 pixels and resolution is 300 pixels/inch (standard size reference image is shown in Figure 4.6a). In order to allow absolute value measurements in mm, a reference copper wire with known thickness 0.25 mm, corresponding to 28 pixels in the standardized picture, was included in each tool image (Figure 4.5).

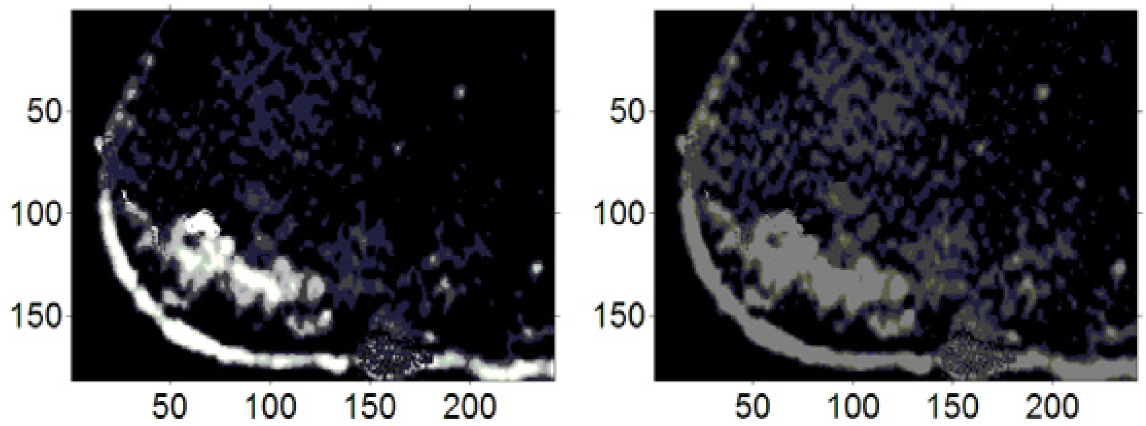
4.3.2 Adjustment of Pixel Contrast and Brightness

Brightness in the tool wear region is not homogenous. It varies with the camera inclination angle that could not be kept constant during the testing program. In Figure 4.6b, it can be seen that some spots in the tool wear region are very bright and some are rather dark. Thus, to find a distinct picture of the tool wear region, the image contrast and brightness value need to be adjusted through an image processing procedure. Characteristics of the tool wear such as the cutting edge border and the crater wear area are aimed to be highlighted with this procedure.



(a) (b)

Figure 4.5: (a) Reference image (fresh tool); (b) standardized image (cutting tool).

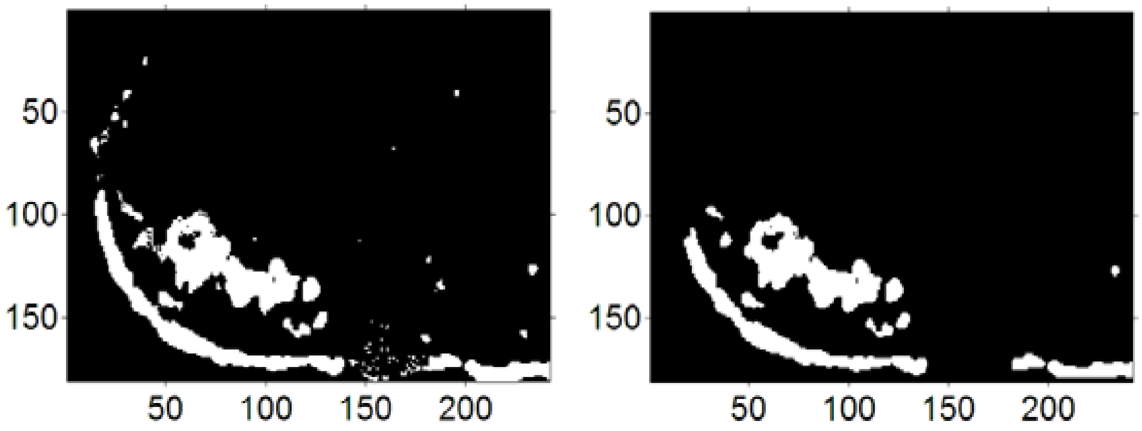


(a) (b)

Figure 4.6: (a) Reference image (fresh tool); (b) standardized image (cutting tool).

4.3.3 Clear Crater Wear Identification and Filtering Out Unrelated Spots

In the cutting tool images, it can be observed that the tool wear is characterized by bright spots within the crater wear zone. In order to clearly identify the crater wear area, these bright spots are converted into white colour (Figure 4.7a). Beside the tool wear, the images may contain further white bright spots that don't belong to the crater wear (Figure 4.7b). These spots need to be removed by a noise removal technique.



(a) (b)

Figure 4.7: (a) Clearly revealed white spots; (b) clearly revealed white spots after noise removal.

4.3.4 Projection Lines Drawing

To find the tool tip edge, the original standard image is converted into an edge image revealing the white cutting edge lines around tool tip (Figure 4.8). In the edge image, imaginary projection lines are vertically drawn from bottom up to obtain the cutting tool edge coordinates. These coordinates of the edge curves are used to evaluate the crater wear area and other tool wear characteristics.

4.3.5 Measurement of Tool Wear Characteristics

The crater wear area is identified by the total number of white pixels enclosed by the crater wear boundary and the tool tip edge. The maximum width of the crater wear area, corresponding to the KB value, is evaluated by counting the maximum number of white pixels in the vertical direction (Figure 4.9).

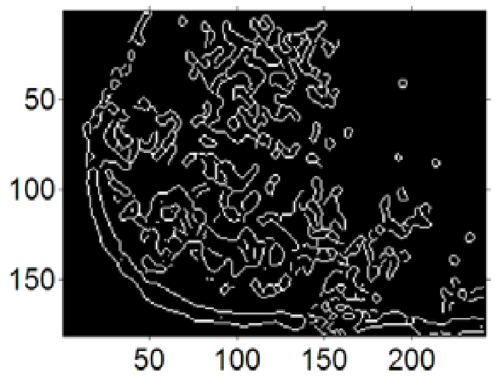


Figure 4.8: Tool Edge Image.

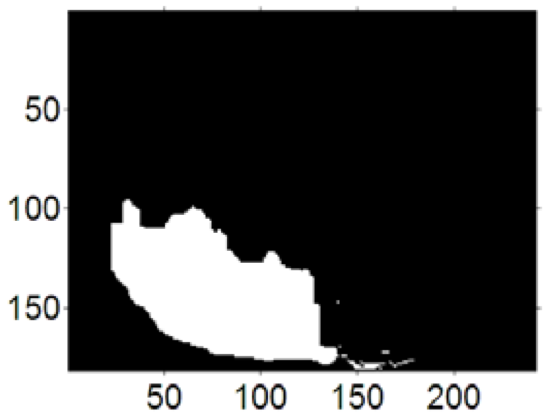


Figure 4.9: Crater wear area and maximum crater wear width.

4.3.6 Standardizing the Images with Matlab

Images were standardized using the software Matlab. Each image was processed on its own. Below is the procedure followed [11]:

- Load image:

Image is read through BMPREAD and matrices corresponding to image data are created;

- Identify the image by its file name:

The machining test and minute are identified by decoding the file name;

- “spess.m” function is used to search in file “fili.wk1” the measure of the reference wire:

File “fili.wk1” is loaded and a variable “fili” is created. The three machining test letters are converted to a numerical code that identifies the test in variable “fili”. The measure of the reference wire is identified.

- Calculate the scale of the image:

The scale of each image is calculated by dividing the real thickness of the wire by its measure in pixels;

- For some images “aggius.m” function is used to increase the width:

Images smaller than the selected standard size are completed by adding columns of numerical values to the image matrix.

- “trunca.m” function us used to clip images to size 1 mm × 2 mm or 2 mm × 2 mm.

- Increase pixel density by using “mataum.m” function.

- Convert the matrix to an image file and save it in folder “c3” or “c4”: an image file given by the calculated matrix and the initial colormap is created and saved on hard disk through the command BMPWRITE.

4.4 Results and Discussion

In Figure 4.10, the KB values measured through direct observation using a tool maker’s microscope and the maximum crater wear width evaluated through the ATWD image processing procedure are plotted versus cutting time for different cutting conditions. In figure 4.11, the KB measurement error, given by difference between the ATWD and the direct KB measurements, is plotted versus cutting time for all examined cases. In the figure, the total error of the KB plot, calculated as:

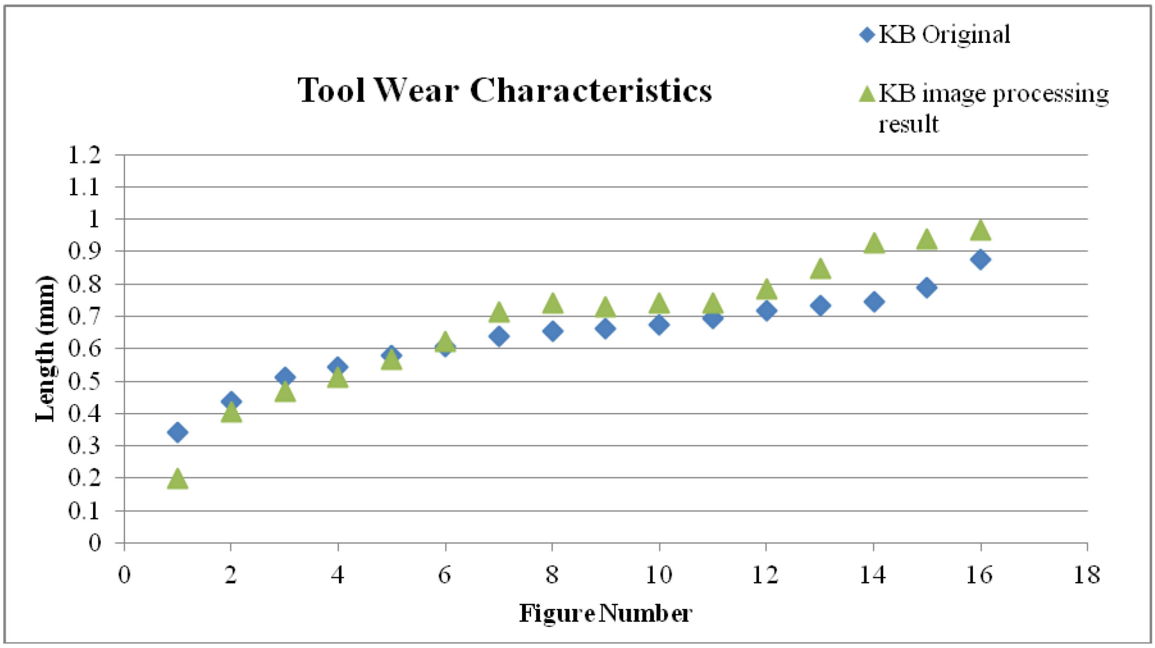
$$\sum_{0}^{n} \left| ATWD\ measurement - direct\ KB\ measurement \right| / n$$

where n=number of images is also reported.

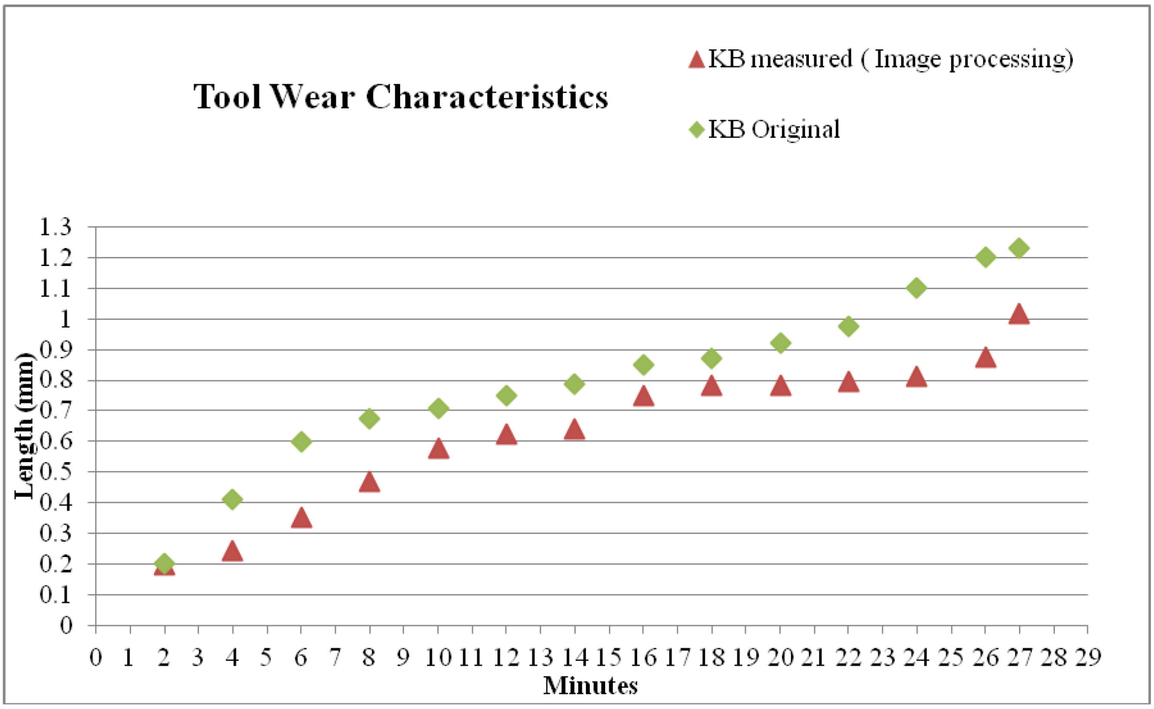
From the plots in Figures 4.10 and 4.11, it can be seen that, for the lest severe cutting condition “bfi”, the ATWD crater width measurements are slightly under estimated in the initial period, very accurate in the middle period, and slightly overestimated in the final period of cutting before the tool failure. Accordingly, the total plot error is as low as 0.09.

For the most severe cutting conditions, “ldi” and “leh”, the ATWD crater wear measurement is overestimated in the initial period of cutting and underestimated in the final phase of cutting. The total plot errors have medium to high values, ranging between 0.12 and 0.19.

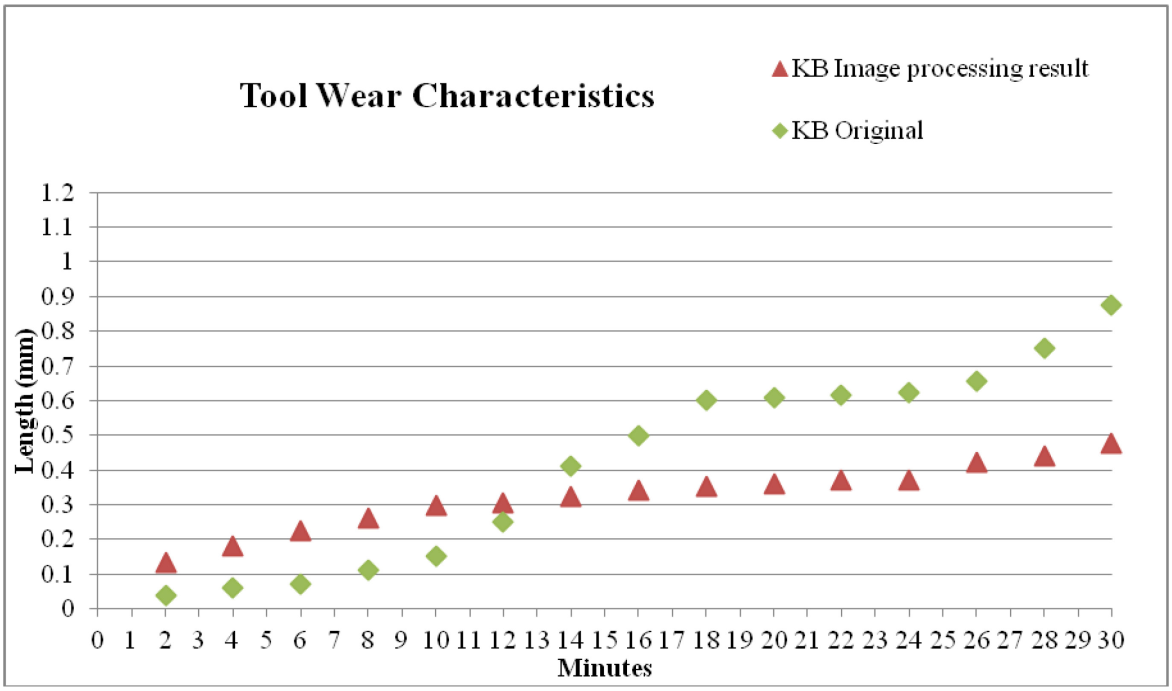
The intermediate cutting condition case, “aeh”, shows underestimated ATWD crater wear measurements for the whole duration of the cutting test with a total plot error of high value 0.17.


Tool Wear Characteristics
KB Original
KB image processing result
Length (mm)
Figure Number

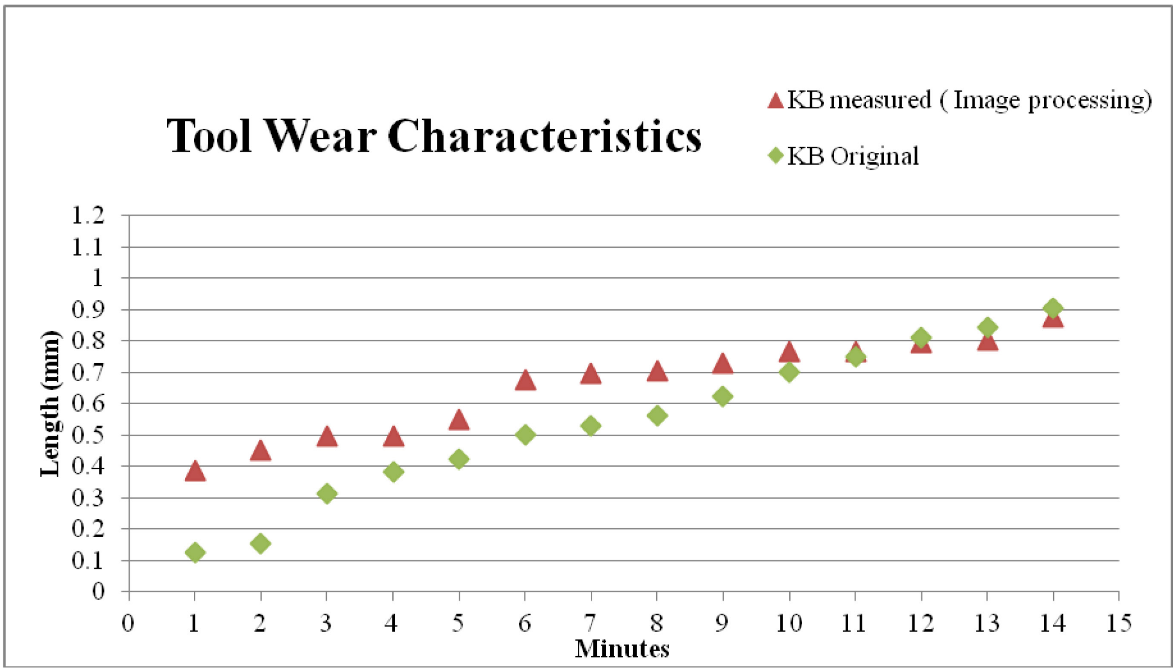
(a)


Tool Wear Characteristics
KB measured (Image processing)
KB Original
Length (mm)
Minutes

(b)



(c)

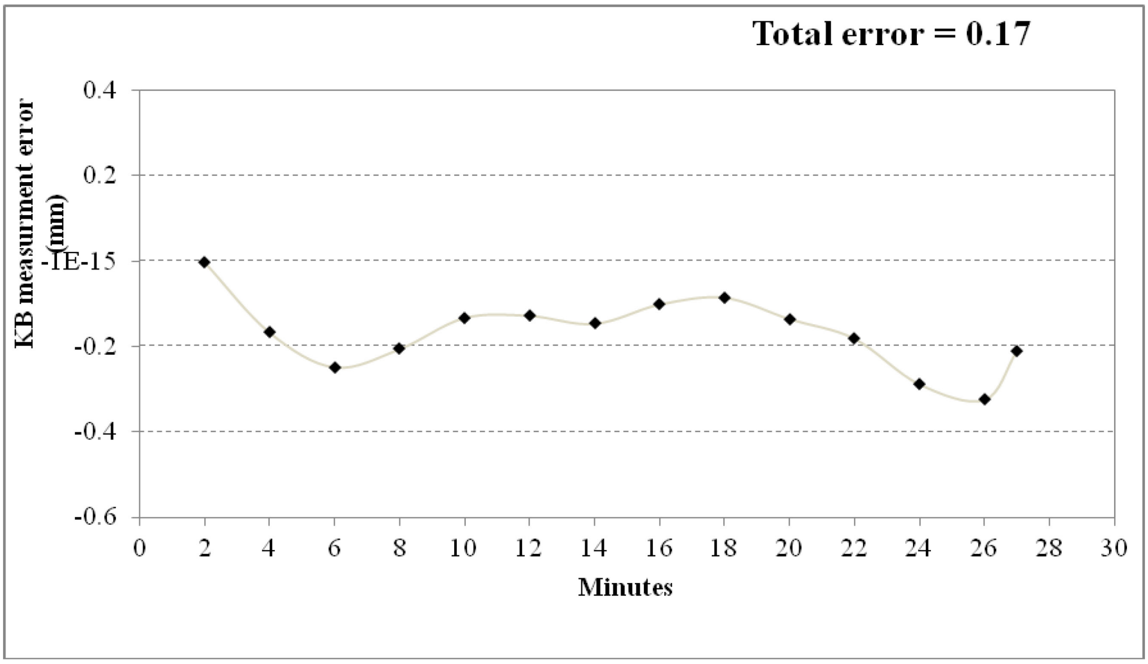


(d)

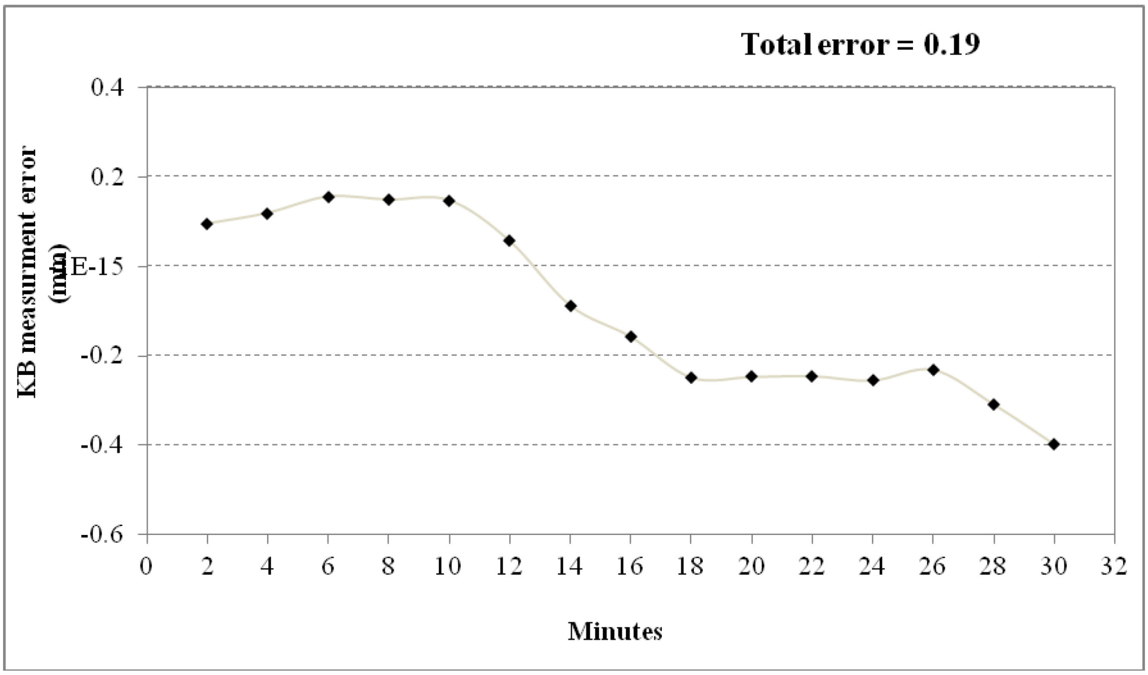
Figure 4.10: Crater wear KB measurements comparison: (a) cutting condition "bfi", (b) cutting condition "aeh", (c) cutting condition "ldi", (d) cutting condition "leh"


Total error = 0.09
KB measurement error (mm)
0.4
0.2
-1E-15
-0.2
-0.4
-0.6
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34
Minutes

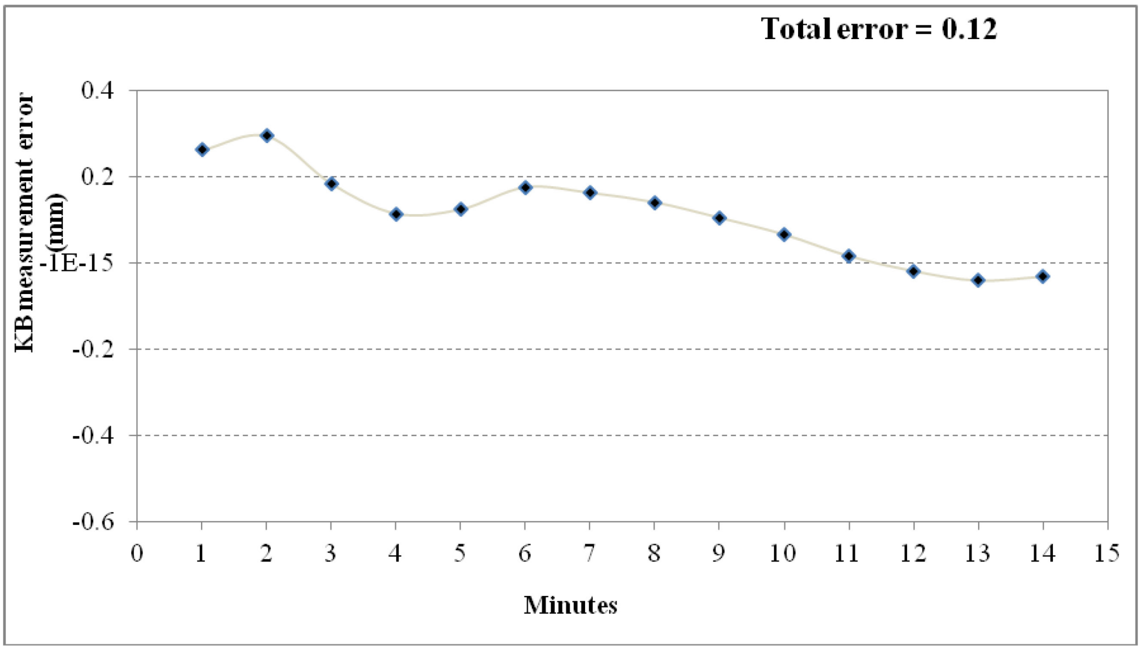
(a)


Total error = 0.17
KB measurment error (mm)
0.4
0.2
-1E-15
-0.2
-0.4
-0.6
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30
Minutes

(b)



(c)



(d)

Figure 4.11: Crater wear KB measurement error: (a) cutting condition “bfi”, (b) cutting condition “aeh”, (c) cutting condition “ldi”,(d) cutting condition “leh"

References

[1] Keshari, A., D'Addona, D. Teti, R., Capece Minutolo, F. 2011, Projection based Image Processing for Automatic Tool Wear Detection, 10th AITEM Conference, 12-14 sept, Naples, Italy, ISBN 978-88-906061-0-1: 89-90

[2] Tool Wear, Wikipedia, the free encyclopedia <http://en.wikipedia.org/wiki/Tool_wear>

[3] Chapter 6: E.J.A. Armarego and R.H. Brown, The Machining of Metals, Prentice-Hall, Inc., 1969

[4] Chapter 9: David A. Stephenson and John S. Agapiou, Metal Cutting Theory and Practice, Marcel Dekker, Inc., 1997

[5] Chapter 23: Cutting Tool Technology, pp. 543-548 Mikell P. Groover, Fundamentals of Modern Manufacturing, John Wiley & Sons, Inc., 2007

[6] Modern Metal Cutting, A practical Handbook, Sandvik Coromant

[7] Byrne, G., Dornfield, D., Inasaki, I., Ketteler, G., Koenig, W., Teti, R.,1995. Tool condition monitoring (TCM) - The status of research and Industrial application, Annals of the CIRP, vol. 44/2, pp. 541-567.

[8] Wang, Y., Ji, S., Zhang, L., Jin, S., Chen, Y., 2008, Detection of tool wear condition based on the computer image processing, Key Engineering Materials, vol. 375-376, pp 553-557.

[9] Teti, R., 1993. Sensor signal frequency analysis for metal cutting process monitoring, 1st AITEM Conference, Ancona, Italy, 22-24 Sept., pp. 55-64.

[10] Teshima, T., Shibasaka, T., Takuma, M., Yamamoto, A., 1993. Estimation of Cutting Tool Life by Processing Tool Image Data with Neural Network, Annals of the CIRP, vol. 42/1, pp. 59-62.

[11] D'Addona, D., Teti, R., 2010. Monitoring of cutting tool wear through image analysis, 6th IPROMS Virtual Conference, 15-26 Nov.

[12] D'Addona, D., Teti, R., 2011. Cutting Tool Image Data Processing for Automatic Tool Wear Recognition Through Artificial Neural Networks, International Conference on Industrial Engineering and Systems Management - IESM 2011, 25-27 May, Metz, France.

CHAPTER 5

Machining Operation Simulation as a Decision Support System for Machining Process Verification

5.1 Introduction

In recent years, computers have been used extensively in all the stages of manufacturing, including product design, process planning, production system design, and process control, in order to make the entire process easier and faster. The application of computers in manufacturing can help reduce costs and lead times in all engineering design stages, improve quality and accuracy, minimize errors, perform accurate control and monitoring of machines and processes, etc. The use of the computer to support Computer-Aided Design (CAD) of products began in the late 1950s. In CAD, computers are used for the design and analysis of products and processes, and they play a critical role in reducing lead time and cost at the design stages of the products/process. Further, computers may be utilized to plan, manage, and control the operations of a manufacturing system, implementing the so-called Computer-Aided Manufacturing (CAM) [1].

Computer-aided manufacturing (CAM) is defined as the effective use of computer technology in manufacturing planning and control. CAM is most closely associated with functions in manufacturing engineering, such as process planning and numerical control (NC) part programming. The applications of CAM can be divided into two broad categories: manufacturing control and manufacturing planning. [2] In CAM, computers are either used directly to control and monitor machines and/or processes (in real-time) or used off-line to support manufacturing operations such as computer-aided process planning (CAPP) or planning of required materials. [3].

Figure 5.1 shows the common applications of CAM software.

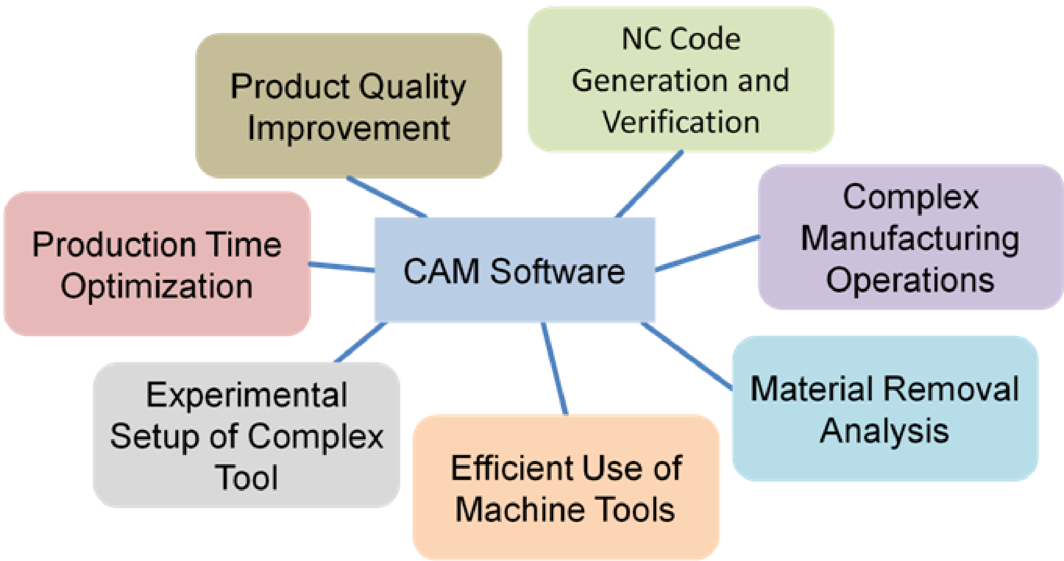


Figure 5.1: Applications of CAM Software.

The evolution of virtual manufacturing has led to the creation of work-cell simulation tools that are capable of developing, simulating and validating manufacturing processes. CAM technology has brought a revolution in manufacturing systems by enabling mass production and greater flexibility and it has also created a direct link between a three-dimensional (3D) CAD model and its production [4,5]

Today, integration of CAD and CAM into manufacturing practises has become a key method for improving quality of products and optimizing production time. This approach greatly influences both industry and engineering education

Machining Process Simulation

The research work illustrated in this chapter presents the features and objectives of machining process simulation, which represents a valuable decision support system to verify and optimize cutting operations. Machining process simulation involves the use of CAM software codes to control machine tools and related machinery in the manufacturing of workpieces to test a process flow before physical experimentation. The primary purpose behind the simulation is to create a faster production process as well as components and tooling with more precise dimensions and improved surface integrity, using only the required amount of raw materials, thus minimizing waste, while simultaneously reducing energy consumption. it can be employed to investigate different solutions in order to optimize the manufacturing process in terms of quality, time, and cost efficiency.

The objective of machining process simulation is to design a completely digital environment where the processes are modeled, machined with optimized process parameters, and resulting errors are predicted with corrective actions being taken in a computer simulation environment. CAM software provides virtual environment to model machining process simulation, 3D visualization and analysis for full range of machine tools application.

The cutting tool path generation for CNC system is another notable industries/research interest in machining tool application and minimization of machine downtime. A lot of constraints, such as cutting tool geometry and material, cutting material, machining operation, machine tool, clamping device, wet or dry machining etc., must be taken into account to generate cutting tool path and optimizing process conditions.

Machining process simulation can fulfill the given below needs of decision making in machining process verification and optimization.

1) Modeling and control of various machine process parameters.
2) Building the real-time control of machining operation through the virtual machining.
3) Maximizing the capacity of report generation.
4) Detailed tooling reports that machining process simulation generates to help the machinists get the setup just right, and the net result is first-run parts with no crashes.
5) Possibility to respond quickly to process planning of new part production.
6) Development and verification of new machining techniques.
7) Easy understanding of complex machinery and machine setup.
8) Efficient use of knowledge-base strategies, knowledge-base-management (Cutting tool knowledge base, workpiece material knowledge base, process technology knowledge, knowledge base of feature recognition).
9) Identification of machining process area where cycle times can be reduced by improving the NC program.

Figure 5.2 illustrates some of the facilities and advantages of machining process simulation: the NC code generated, facilitation of complex manufacturing processes, variable axis mill, toolpath inspection, and combination of milling and turning operations.

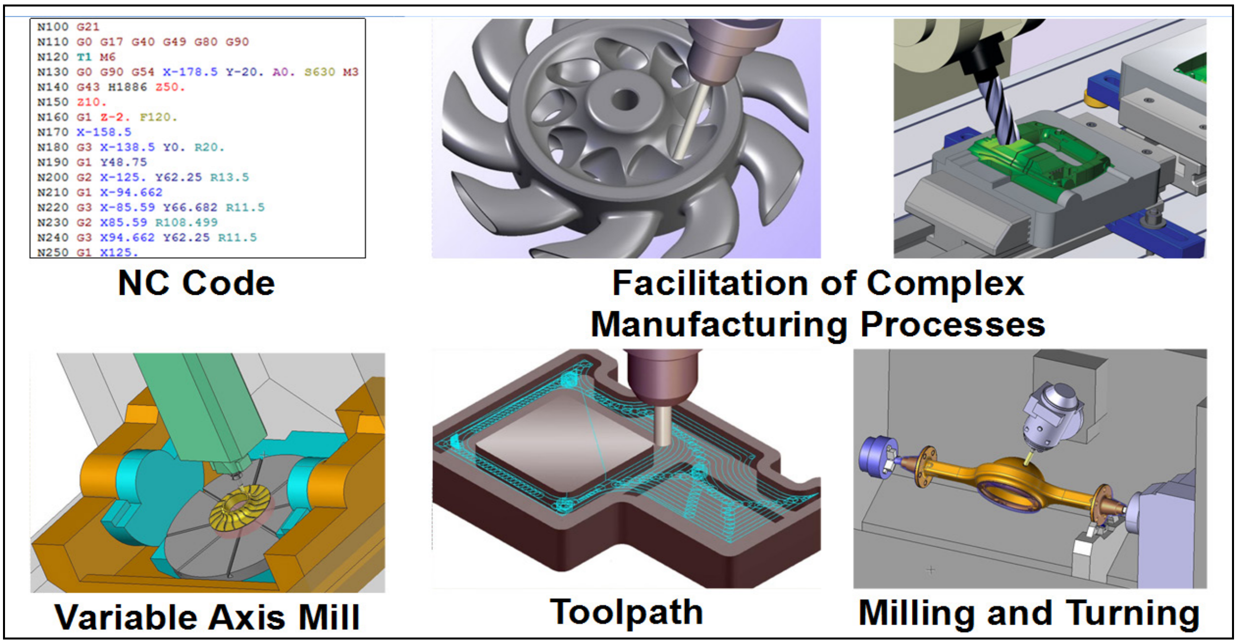


Figure 5.2: Examples of Machining Process Simulation Activities.

A conventional CAD/CAM system implementation can be represented as illustrated in Figure 5.3. A new product enters a machining shop as engineering drawing or CAD model. The CAD geometry is then processed to analyze the machining operations which are required to cut the final geometry features.

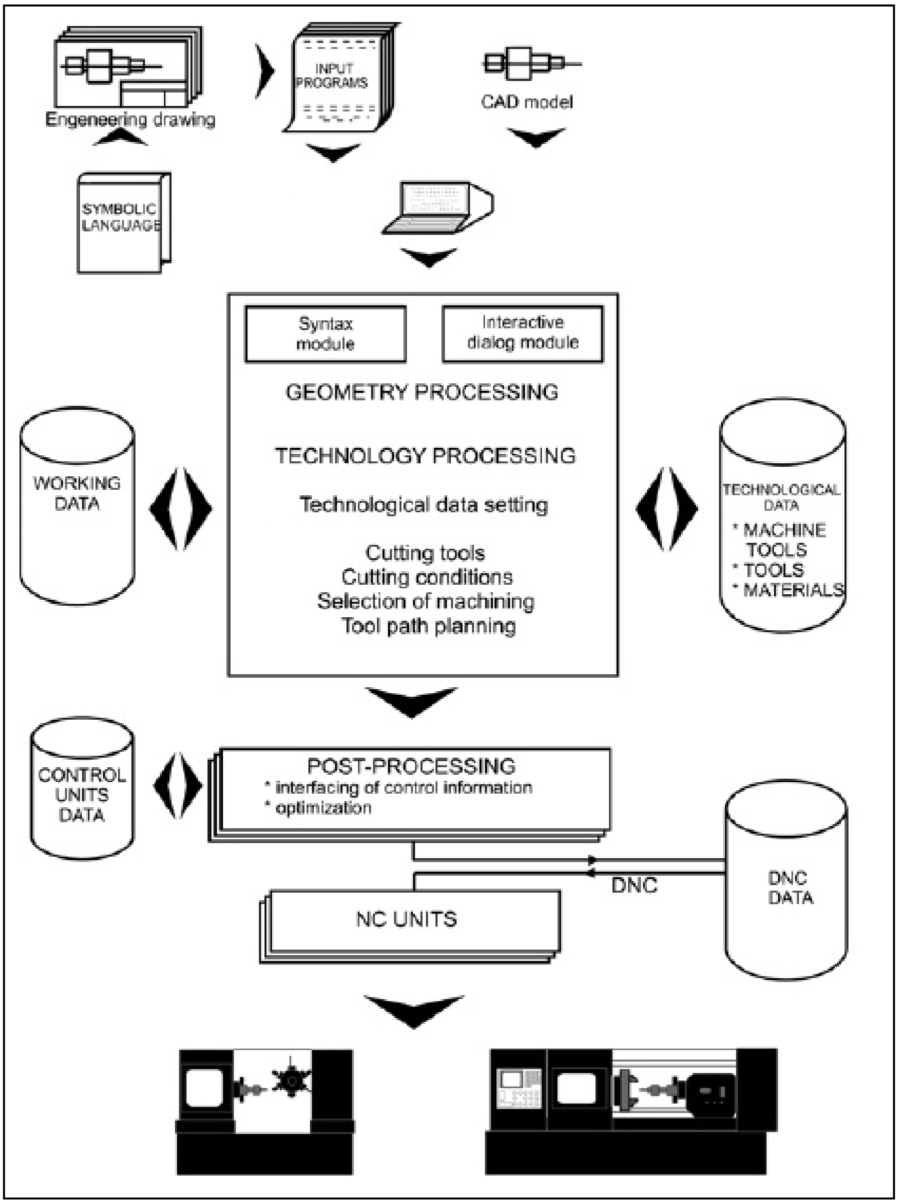


Figure 5.3: Conventional CAD/ CAM System [6].

5.2 CAM Software Features and Facilities to Create Machining Process Simulation

The steps to create a machining process simulation can be summarized as shown in Figure 5.4, where illustration is focused on milling and turning processes.

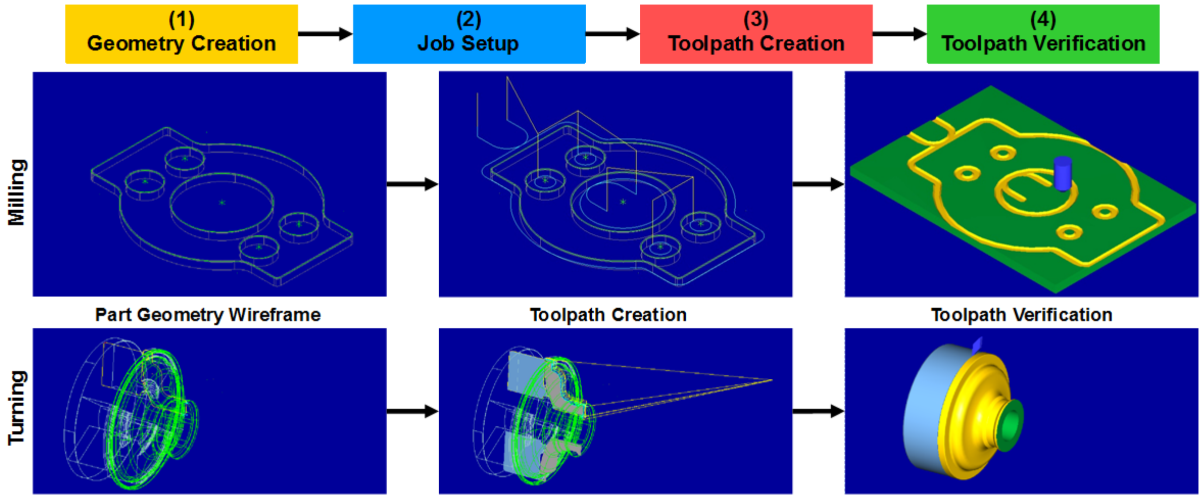


Figure 5.4: Steps for machining process simulation in milling and turning.

This research activity was carried out utilizing software tools. In the next paragraphs, MASTERCAM® and ESPRIT® software tools employed for the research activities on machining process simulation are described in details.

5.2.1 ESPRIT® Software

ESPRIT® is a leading Computer-Aided Manufacturing (CAM) simulation software package for a full range of machine tool applications. It includes machining of any part geometry (solid, surface, or wireframe), universal post processing to format G-code for virtually any machine tool, and solid simulation and verification with dry runs rendered in dynamic solids for optimal part quality and consistency. ESPRIT® software can deal with Milling operations, Turning operations and integrated operation of milling and turning.

ESPRIT® supports the given below CAM/ CAD software tools:

- AutoDesk Inventor
- Catia
- Pro Engineering
- Solid Edge
- SolidWorks

5.2.1.1 ESPRIT® Software Features

Create Geometry Features

ESPRIT® bases all cutting operations on machinable features to improve the automation of NC programming.

Prepare for Machining

Define any type of NC machine, including all machine motion, and simplify the programming of multiple work pieces.

Create Cutting Operations

Machine any part to suit your particular machining needs—milling, turning, mill/turn, and wire EDM—using advanced technology.

Manage Cutting Operations The Project Manager displays every cutting operation, tool and feature in the current session. Use the Project Manager to edit, rename, delete, sort, and simulate operations.

ESPRIT® KnowledgeBase

Use the software Knowledge Base to set up and store commonly used tools, materials, and cutting parameters, then use feature recognition to automatically associate machining processes to a part.

Simulate

Simulate dry runs of material removal and cutting conditions to easily visualize the entire machining environment generated in dynamic solids.

Convert to NC Code

ESPRIT® provides a powerful universal post processor and an extensive library of pre-defined posts capable of formatting your G-code for virtually any CNC machine tool.

5.2.1.2 Turning Processes in ESPRIT®

Table 5.1 summarizes the turning processes that are provided by ESPRIT®.

Cutting Operations Mode	**Turning operation Mode**	**Turning operations**	**Types of Turning tool Insert**
Turning/ Milling Turn operations	Solid Turn	Roughing	Turning Insert Grooving Insert Top Notch Insert Laydown Insert Mini-Turning Insert Mini-Grooving Insert: Mini-Boring Insert Custom Insert
		Balanced Roughing	
		Contouring	
		B-Axis Contouring	
		Grooving	
		Drilling	
		Threading	
		Cutoff	
		Bar Feed	
		Pickup	
		Release	
		Steady Rest	
		Tailstock	
		Manual Turning	
	Solid Mill Turn	Facing	
		Pocketing	
		Trochoidal Pocketing	
		Contouring	
		Rest Machining	
		Drilling	
		Spiraling	
		Threading	
		Manual Milling	
		Wire Frame Milling	
		Wrap Pocketing	
		Wrap Drilling	
		Wrap Contouring	
		Rotary Face Pocketing	
		Rotary Face Contouring	
		Legacy Wrap Pocketing	
		Legacy Wrap Contouring	

Table 5.1: Turning Processes Provided by Esprit

Summary of Turning Tools

A turning tool is defined by the shape of the insert, the holder, and a set of parameters that define the position of the tool in relation to the machine. Users can create new tools from a set of predefined tool types that are common to turning, such as grooving and top notch, or create custom profiling or form tools from user-defined geometry.

Turning Insert: Ideal for general turning applications. The shape of this versatile insert can be defined as a square, triangle, diamond, trigon, or round.

Grooving Insert: Ideal for grooving and cut off operations along vertical faces. The shape can be defined with straight edges or with a full radius.

Top Notch Insert: Ideal for course-pitch and heavy-duty threading applications.

Laydown Insert: Ideal for general and fine-pitch threading applications.

Mini-Turning Insert: Ideal for precision turning.

Mini-Grooving Insert: Ideal for shallow grooves and cut-offs. The style can be defined as back turning, front turning, and cutoff.

Mini-Boring Insert: The style can be defined as back turning, front turning, radius, and full form.

Custom Insert: A tool created from a user-defined profile which can be defined as a custom profiling tool or as a custom form tool.

5.2.1.3 Milling Process in ESPRIT®

Table 5.2 summarizes the milling processes that are provided by ESPRIT®.

<table>
<tr><th>Cutting Operations Mode</th><th>Milling operation Mode</th><th>Milling operations</th><th>Types of Milling tools</th></tr>
<tr><td rowspan="30">Milling operations</td><td rowspan="9">SolidMill Traditional</td><td>Facing</td><td rowspan="30">Face Mill
End Mill
Bull Nose End Mill
Ball End Mill
Undercut Mill
Center Drill
Drill
Tap
Taper End Mill
Chamfer End Mill
Corner End Mill
Dovetail End Mill
Boring Bar
Thread Mill
Reamer
Slot Mill
Custom Mill</td></tr>
<tr><td>Pocketing</td></tr>
<tr><td>Trochoidal Pocketing</td></tr>
<tr><td>Contouring</td></tr>
<tr><td>Rest Machining</td></tr>
<tr><td>Drilling</td></tr>
<tr><td>Spiraling</td></tr>
<tr><td>Threading</td></tr>
<tr><td>Manual Milling</td></tr>
<tr><td rowspan="8">SolidMill Production</td><td>Wire Frame Milling</td></tr>
<tr><td>Wrap Pocketing</td></tr>
<tr><td>Wrap Drilling</td></tr>
<tr><td>Wrap Contouring</td></tr>
<tr><td>Rotary Face Pocketing</td></tr>
<tr><td>Rotary Face Contouring</td></tr>
<tr><td>Legacy Wrap Pocketing</td></tr>
<tr><td>Legacy Wrap Contouring</td></tr>
<tr><td rowspan="7">SolidMill FreeForm</td><td>Roughing</td></tr>
<tr><td>Variable-Z Roughing</td></tr>
<tr><td>Finishing</td></tr>
<tr><td>Z-Level Finishing</td></tr>
<tr><td>Projection Finishing</td></tr>
<tr><td>Re-machining</td></tr>
<tr><td>STL Feature</td></tr>
<tr><td rowspan="6">SolidMill Mold 5-Axis</td><td>Milling of free from feature</td></tr>
<tr><td>Milling of ruled feature</td></tr>
<tr><td>5-Axis Swarf Milling</td></tr>
<tr><td>5-Axis Contour Milling</td></tr>
<tr><td>5-Axis Composite</td></tr>
<tr><td>External Rapid Links</td></tr>
</table>

Table 5.2: Milling Processes Provided by Esprit

Summary of Milling Tools

A milling tool is defined by the shape of the revolved shank and cutting edge, the holder, and a set of parameters that define the position of the tool in relation to the machine. Users can create new tools from a set of pre-defined tool types that are common to milling, such as end mills and drills, or create custom milling tools from user-defined geometry.

Face Mill: An indexable mill designed to cut large flat surfaces. The tool definition supports a cutter body designed to hold multiple cutting inserts of various geometric shapes (round, square, triangular). This tool is typically used with facing operations.

End Mill: A versatile tool with a flat bottom and straight cutting edges that can remove material quickly. This tool can be used with most milling operations.

Bull Nose End Mill: An end mill with a radiused corner.

Ball End Mill: An end mill with a hemispherical bottom ideal for machining 3-dimensional contoured shapes.

Undercut Mill: An end mill with a cutting diameter that is larger than the shank diameter.

Center Drill: A drill with a smaller chamfered tip designed to provide a starting hole for a larger-sized drill or to make a conical indentation at the end of a workpiece mounted on a lathe.

Drill: A tool designed to cut holes efficiently. This tool is typically used with drilling operations.

Tap: A tool that cuts an internal thread inside a pre-drilled hole. Taps are manufactured to the dimensional size of the thread and are fully engaged with the workpiece during the cutting process.

Taper End Mill: An end mill with sides that taper out from the bottom of the tool.

Chamfer End Mill: An end mill with an angled corner. This tool can be used with a standard contouring operation to chamfer, or deburr, the edges of a part.

Corner End Mill: An end mill with a concave corner. This tool can be used with a standard contouring operation to round the edges of a part.

Dovetail End Mill: An end mill with sides that taper in from the bottom of the tool. This type of tool is designed to cut dovetail grooves.

Boring Bar: A cylindrical bar with a triangular cutting insert on the bottom. The tool definition supports a standard boring bar with the insert positioned to cut with the bottom of the tool and a back boring bar with the insert reversed to allow for "bottom-up" milling. Boring bars are ideal for cutting large-diameter holes.

Thread Mill: A thread mill can be used on any 3-axis mill capable of helical interpolation to cut internal and external threads. Thread mills have a lower cutting torque than taps and reduce the problem of chip evacuation. The tool definition supports standard thread mills and single-point thread mills.

Reamer: A tool with a set of parallel straight cutting edges used to enlarge holes with more accuracy than a standard drill.

Slot Mill: A tool designed to cut slots in a work-piece. The tool definition supports a "T-Slot" mill with the cutting edge positioned at the bottom of the tool or a "Side-Slot" mill with clearance between the bottom of the shank and the bottom of the cutting edge. This tool is typically used with contouring or "bottom-up" contouring operations.

Custom Mill: A tool created from a user-defined profile for custom milling purposes.

5.2.2 MASTERCAM® Software

MASTERCAM® facilitates CAD/CAM applications to design parts and to create complete machining operations in a virtual machining environment. It can simulate all the turning, milling, and router operations and can generate and validate the NC code.

Geometry Creation Facilities

- 3D wireframe and solid geometry creation including splines, curves, surfaces, and Work Coordinate System
- Complete dimensioning capabilities
- In MASTERCAM®, we can directly import given below file types for best machining accuracy and efficiency.

    - ProEngineer (.prt, .des, .dra, .alb, .ses, .asm, .pdt, .g)
    - AutoCad (.dwg, .dxf, .ipt, .dwf, .rml, .iam, .idw)
    - SolidWorks (.sldprt, .slddrw, .sldasm)
    - IGES (.igs)

    - CadKey (.cdl)
    - Parasolids (.x_t)
    - Stereolithography (.stl)
    - VDA (.vda)
    - Acis(R) Solids (.sat)
    - MasterCAM (.mc7, .mc8, .mc9, .ge3)
    - Misc (.dgn, .cel, .gcd, .cmp, .pcl5, .oda, .mrk, .gtx, .hrf, .tif, .rlc)
- Optional CATIA and Pro/E

Milling operation facilities

Design aspects

- 3D Wireframe Geometry Creation including Splines and WCS
- Squash, Spiral, Helix, and Bounding Box
- Complete Dimensioning capabilities
- Read/Write translators for STEP, IGES, VDA, DXF/DWG/Inventor, CADL, ASCII, SAT, STL, Parasolids
- Optional CATIA and Pro/E
- Complete Surface creation and editing
- Create Curves on surfaces for edges, intersections, parting lines, and slices.
- Solids add-on (available for an additional charge)

Toolpaths aspects

- Toolpaths supported only in the Top construction and tool planes
- Contour - 2D only, rotary axis is supported; tabs are not supported.
- Pocket – 2D only, Standard pocketing method supporting only Zigzag or One-Way cutting
- Drilling
- Facing
- Point Toolpaths
- Manual Entry
- Safe-Zones
- Dynamic Chaining

- Toolpath Transform, Translate, Rotate, Mirror in Top plane only
- MCX files with Solids can be loaded and machined using the Solids selection options for Face and Edges.
- Support for all Construction and Toolplanes for tombstone work
- Complete Contour and Pocketing capabilities including all methods and options including tabs
- All Circle toolpaths Circle Mill, Thread Mill, Auto Drill, Start Hole, Slot Mill, and Helix Bore
- Wireframe toolpaths including 2D Swept, Revolved, Ruled (3-axis only)
- 3 plus 2 Toolpaths
- Trim toolpaths
- Import NCI (Intermediate NC code) into the Toolpath Manager
- Highfeed Machining
- Toolpath Editor
- Full Toolpath Transform functionality supporting all planes

- Toolpath, Project (onto cone, cylinder, plane, etc.)
- Single Surface Rough machining: Parallel, Radial, Project, Flowline, Contour, Restmill, Pocket, and Plunge
- Single Surface Finish machining: Radial, Project, Flowline, and Contour
- Multiple Surface Finish Parallel toolpath with no restrictions or limitations
- Multiple Surface Rough Pocket
  - Zig-Zag and One-Way cutting
  - Roughing always on, with a step over up to 100%
  - One finish pass
- Surface machining with multiple containment boundaries and check surfaces
- Wireframe toolpaths in addition to those in Level 1: Loft, Coons, 3DSwept (3-axis only)
- 5-axis functionality in wireframe toolpaths
- Multiple surface rough machining: Parallel, Radial, Project, Flowline, Contour, Pocket, Restmill, Pocket, and Plunge
- Multiple surface finish machining : Parallel, Parallel Steep, Radial, Project, Contour, Shallow, Pencil, Leftover, and Scallop

Add-ons aspects

- Curve 5-axis and Drill 5-axis
- Solid Drill available as part of the Solids add-on
- Right-angle head support with the Aggregate add-on
- Multiaxis Toolpaths include Rotary 4-axis, and 5-Axis Curve, Drill, and Swarf
- 5-axis Multisurface Rough and Flowline supporting check surfaces

Verification aspects

- Standard Technology
- TrueSolids Technology
- Rectangular, Cylindrical, and STL Stock definition
- Create STL models from results in TrueSolids
- STL Compare
- 5-axis support in Standard Technology
- Prompting for chip removal in TrueSolids
- Support for specialized custom tools

Lathe Operation Facilities

Design aspects

- 3D Wireframe, solid and surface Geometry Creation including Splines and WCS
- Squash, Spiral, Helix, and Bounding Box
- Complete Dimensioning capabilities
- Read/Write translators for IGES, VDA, DXF/DWG/Inventor, CADL, ASCII, SAT, STL, Parasolids

Toolpaths aspects

- Associative toolpaths
- Dynamic Chaining
- Selection of Solid profiles
- Inside and Outside Roughing
- Facing
- Roughing to an outer boundary for castings

- Finish contouring
- Grooving
- Threading
- Cutoff
- Boring and Drilling
- Surface creation and editing
- Curve creation on surfaces for edges, intersections, parting lines, and slices
- Solids add-on (available for an additional charge)
- C-axis toolpaths: Face Contour, Cross Contour, Face Drill, Cross Drill
- Automatically set cutting plane based on cross, face or axial substitution type milling for parallel, perpendicular or Swiss cutting planes
- C-axis toolpath support for Pocketing and Surface machining. The toolpaths available depend on the level of Mill that is installed

Verification aspects

- Backplot for toolpath verification
- Stock view utility from Operations Manager (creates Solids or Surfaces of toolpath results)
- Standard Technology
- TrueSolids Technology
- Cylindrical Stock definition
- Display 2D, 3D, or ¾ view stock
- Support for specialized custom tools

5.3 Development of Machining Operation Simulation

Machining operation simulation and generation of NC program:

Computer-assisted NC part programming represents a much more efficient method of generating the control instructions for the machine tool than manual part programming is, particularly for complex part geometries. Figure 5.5 shows a scheme of NC program file generation using machining process simulation.

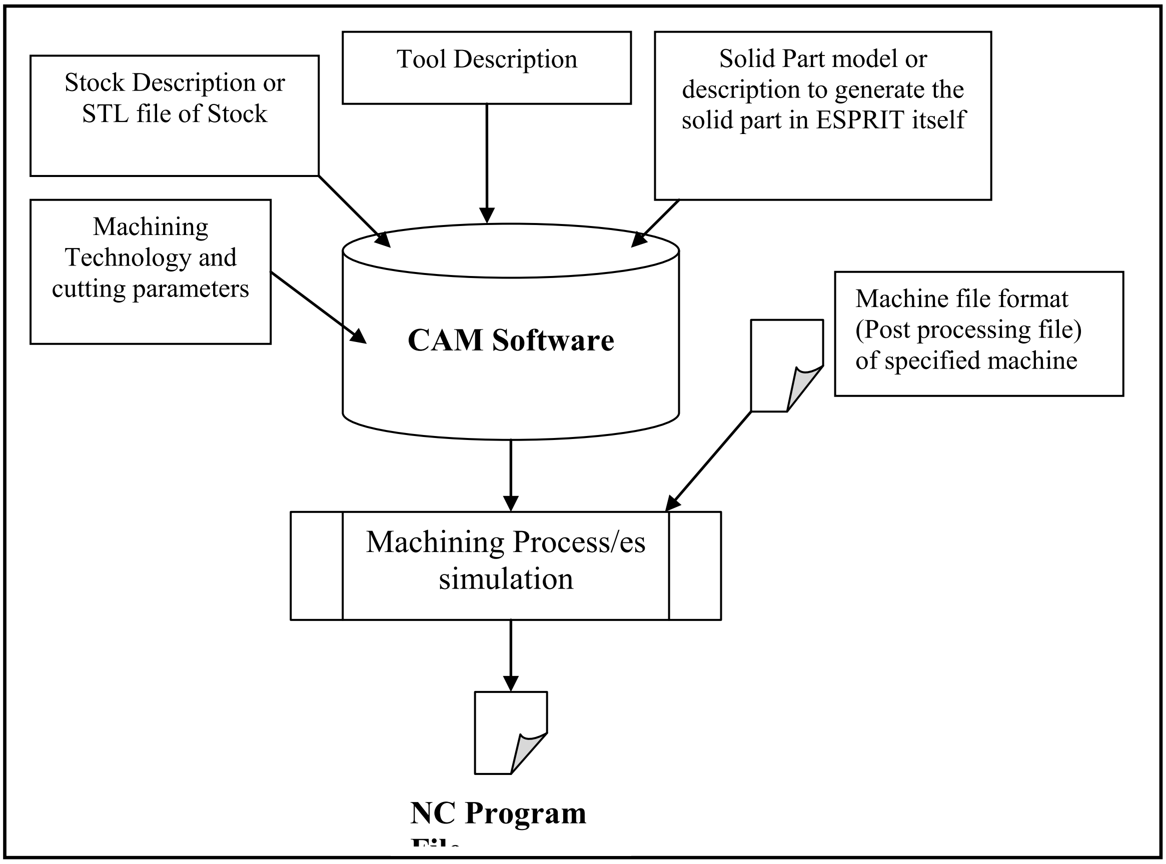


Figure 5.5: Generation of NC program file using machining process simulation.

The typical workflow to create a machining process simulation includes the following phases:

1. Import or draw the part (Figure 5.6).

Most CAM software can bring in CAD geometry from the CAD software given below:

- AutoDesk Inventor
- Catia
- Pro Engineering
- Unigrafics
- Solid Edge
- SolidWorks

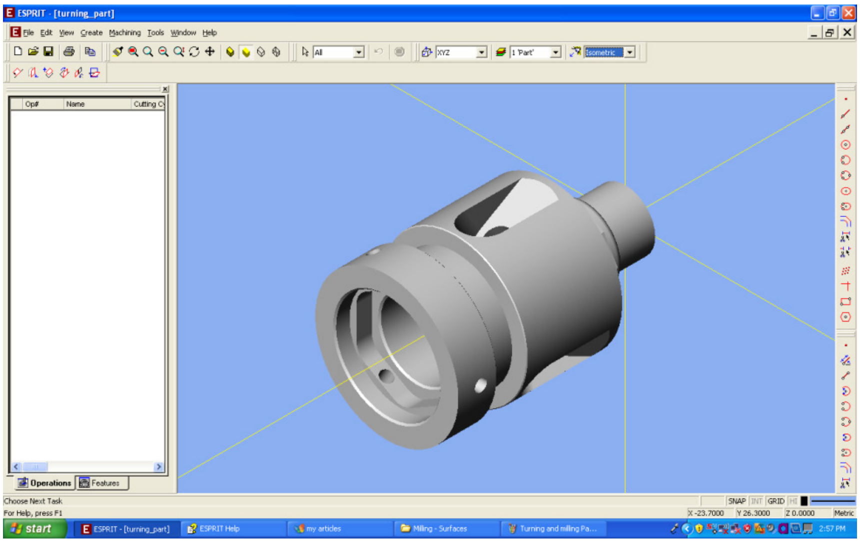


Figure 5.6: CAD geometry imported in the CAM software.

2. Create features (Figure 5.7).

Features are used as the basis for machining operations. They contain machining properties, such as depth, cutting side, and work coordinate, which can be used to create machining operations that automatically adopt those properties. When you create NC operations, CAM software typically prompts you to select features.

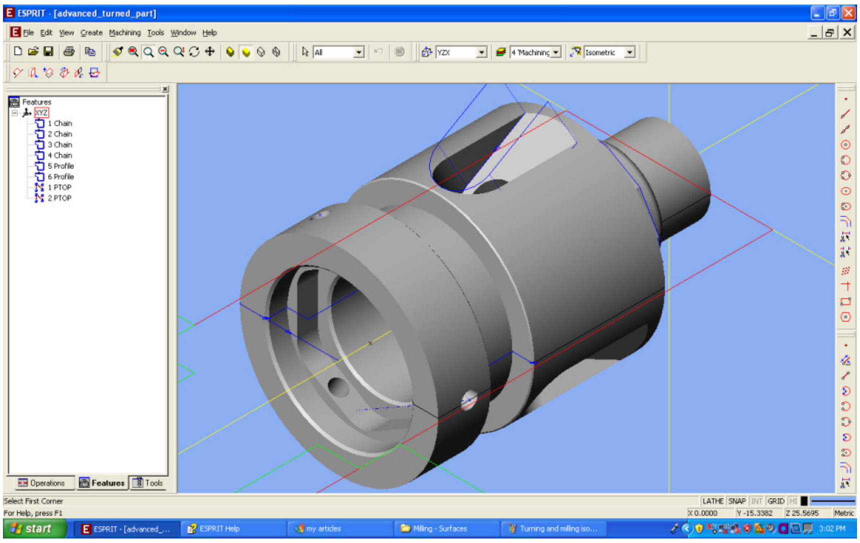


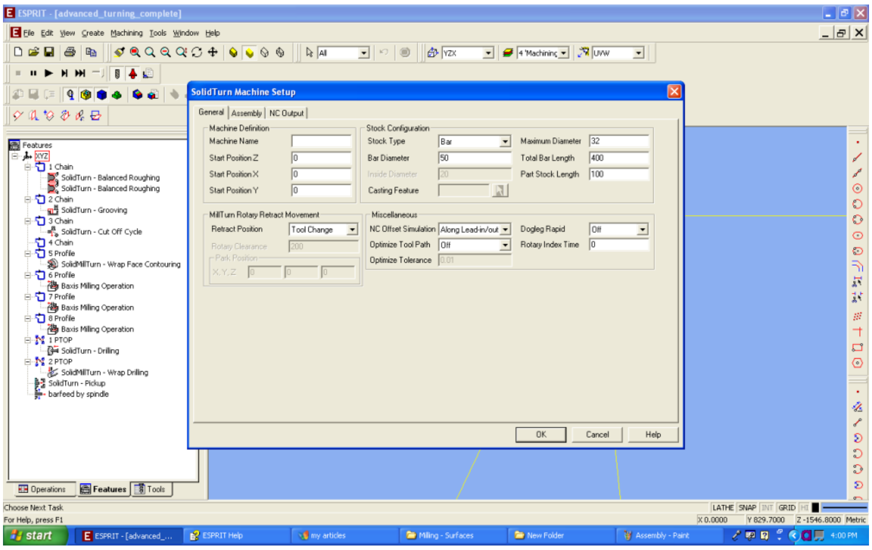
Figure 5.7: Features created in the CAM software.

3. Select a machining mode (Figure 5.8 - a).

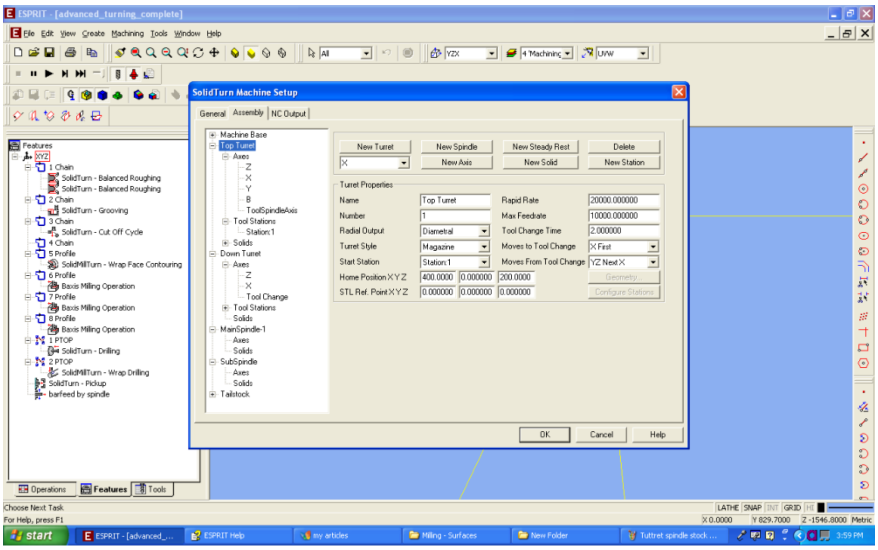
Machining mode generally give an option for selecting the type of operation that should be performed (Turning, Milling or Turning and milling together).

4. Establish required machine setup (Figures 5.8 - b and c).

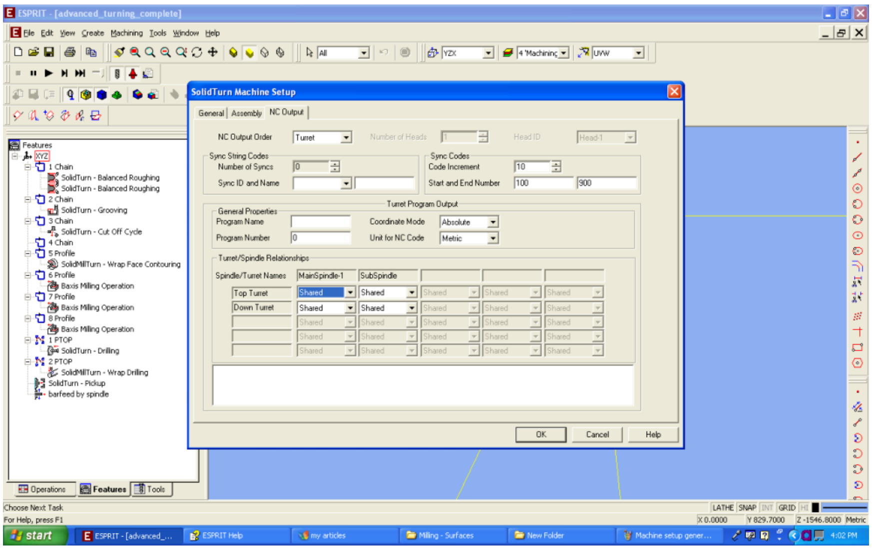
According to the selected machining mode, number of turret in use, spindle setting, tool configuration and settings, Required NC output, stock setting etc., machine setup is established.



(a)



(b)



(c)

Figures 5.8 (a), (b), and (c): Machine setup.

5. Create required tool paradigm for the operation (Figure 5.9).

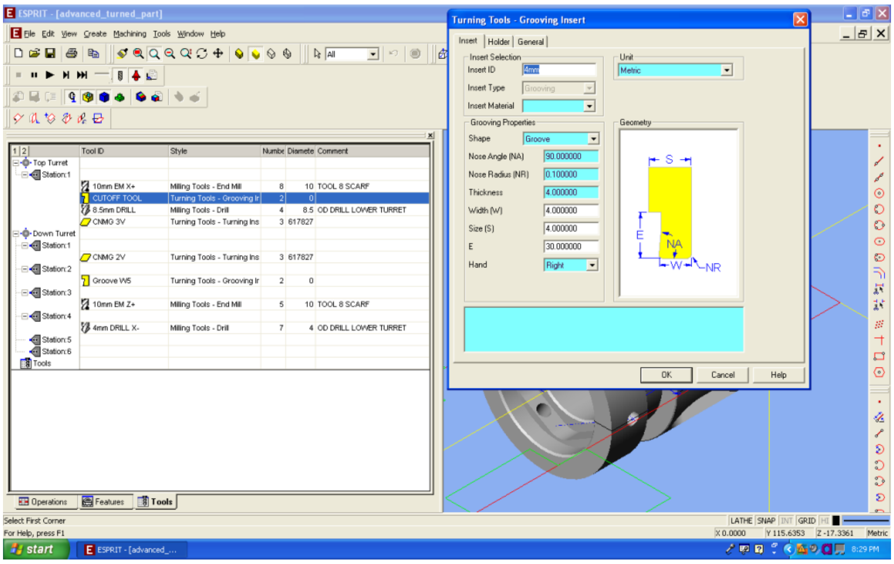


Figure 5.9: Cutting tool setup.

6. Select a feature for the operation.
7. Select appropriate operation.
8. Select a machining tool, select the toolpath pattern, and select a step over and incremental Z steps.
9. Click OK to create the operation.
10. Repeat for every operation required to machine the part

5.4 Case Studies on Machining Process Verification

With the employment of the software tool described above, simulations of machining operations have been developed with reference to diverse case studies.

5.4.1 First Milling Process Simulation

The milling operation has been carried out starting from a square plate, 55x55x10 mm as shown in figure 5.10 – a.

The milling operation consists in 2 mm thickness reduction as shown in figure 5.10- b.

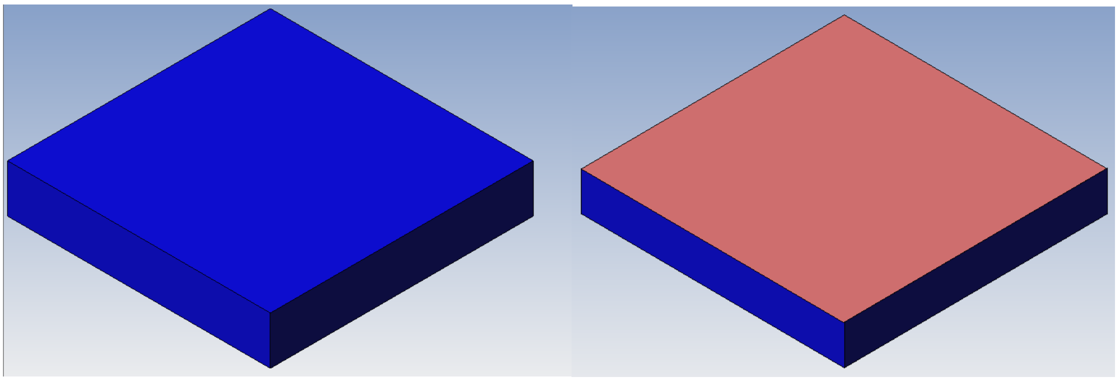


Figure 5.10: Stock part (a) and finished part (b)

The cutting simulation has been carried out under the cutting conditions reported in table 5.3

Process typology	Down milling
Cutting speed	50 m/min
Holder diameter	50 mm
Feed rate per tooth	0.375 mm/rev, tooth
Depth of cut	2 mm
Cutting length	6 mm

Table 5.3: Cutting conditions

Esprit Software allows to set features for tooling properties and operation properties.

Tooling

The first series of features set in Esprit software regard the general information of the tool. In the window shown in figure 5.11, the general information of the customized cutting tool created in the software environment

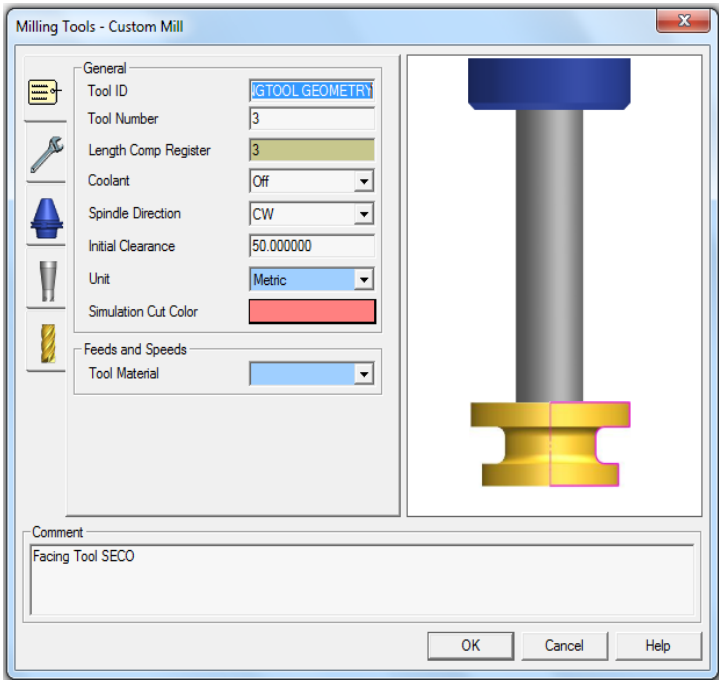


Figure 5.11: General information of custom tool

The second series of selectable cutting tool properties is found in the "Tool Change Strategy" window that allows setting the tool mounting turret, tool position and tool axes orientation. These features are summarized in figure 5.12.

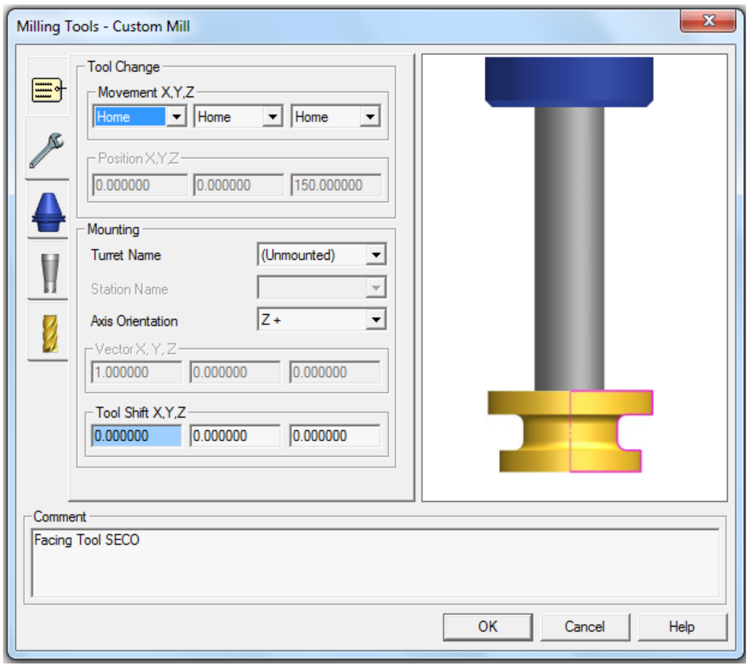


Figure 5.12: Cutting tool strategy

Going on with tooling configuration, it is possible to set up the holder properties, such as shape and dimensions. This Esprit option window is shown in figure 5.13.

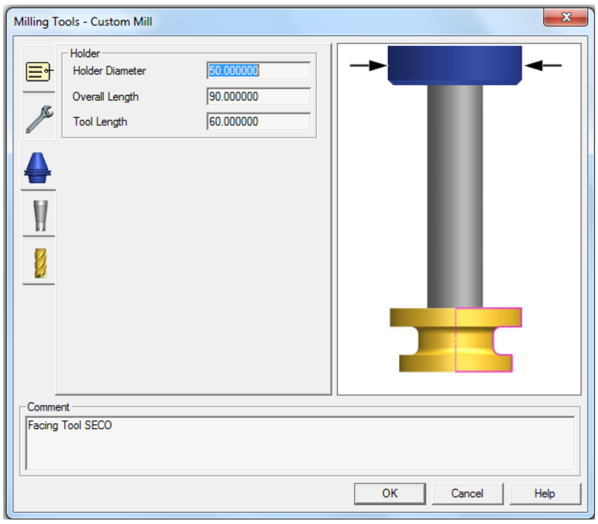


Figure 5.13: Tool holder properties

A further series of cutting tool features can be edited in the shank properties window, in which it is possible to set the dimensions of the shank. A screenshot of this window is reported in figure 5.14.

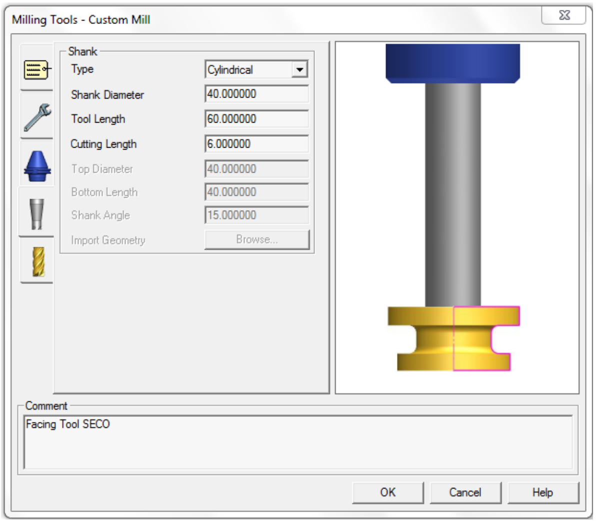


Figure 5.14: Shank properties of cutting tool

The cutter properties can be set as well in Esprit software as shown in figure 5.15. For this application, it has been used a 4-flutes milling tool.

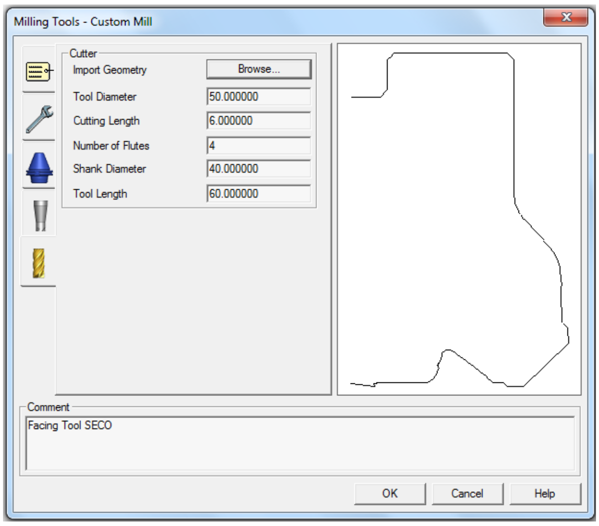


Figure 5.15: Cutter geometry properties

A complete visualization of the cutting tool created in Esprit software is reported in figure 5.16.

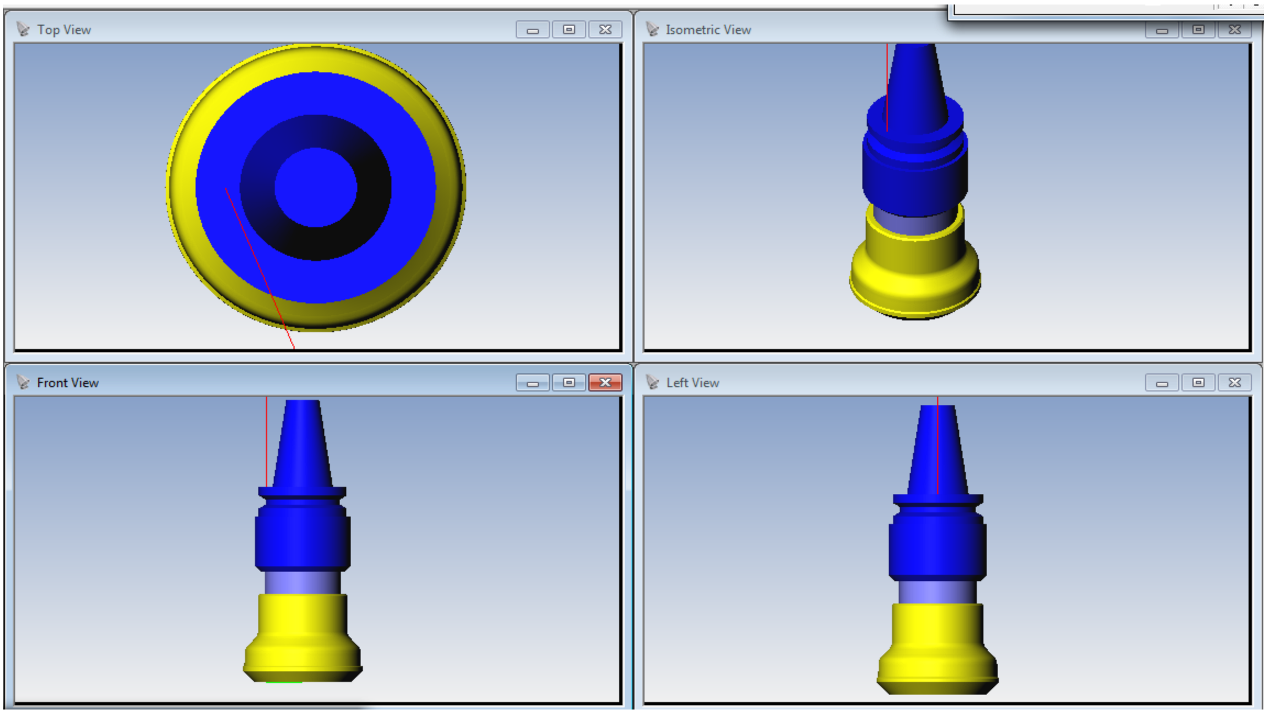


Figure 5.16: Cutting tool views: Top, isometric, front, left.

Milling Simulation

In order to carry out the simulation, several parameters and features have to be selected. The three option windows that Esprit software allows to control regard respectively

- General information of cutting operation
- Cutting Strategy

- Link information

The general information window contains options regarding tool selection and cutting parameters, as shown in figure 5.17.

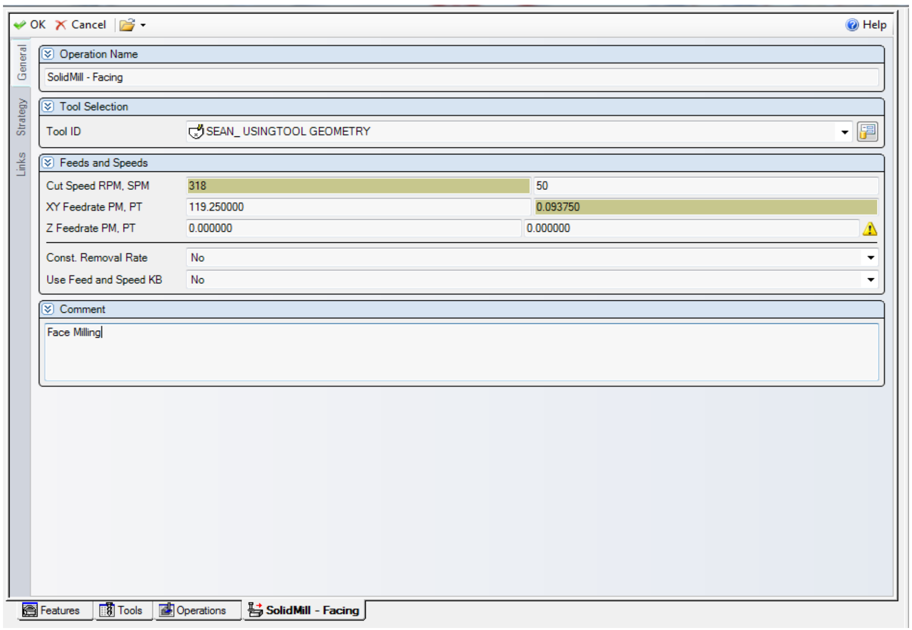


Figure 5.17: General information of operation

In cutting strategy window it is possible to set the number of passes, cutting angle, cutting over percentage. The values chosen for this application have been reported in figure 5.18.

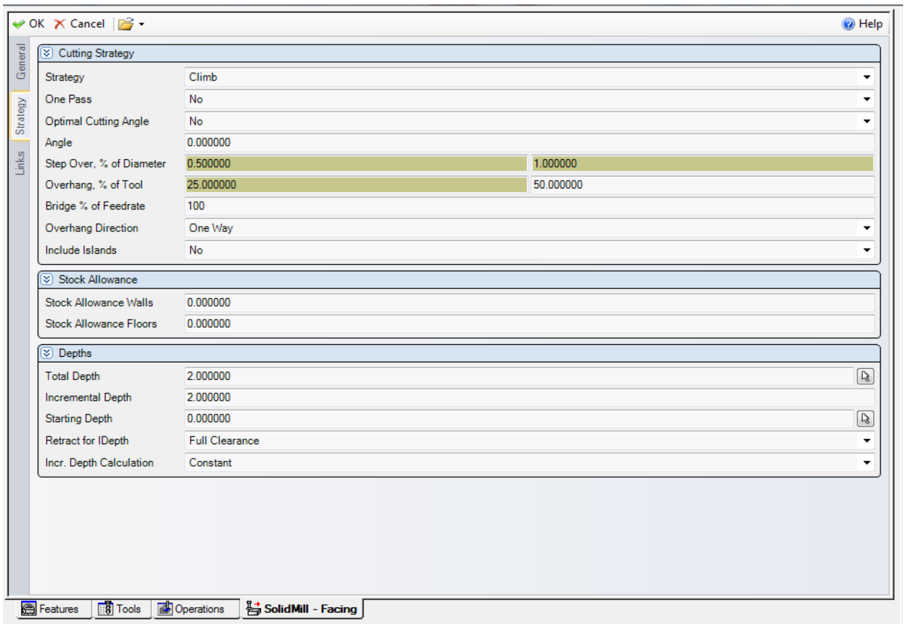


Figure 5.18: Cutting strategy options

Another important option window regards the link information, in which it is possible to set the clearance values, return and retract strategies, tool entry and tool exit mode. A screenshot of this window is shown in figure 5.19.

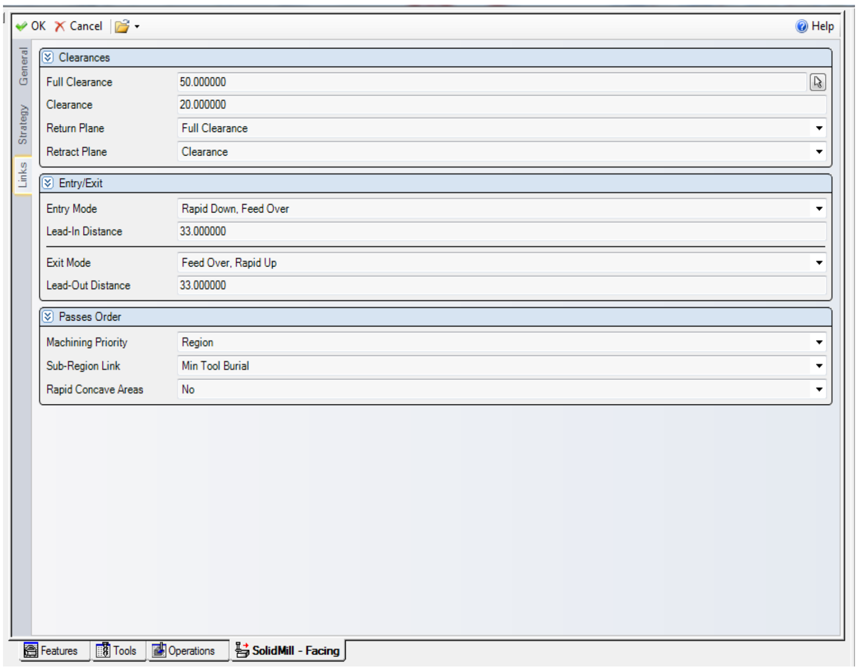


Figure 5.19: Link information of cutting operation

Output

For the milling operation simulation, the CNC code has been generated by Esprit software, and it is reported below.

```
%N0(INCONEL 718_EXP)
N1G0X0Y0Z0PA1
N2(FACING TOOL SECO)
N3G0Z0
N4M01
N5S318M03
N6G0Z50.
N7G0X-33.Y79.5
N8G0Z-2.
N9G1X77.108F119
N10G0Z50.
N11G0X-22.65Y79.
N12G0Z-2.
N13G1X77.65
N14G0Z50.
N15G0X-23.168Y78.5
N16G0Z-2.
N17G1X78.168
N18G0Z50.
N19G0X-23.664Y78.
N20G0Z-2.
N21G1X78.664
```

```
N22G0Z50.
N23G0X-24.14Y77.5
N24G0Z-2.
N25G1X79.14
N26G0Z50.
N27G0X-24.597Y77.
N28G0Z-2.
N29G1X79.597
N30G0Z50.
N31G0X-25.035Y76.5
N32G0Z-2.
N33G1X80.035
N34G0Z50.
N35G0X-25.456Y76.
N36G0Z-2.
N37G1X80.456
N38G0Z50.
N39G0X-25.86Y75.5
N40G0Z-2.
N41G1X80.86
N42G0Z50.
N43G0X-26.249Y75.
N44G0Z-2.
N45G1X81.249
N46G0Z50.
N47G0X-26.622Y74.5
N48G0Z-2.
N49G1X81.622
N50G0Z50.
N51G0X-26.981Y74.
N52G0Z-2.
N53G1X81.981
N54G0Z50.
N55G0X-27.327Y73.5
N56G0Z-2.
N57G1X82.327
N58G0Z50.
N59G0X-27.659Y73.
N60G0Z-2.
N61G1X82.659
N62G0Z50.
N63G0X-27.978Y72.5
N64G0Z-2.
N65G1X82.978
N66G0Z50.
N67G0X-28.284Y72.
N68G0Z-2.
N69G1X83.284
N70G0Z50.
N71G0X-28.579Y71.5
N72G0Z-2.
N73G1X83.579
N74G0Z50.
N75G0X-28.862Y71.
N76G0Z-2.
N77G1X83.862
N78G0Z50.
N79G0X-29.133Y70.5
N80G0Z-2.
N81G1X84.133
N82G0Z50.
```

N83G0X-29.394Y70.
N84G0Z-2.
N85G1X84.394
N86G0Z50.
N87G0X-29.644Y69.5
N88G0Z-2.
N89G1X84.644
N90G0Z50.
N91G0X-29.883Y69.
N92G0Z-2.
N93G1X84.883
N94G0Z50.
N95G0X-30.112Y68.5
N96G0Z-2.
N97G1X85.112
N98G0Z50.
N99G0X-30.332Y68.
N100G0Z-2.
N101G1X85.332
N102G0Z50.
N103G0X-30.541Y67.5
N104G0Z-2.
N105G1X85.541
N106G0Z50.
N107G0X-30.741Y67.
N108G0Z-2.
N109G1X85.741
N110G0Z50.
N111G0X-30.931Y66.5
N112G0Z-2.
N113G1X85.931
N114G0Z50.
N115G0X-31.113Y66.
N116G0Z-2.
N117G1X86.113
N118G0Z50.
N119G0X-31.285Y65.5
N120G0Z-2.
N121G1X86.285
N122G0Z50.
N123G0X-31.448Y65.
N124G0Z-2.
N125G1X86.448
N126G0Z50.
N127G0X-31.603Y64.5
N128G0Z-2.
N129G1X86.603
N130G0Z50.
N131G0X-31.749Y64.
N132G0Z-2.
N133G1X86.749
N134G0Z50.
N135G0X-31.887Y63.5
N136G0Z-2.
N137G1X86.887
N138G0Z50.
N139G0X-32.016Y63.
N140G0Z-2.
N141G1X87.016
N142G0Z50.
N143G0X-32.136Y62.5

```
N144G0Z-2.
N145G1X87.136
N146G0Z50.
N147G0X-32.249Y62.
N148G0Z-2.
N149G1X87.249
N150G0Z50.
N151G0X-32.354Y61.5
N152G0Z-2.
N153G1X87.354
N154G0Z50.
N155G0X-32.45Y61.
N156G0Z-2.
N157G1X87.45
N158G0Z50.
N159G0X-32.538Y60.5
N160G0Z-2.
N161G1X87.538
N162G0Z50.
N163G0X-32.619Y60.
N164G0Z-2.
N165G1X87.619
N166G0Z50.
N167G0X-32.692Y59.5
N168G0Z-2.
N169G1X87.692
N170G0Z50.
N171G0X-32.757Y59.
N172G0Z-2.
N173G1X87.757
N174G0Z50.
N175G0X-32.814Y58.5
N176G0Z-2.
N177G1X87.814
N178G0Z50.
N179G0X-32.863Y58.
N180G0Z-2.
N181G1X87.863
N182G0Z50.
N183G0X-32.905Y57.5
N184G0Z-2.
N185G1X87.905
N186G0Z50.
N187G0X-32.939Y57.
N188G0Z-2.
N189G1X87.939
N190G0Z50.
N191G0X-32.966Y56.5
N192G0Z-2.
N193G1X87.966
N194G0Z50.
N195G0X-32.985Y56.
N196G0Z-2.
N197G1X87.985
N198G0Z50.
N199G0X-32.996Y55.5
N200G0Z-2.
N201G1X87.996
N202G0Z50.
N203G0X-33.Y55.
N204G0Z-2.
```

```
N205G1X88.
N206G0Z50.
N207G0X-33.Y54.5
N208G0Z-2.
N209G1X88.
N210G0Z50.
N211G0X-33.Y54.
N212G0Z-2.
N213G1X88.
N214G0Z50.
N215G0X-33.Y53.5
N216G0Z-2.
N217G1X88.
N218G0Z50.
N219G0X-33.Y53.
N220G0Z-2.
N221G1X88.
N222G0Z50.
N223G0X-33.Y52.5
N224G0Z-2.
N225G1X88.
N226G0Z50.
N227G0X-33.Y52.
N228G0Z-2.
N229G1X88.
N230G0Z50.
N231G0X-33.Y51.5
N232G0Z-2.
N233G1X88.
N234G0Z50.
N235G0X-33.Y51.
N236G0Z-2.
N237G1X88.
N238G0Z50.
N239G0X-33.Y50.5
N240G0Z-2.
N241G1X88.
N242G0Z50.
N243G0X-33.Y50.
N244G0Z-2.
N245G1X88.
N246G0Z50.
N247G0X-33.Y49.5
N248G0Z-2.
N249G1X88.
N250G0Z50.
N251G0X-33.Y49.
N252G0Z-2.
N253G1X88.
N254G0Z50.
N255G0X-33.Y48.5
N256G0Z-2.
N257G1X88.
N258G0Z50.
N259G0X-33.Y48.
N260G0Z-2.
N261G1X88.
N262G0Z50.
N263G0X-33.Y47.5
N264G0Z-2.
N265G1X88.
```

```
N266G0Z50.
N267G0X-33.Y47.
N268G0Z-2.
N269G1X88.
N270G0Z50.
N271G0X-33.Y46.5
N272G0Z-2.
N273G1X88.
N274G0Z50.
N275G0X-33.Y46.
N276G0Z-2.
N277G1X88.
N278G0Z50.
N279G0X-33.Y45.5
N280G0Z-2.
N281G1X88.
N282G0Z50.
N283G0X-33.Y45.
N284G0Z-2.
N285G1X88.
N286G0Z50.
N287G0X-33.Y44.5
N288G0Z-2.
N289G1X88.
N290G0Z50.
N291G0X-33.Y44.
N292G0Z-2.
N293G1X88.
N294G0Z50.
N295G0X-33.Y43.5
N296G0Z-2.
N297G1X88.
N298G0Z50.
N299G0X-33.Y43.
N300G0Z-2.
N301G1X88.
N302G0Z50.
N303G0X-33.Y42.5
N304G0Z-2.
N305G1X88.
N306G0Z50.
N307G0X-33.Y42.
N308G0Z-2.
N309G1X88.
N310G0Z50.
N311G0X-33.Y41.5
N312G0Z-2.
N313G1X88.
N314G0Z50.
N315G0X-33.Y41.
N316G0Z-2.
N317G1X88.
N318G0Z50.
N319G0X-33.Y40.5
N320G0Z-2.
N321G1X88.
N322G0Z50.
N323G0X-33.Y40.
N324G0Z-2.
N325G1X88.
N326G0Z50.
```

```
N327G0X-33.Y39.5
N328G0Z-2.
N329G1X88.
N330G0Z50.
N331G0X-33.Y39.
N332G0Z-2.
N333G1X88.
N334G0Z50.
N335G0X-33.Y38.5
N336G0Z-2.
N337G1X88.
N338G0Z50.
N339G0X-33.Y38.
N340G0Z-2.
N341G1X88.
N342G0Z50.
N343G0X-33.Y37.5
N344G0Z-2.
N345G1X88.
N346G0Z50.
N347G0X-33.Y37.
N348G0Z-2.
N349G1X88.
N350G0Z50.
N351G0X-33.Y36.5
N352G0Z-2.
N353G1X88.
N354G0Z50.
N355G0X-33.Y36.
N356G0Z-2.
N357G1X88.
N358G0Z50.
N359G0X-33.Y35.5
N360G0Z-2.
N361G1X88.
N362G0Z50.
N363G0X-33.Y35.
N364G0Z-2.
N365G1X88.
N366G0Z50.
N367G0X-33.Y34.5
N368G0Z-2.
N369G1X88.
N370G0Z50.
N371G0X-33.Y34.
N372G0Z-2.
N373G1X88.
N374G0Z50.
N375G0X-33.Y33.5
N376G0Z-2.
N377G1X88.
N378G0Z50.
N379G0X-33.Y33.
N380G0Z-2.
N381G1X88.
N382G0Z50.
N383G0X-33.Y32.5
N384G0Z-2.
N385G1X88.
N386G0Z50.
N387G0X-33.Y32.
```

```
N388G0Z-2.
N389G1X88.
N390G0Z50.
N391G0X-33.Y31.5
N392G0Z-2.
N393G1X88.
N394G0Z50.
N395G0X-33.Y31.
N396G0Z-2.
N397G1X88.
N398G0Z50.
N399G0X-33.Y30.5
N400G0Z-2.
N401G1X88.
N402G0Z50.
N403G0X-33.Y30.
N404G0Z-2.
N405G1X88.
N406G0Z50.
N407G0X-33.Y29.5
N408G0Z-2.
N409G1X88.
N410G0Z50.
N411G0X-33.Y29.
N412G0Z-2.
N413G1X88.
N414G0Z50.
N415G0X-33.Y28.5
N416G0Z-2.
N417G1X88.
N418G0Z50.
N419G0X-33.Y28.
N420G0Z-2.
N421G1X88.
N422G0Z50.
N423G0X-33.Y27.5
N424G0Z-2.
N425G1X88.
N426G0Z50.
N427G0X-33.Y27.
N428G0Z-2.
N429G1X88.
N430G0Z50.
N431G0X-33.Y26.5
N432G0Z-2.
N433G1X88.
N434G0Z50.
N435G0X-33.Y26.
N436G0Z-2.
N437G1X88.
N438G0Z50.
N439G0X-33.Y25.5
N440G0Z-2.
N441G1X88.
N442G0Z50.
N443G0X-33.Y25.
N444G0Z-2.
N445G1X88.
N446G0Z50.
N9999%
```

5.4.2 Turning operation simulation on aircraft engine components

Similar to the real roughing operation on aircraft engine components, a virtual simulation model has been build to realize roughing operation and cutting tool movements.

5.4.2.1 Support Shroud

The workpiece studied for this application is a **Support Shroud**, a part of **CFM-56^{tm}** aircraft engine (Figure 5.20) by General Electric. It is a turbo-fan - high bypass ratio engine.

The Support Shroud is located at the exit of the combustion chamber, in correspondence of the highest exercise temperature. The air, previously compressed in the compressor and heated because of the combustion, must now transfer the energy in the turbine.

The principal aim of the Support Shroud is to keep constant the distance between the inner rotor blades and the static outer part. This distance is called "tip clearance" and it must be minimized in order to bound the air-flow inside it, to reduce the energy loss.

The Support Shroud, as finished product, is shown in Figure 5.11.

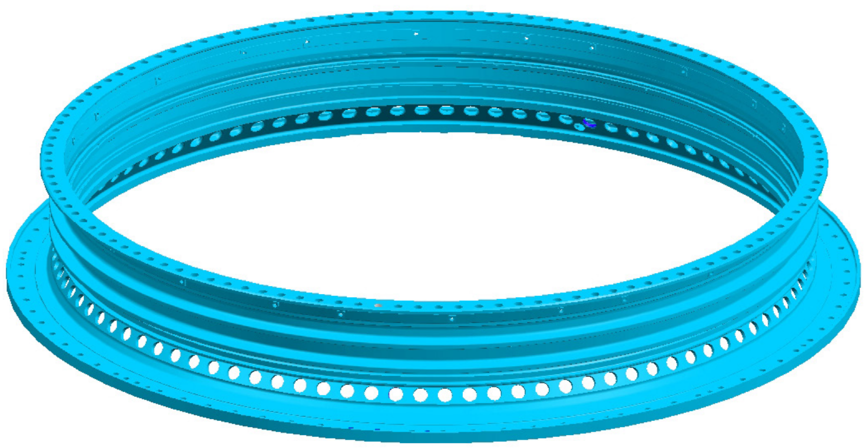


Figure 5.20: Finished Support Shroud

5.4.2.2 Operation and Tooling

The first simulation carried out by using Esprit Software is the turning of the base shown in Figure 5.21. This operation is called T21.

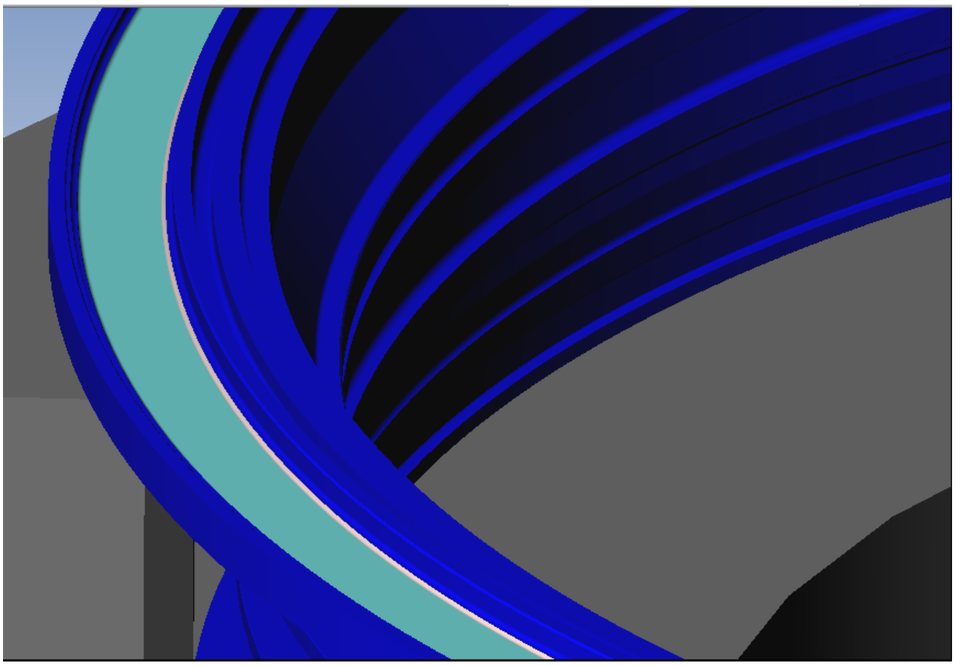


Figure 5.21: Turning operation T21 interested area

The T21 turning operation consists in 0.7 mm height reduction as shown in Figure5.22 (red area).

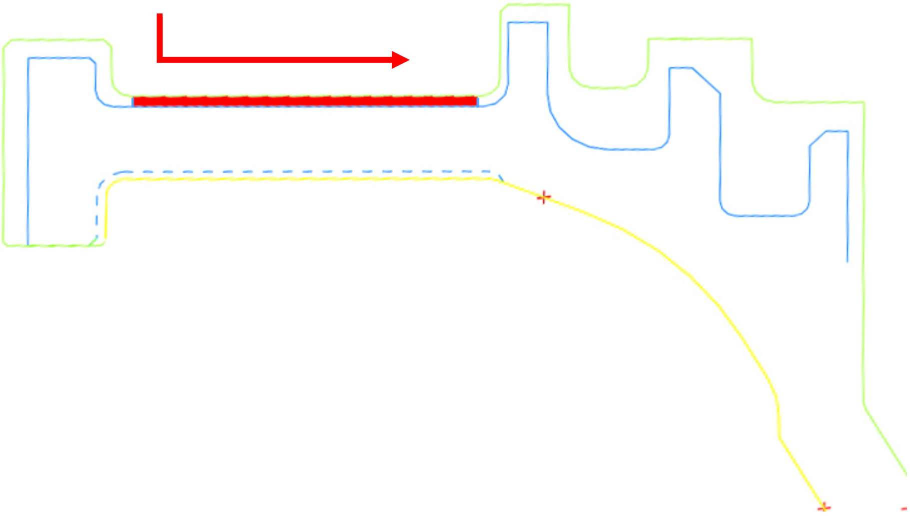


Figure 5.22: Turning operation T21 and tool motion direction

The tool path generated for this application consists of two linear paths. Each tool movement removes 0.35 mm of material. Both paths begin from the external side and move inward (red arrow).

The second operation simulated by Esprit for this application is called Operation T17, and it regards the conical inner surface indicated in green in figure 5.23.

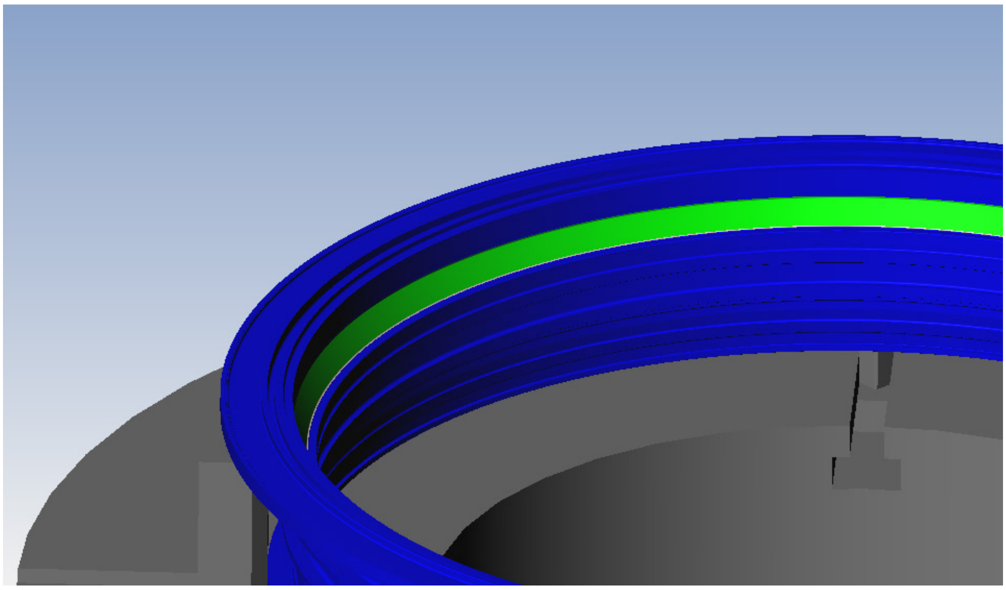


Figure 5.23: Turning operation T17 interested area.

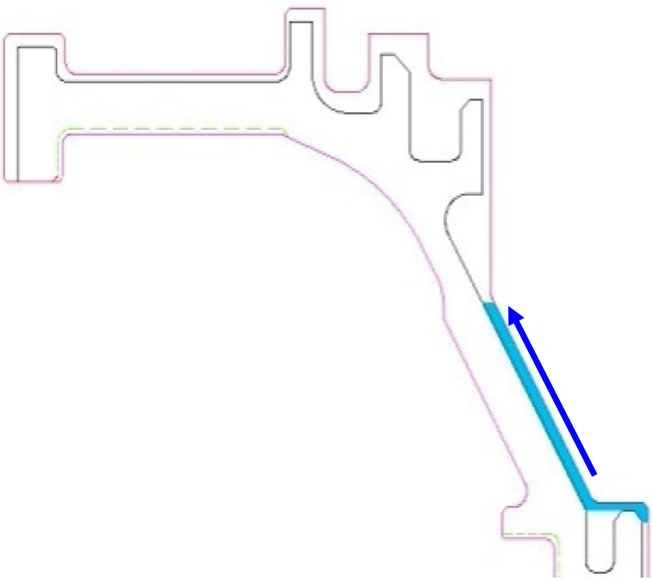


Figure 5.24: Turning operation T17 and tool motion direction.

The T17 turning operation consists in removing 0.91 mm material from the conical inner surface as shown in figure 5.24 in 7 sequential passes from bottom to top (depth of cut = 0.13 mm for each pass).

Esprit Software allows to manage a wide selection of tooling parameters

Here it follows a series of screenshots describing the tool features adopted for the operation T21 (figures 5.25, 5.26, and 5.27).

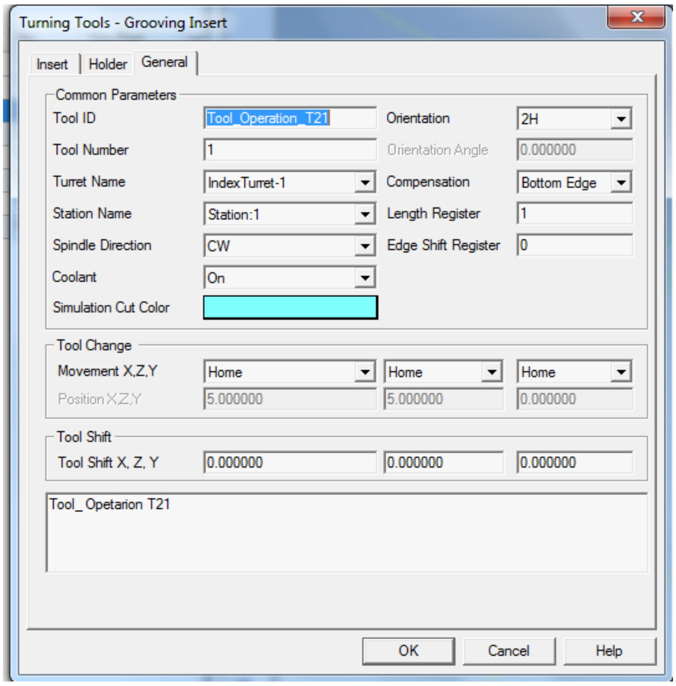


Figure 5.25: General information of the cutting tool for operation T21

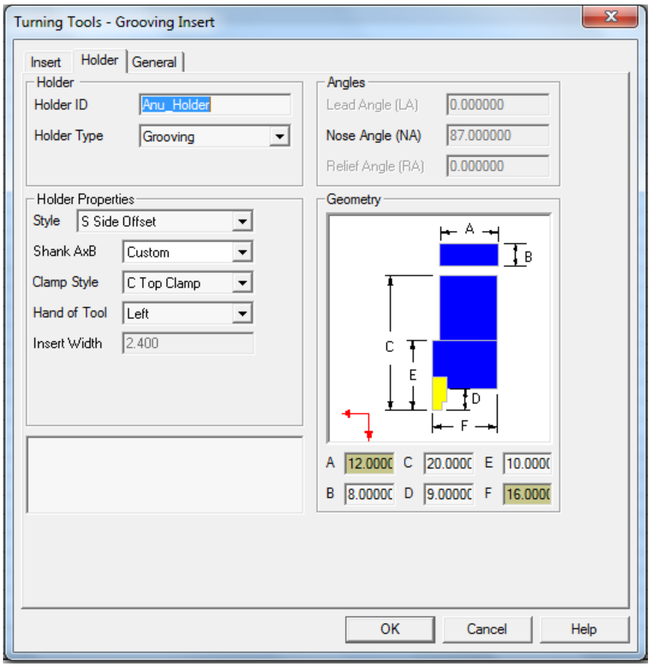


Figure 5.26: Tool holder information for operation T21

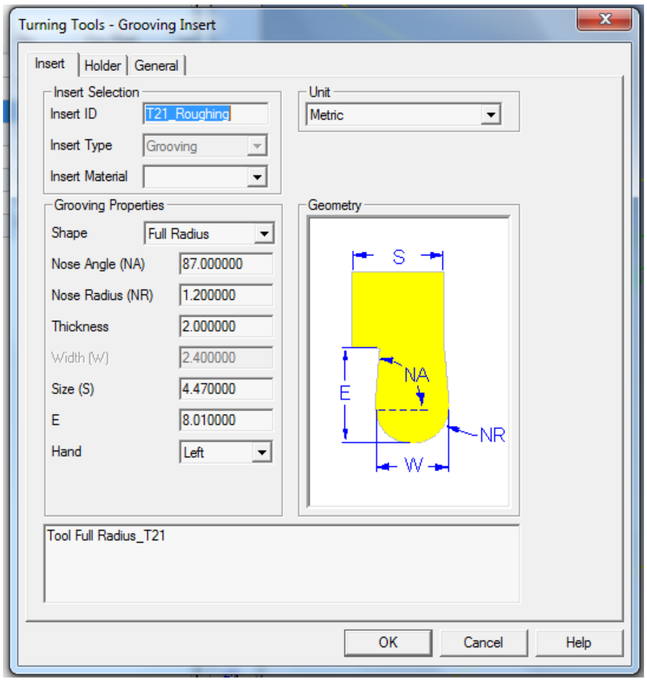


Figure 5.27: Cutting insert properties for operation T21

To carry out the roughing turning operation simulation, Esprit supplies a series of options to be set-up. The first series of parameters to select regards mainly the general properties of the operation, such as cutting parameters (e.g. cutting speed, feed rate) measurement units and sizing.

The figure 5.28 summarizes these parameters selection.

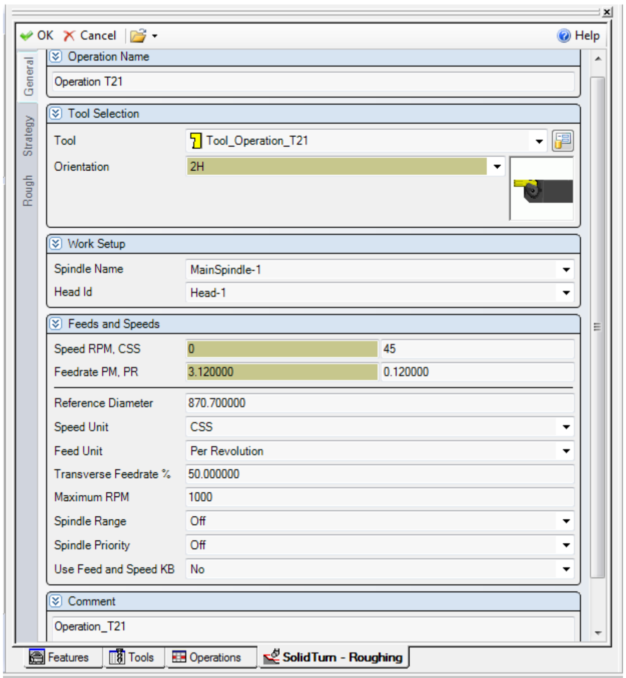


Figure 5.28: General information of roughing simulation for operation T21

It is possible to select a second series of parameters in the strategy window, as shown in figure 5.29, here it is possible to edit the typology of turning operation required as well as the collision detection.

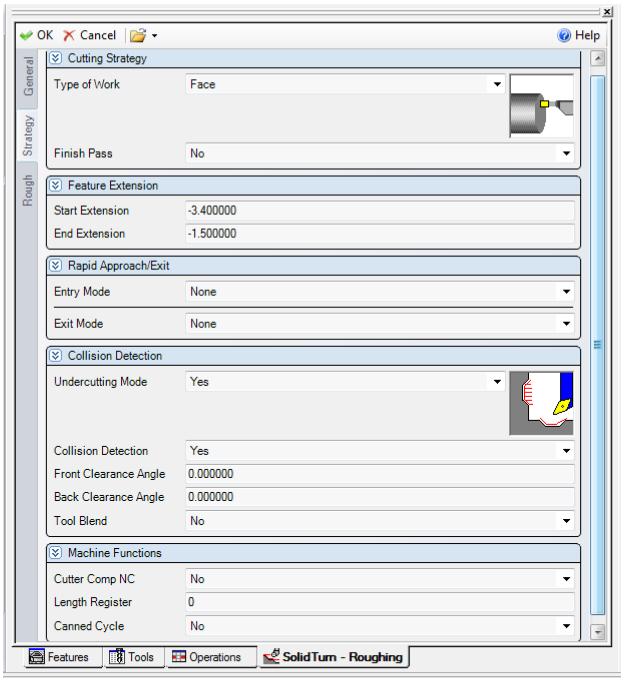


Figure 5.29: Strategy window options for operation T21

Another series of selectable parameters is shown in figure 5.30, there the Roughing software window is reported. Here it is possible to select the stock typology, the stock allowances, the passes features and other characteristic useful to carry out the simulation.

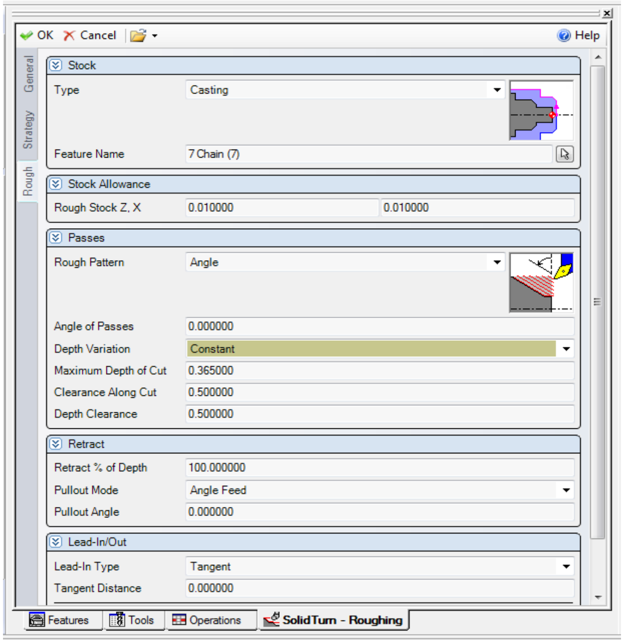


Figure 5.30: Roughing parameters for operation T21

Analogue selection of tooling and operation properties has been done for the operation T17.

Here it follows, in figures 5.31 through 5.36, a series of screenshots summarizing all the features adopted.

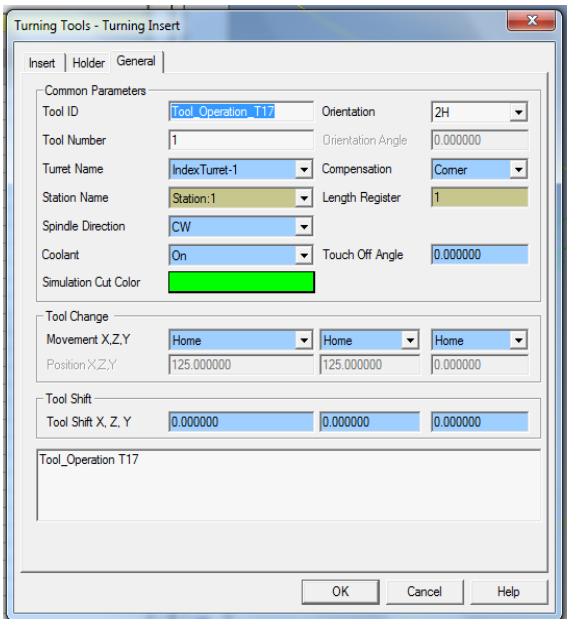


Figure 5.31: General information of the cutting tool for operation T17

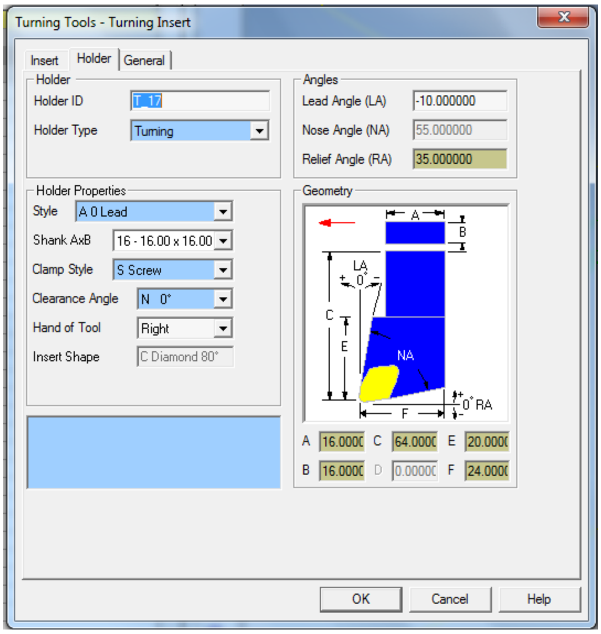


Figure 5.32: Tool holder information for operation T17

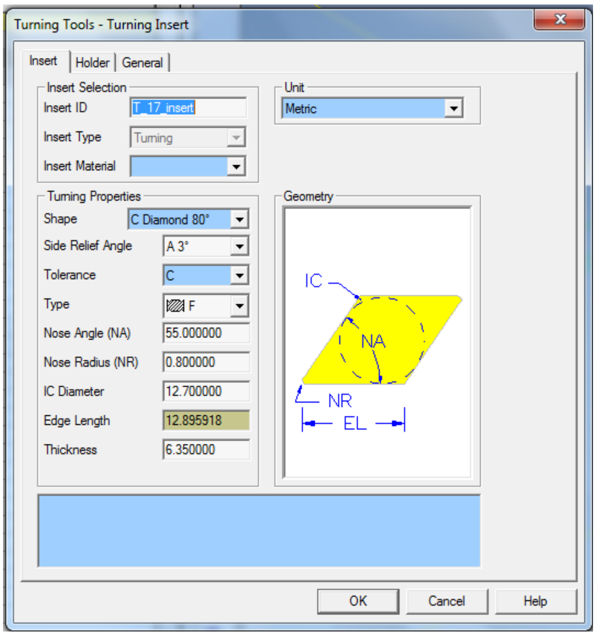


Figure 5.33: Cutting insert properties for operation T17

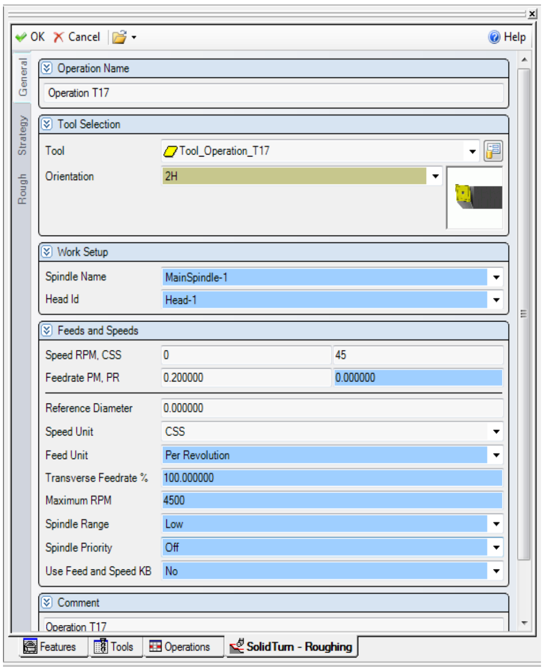


Figure 5.34: General information of simulation for operation T21

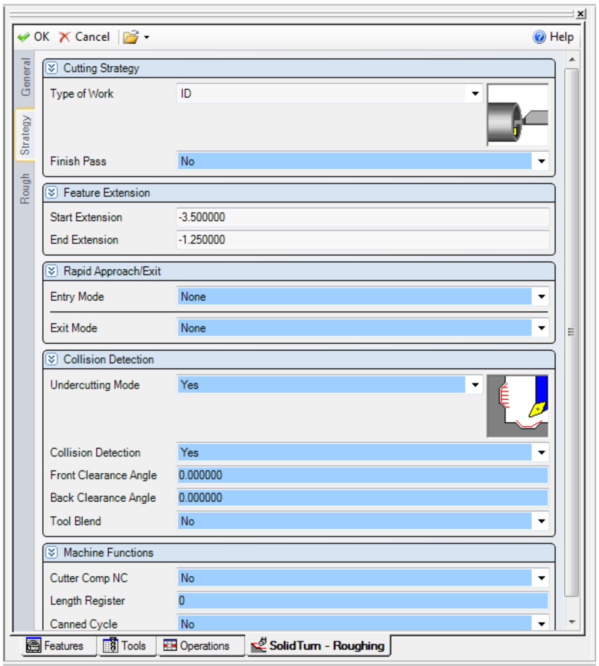


Figure 5.35: Strategy window options for operation T17

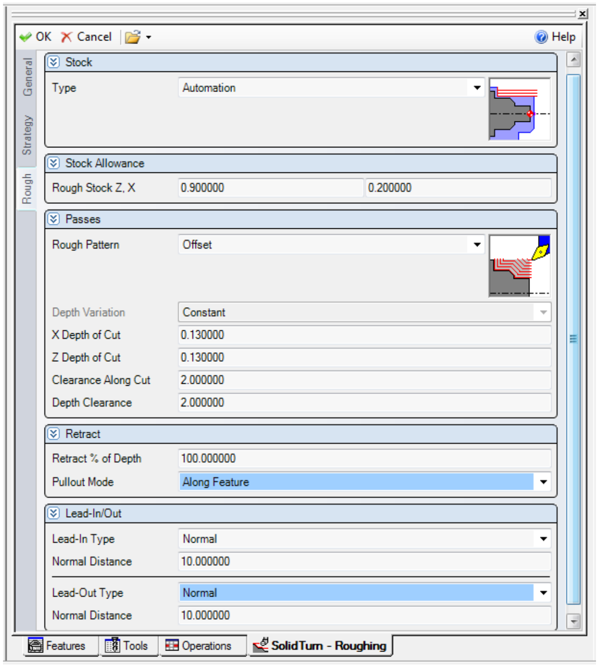


Figure 5.36: Roughing parameters for operation T17

5.4.2.3 Simulation Output

The simulation output is made of the CNC code and the Esprit final report.

The CNC code for the operation T21 is the following

N1 (TOOL_ OPERATION T21)
G40 G99 T0101 G0 G97 S0 M3
M8
(OPERATION_T21)
G0 X33.459 Z.0644
G50 S1000
G96 S45
G1 X34.9331 F.0047
X34.9043
G0 X33.4405
Z.0507
G1 X34.9331
X34.9057
G0 X.3937 Z.1969
M1

The CNC code generated for the operation T17 is the following:

N1 (TOOL_OPERATION T17)
G40 G99 T0101 G0 G97 S0 M3
M8
(OPERATION T17)
G0 X29.9947 Z-1.3124
G50 S4500
G96 S45
G1 X30.6766 Z-1.5092
X30.7554 Z-1.441
X31.4399 Z-.8482
G0 X30.5133
Z-1.5118
X30.6855
G1 X30.7642 Z-1.4436
X31.4517 Z-.8482
G0 X30.5104
Z-1.5144
X30.6943
G1 X30.7731 Z-1.4462
X31.4636 Z-.8482
G0 X30.5074
Z-1.5169
X30.7032
G1 X30.7819 Z-1.4487
X31.4754 Z-.8482
G0 X30.5045
Z-1.5195
X30.7121

G1 X30.7908 Z-1.4513
X31.4872 Z-.8482
G0 X30.5015
Z-1.522
X30.7209
G1 X30.7997 Z-1.4538
X31.499 Z-.8482
G0 X30.4986
Z-1.5246
X30.7298
G1 X30.8085 Z-1.4564
X31.5108 Z-.8482
X30.8289 Z-.6513
G0 X9.8425 Z4.9213
M30

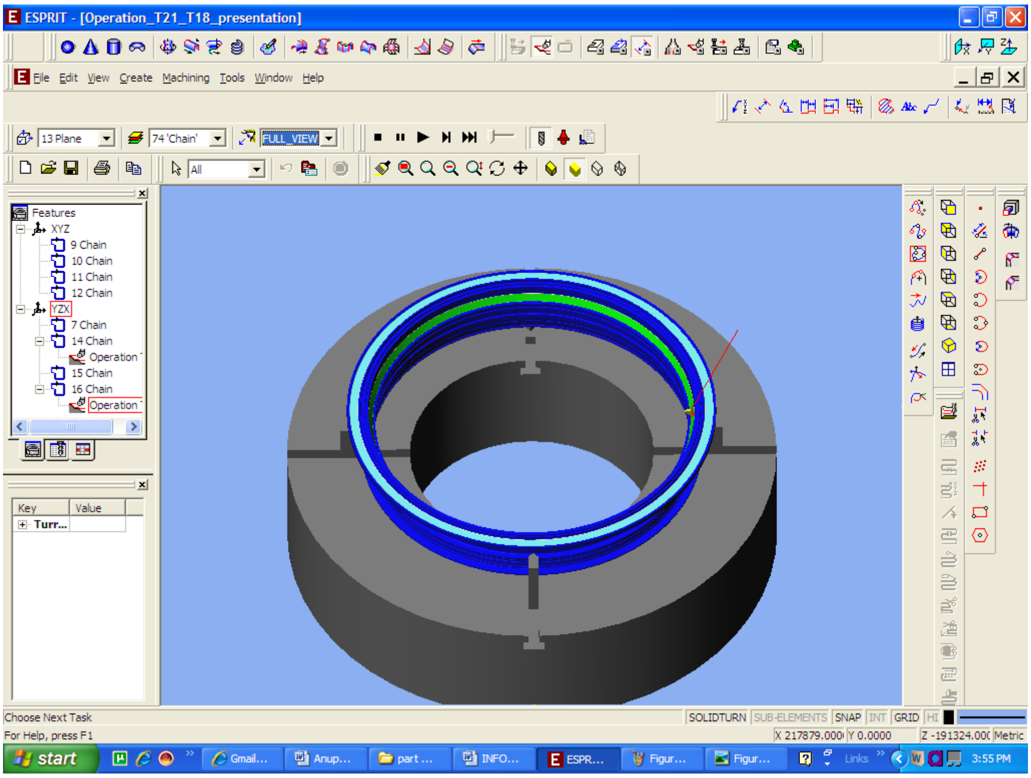


Figure 5.37: Simulation of turning.

Advantages:

- The user can bring in a wide range of CAD file to ESPRIT® for simulation.
- Appropriate turning operation facilities can be easily selected with help of the user-friendly simulation model environment.
- Collisions and errors of tool orientation and positioning can be avoided easily.
- Any subjected changes and improvement ideas can be verified and CNC codes can be found immediately in accordance with the changes.

Disadvantages:

- If the tool geometry is not available in tool library, its need to be created appropriate tool creating its geometry, insert and tool holder.
- The Machine Format file, also is referred as post processor file translates the machining process simulation into NC code for a specific NC machine. Therefore, NC code generation needs specific machine file format for the utilizing machine tool.
- A find the virtual process simulation exactly similar to the real machining processes needs all technical details subjected to machine setup, cutting strategies, cutting tool.

General Technical details

(1) Machine Base Origin Coordinate (X, Y, Z), Turret home position, Turret style Index/ Gang / Magazine, Rapid rate of Turret, Home position of Main Spindle, Orientation of Main Spindle, Turning Direction CCW/CW, Turret / spindle relationship (Shared / exclusive/ Never), NC output order (Turret or spindle), Part orientation on Machine, machine file format.

(2) Holder properties (type, style, size, shape etc.).

(3) Cutting Tool specifications (Cutting insert, Nose angle, relief angle, tool compensation, Tool orientation, lead angle)

5.4.3 Second milling process simulation in MASTERCAM®

This example reports a Milling simulation to performing a 2D chamfer milling. The operation is performed on a generic mill machine.

The starting workpiece is a 13x10x0.5 inches rectangular plate, as the one shown in figure 5.38.

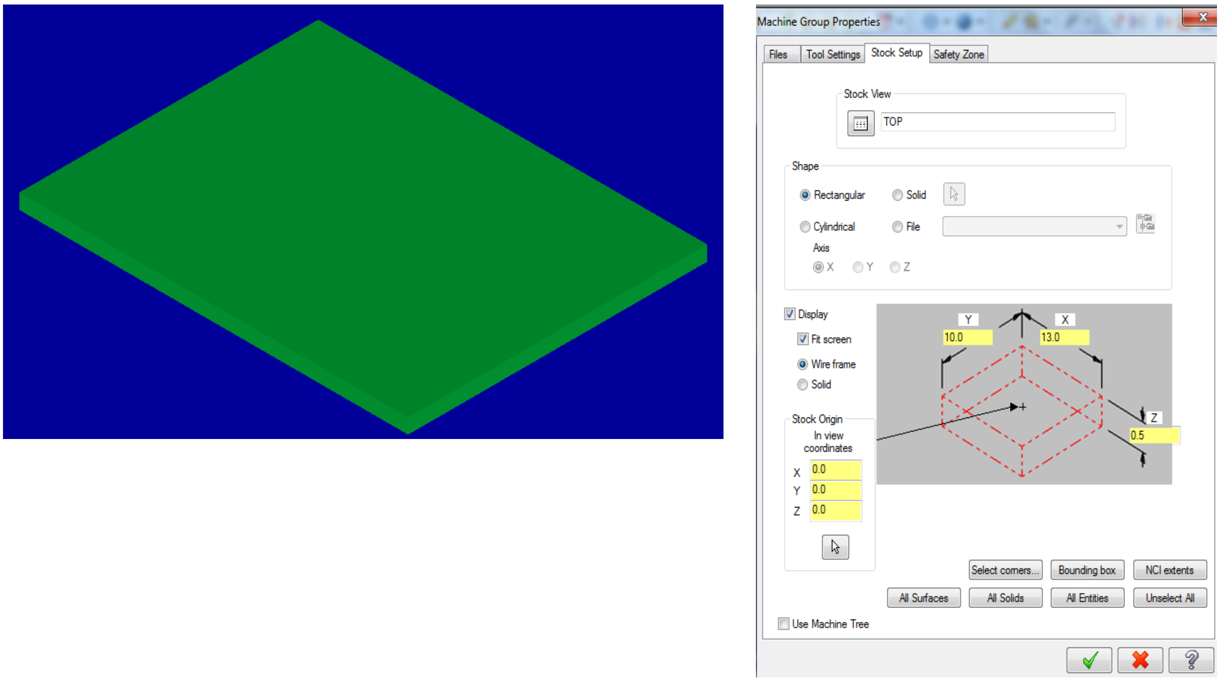


Figure 5.38: Plate and stock geometrical properties

The final shape to be obtained after the milling operation is the one reported in figure below (figure 5.39).

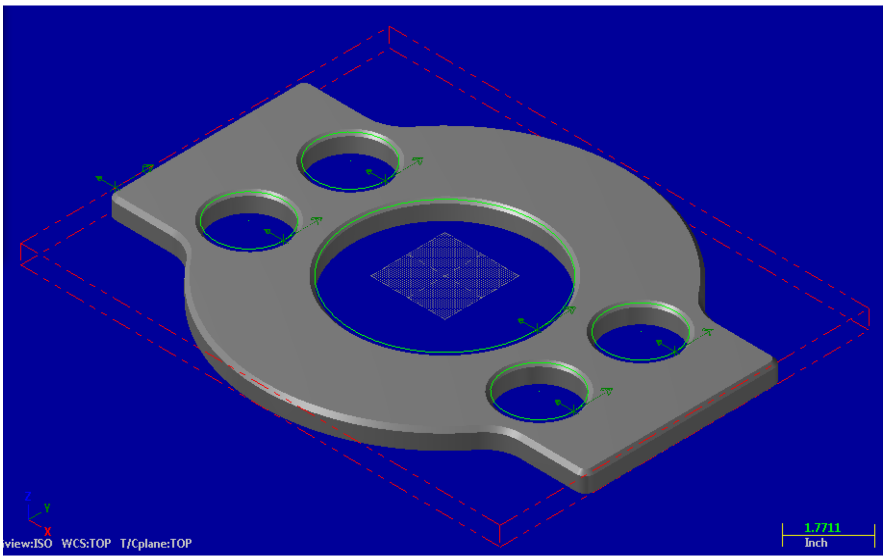


Figure 5.39: Final geometry for milling operation.

The simulation actually performed is a "chamfer milling" which consists of creating the yellow profile shown in figure 5.40. It has been found the curve from the final geometry (figure 5.39) and the features that govern the tool path have been created.

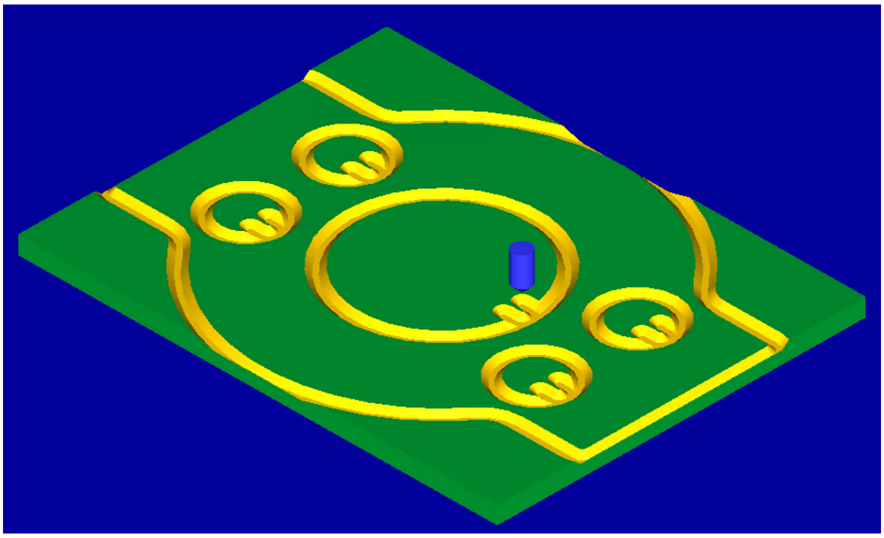


Figure 5.40: Simulation of chamfer milling

Mastercam allows defining several cutting tool features. For this operation it is possible to select:

- Typology
- Geometrical features
- Parameters

In this application, the selected type of tool is the "chamfer mill", as shown in figure 5.41.

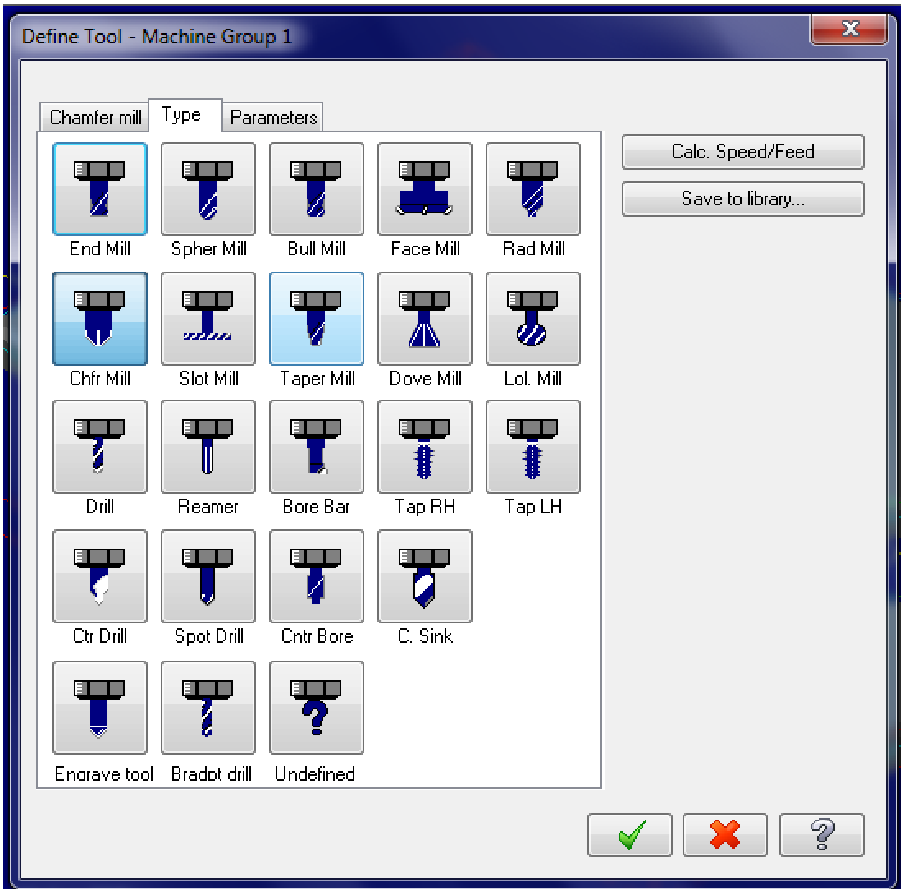


Figure 5.41: Tool Type Selection

The geometrical features selected for the milling operation simulation are summarized in the figure 5.42.

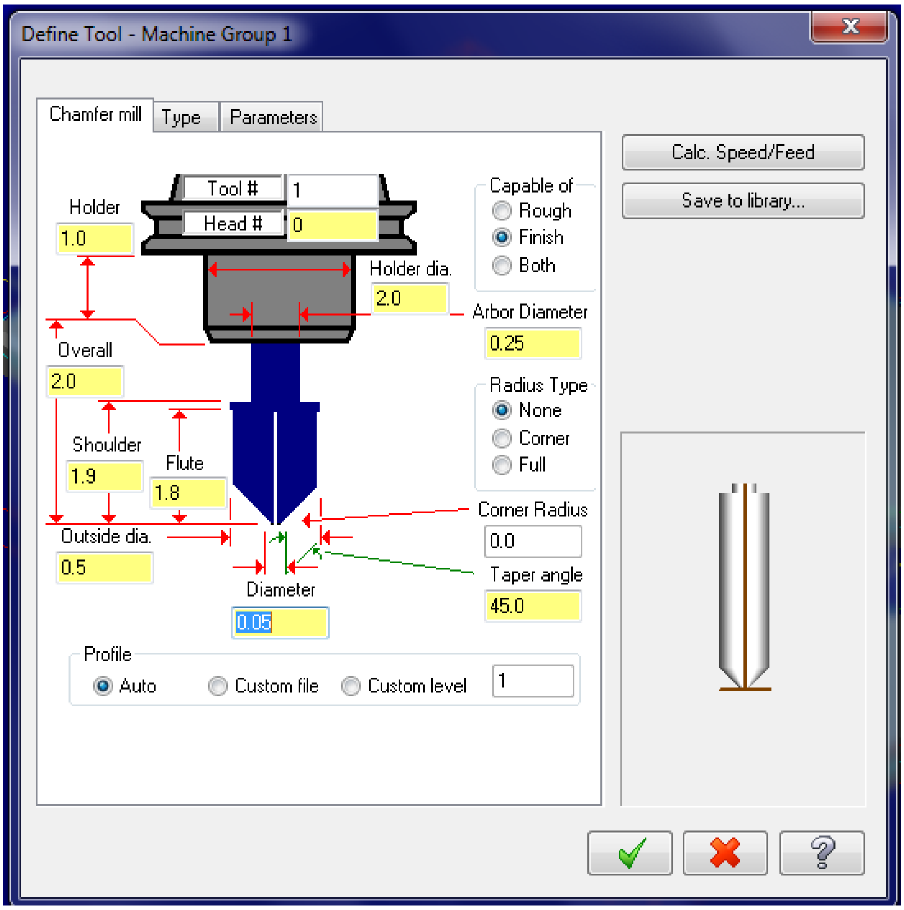


Figure 5.42: Chamfer mill geometrical features

The figure 5.42 reports the parameters used for the tool configuration

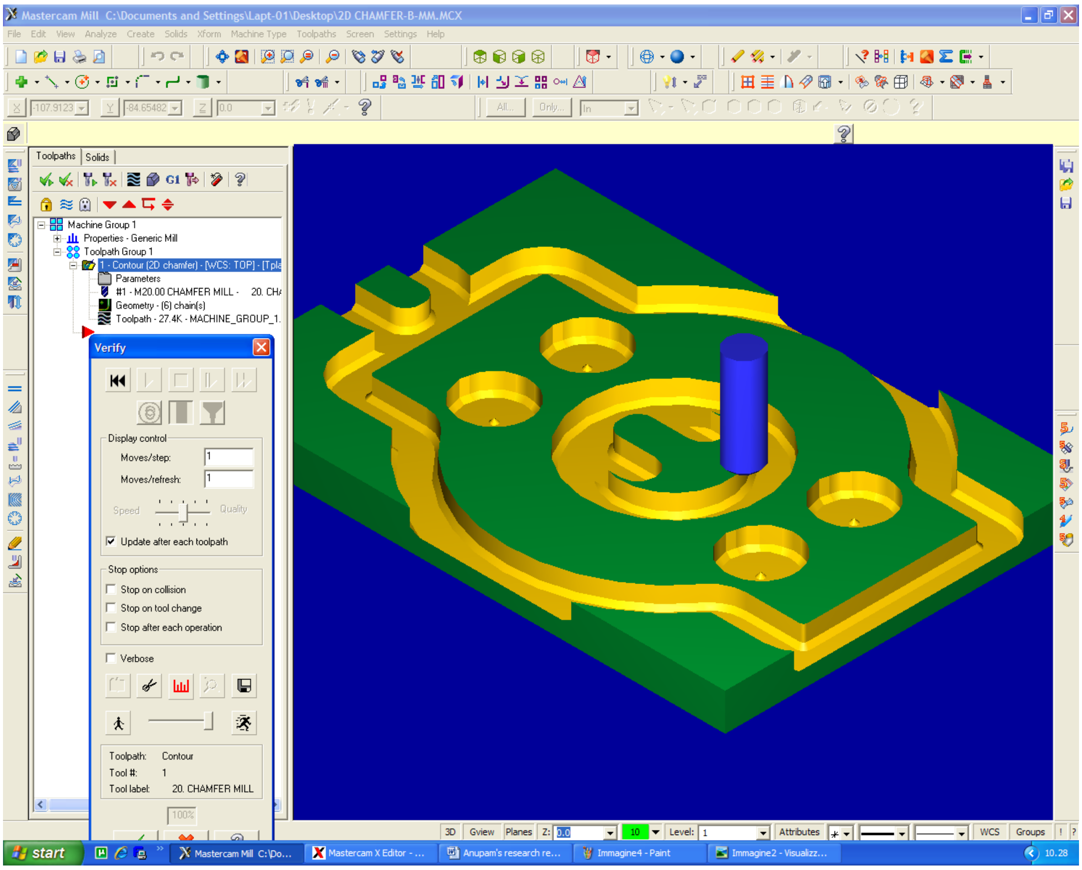


Figure 5.43: Simulation of Milling.

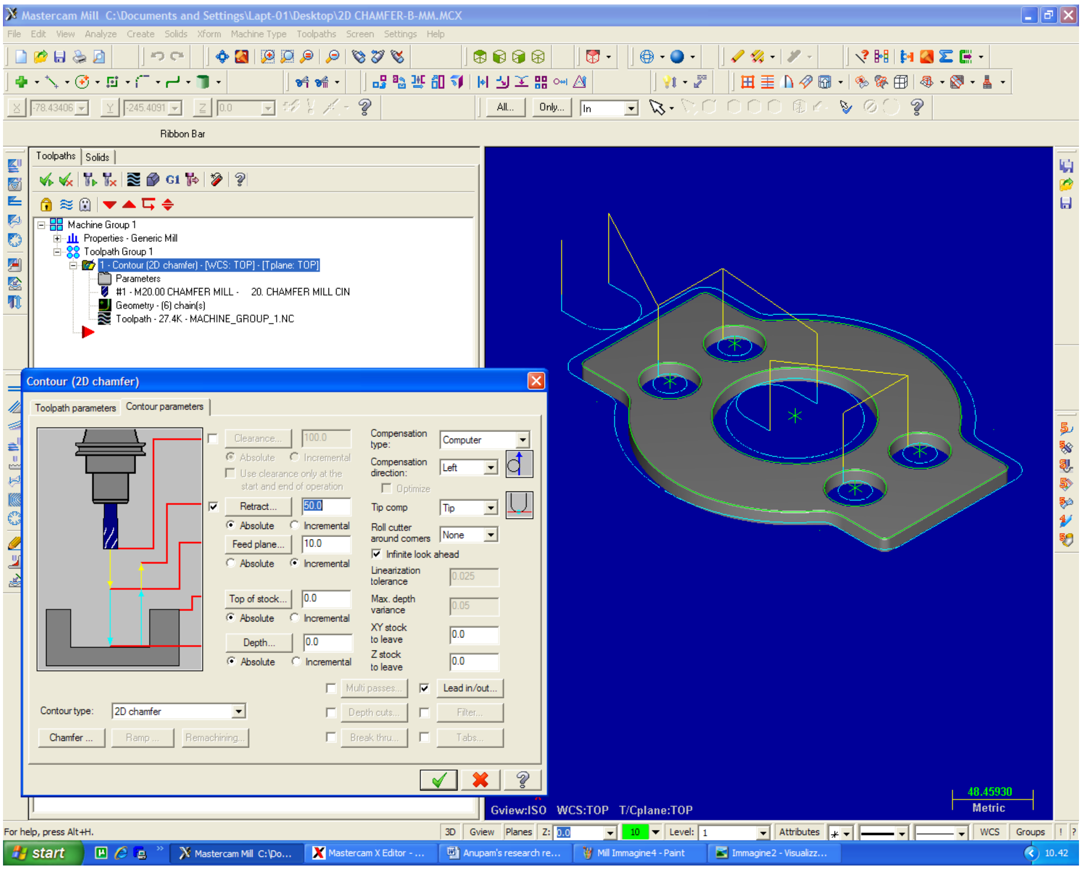


Figure 5.44: Simulation of Milling.

The operation accuracy, tool selection, tool path and collisions error can be analysed and parameters can be adjusted easily. And after simulation finally obtained part can be compared with real part geometry to verify dimensional accuracy.

The milling simulation by Mastercam generated the following CNC code

%
O0000(MACHINE_GROUP_2)
(DATE=DD-MM-YY - 28-11-11 TIME=HH:MM - 23:51)
(MCX FILE - C:\USERS\SARA\DESKTOP\MCX\MILL\SAMPLES\INCH\2D TOOLPATHS\2D-CHAMFER.MCX)
(NC FILE - C:\MCAMX\MILL\NC\MACHINE_GROUP_2.NC)
(MATERIAL - ALUMINUM INCH - 2024)
(T1 | 1/2 CHAMFER MILL | H305)
G20
G0 G17 G40 G49 G80 G90
(GENERIC MILL)
T1 M6
G0 G90 G54 X-7.075 Y-2.6875 A0. S1069 M3
G43 H305 Z.25 M8
Z.1
G1 Z-.15 F8.56
X-6.825
G3 X-6.575 Y-2.4375 R.25

```
G1 Y2.4375
G2 X-6.25 Y2.7625 R.325
G1 X-4.7331
G3 X-4.0034 Y3.119 R.925
G2 X4.0034 R5.075
G3 X4.7331 Y2.7625 R.925
G1 X6.25
G2 X6.575 Y2.4375 R.325
G1 Y-2.4375
G2 X6.25 Y-2.7625 R.325
G1 X4.7331
G3 X4.0034 Y-3.119 R.925
G2 X-4.0034 R5.075
G3 X-4.7331 Y-2.7625 R.925
G1 X-6.25
G2 X-6.575 Y-2.4375 R.325
G3 X-6.825 Y-2.1875 R.25
G1 X-7.075
Z-.05
G0 Z.25
X-3.5738 Y-1.625
Z.1
G1 Z-.15
X-3.3238
G3 X-3.0738 Y-1.375 R.25
X-4.7988 R.8625
X-3.0738 R.8625
X-3.3238 Y-1.125 R.25
G1 X-3.5738
Z-.05
G0 Z.25
Y1.125
Z.1
G1 Z-.15
X-3.3238
G3 X-3.0738 Y1.375 R.25
X-4.7988 R.8625
X-3.0738 R.8625
X-3.3238 Y1.625 R.25
G1 X-3.5738
Z-.05
G0 Z.25
X4.2988 Y1.125
Z.1
G1 Z-.15
X4.5488
G3 X4.7988 Y1.375 R.25
X3.0738 R.8625
X4.7988 R.8625
X4.5488 Y1.625 R.25
G1 X4.2988
Z-.05
G0 Z.25
Y-1.625
Z.1
```

```
G1 Z-.15
X4.5488
G3 X4.7988 Y-1.375 R.25
X3.0738 R.8625
X4.7988 R.8625
X4.5488 Y-1.125 R.25
G1 X4.2988
Z-.05
G0 Z.25
X1.925 Y-.25
Z.1
G1 Z-.15
X2.175
G3 X2.425 Y0. R.25
X-2.425 R2.425
X2.425 R2.425
X2.175 Y.25 R.25
G1 X1.925
Z-.05
G0 Z.25
M5
G91 G28 Z0. M9
G28 X0. Y0. A0.
M30
%
```

5.4.4 Turning process simulation in MASTERCAM®

This application regards the simulation of a turning operation performed on two axis slant bed lathe machine.

The workpiece studied was a cylindrical bar as the one shown in the figure below (figure 5.45), the dimensions are: diameter = 4’’ and length = 5’’.

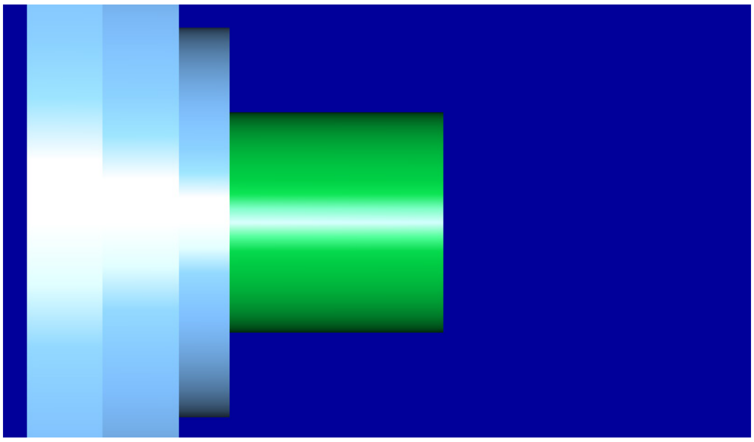


Figure 5.45: Raw workpiece, in green the metal stock and in light blue the fixture

From the cylindrical bar a series of two sequential operations, roughing and semi-finishing, were performed in order to obtain the final shape shown in figure 5.46.

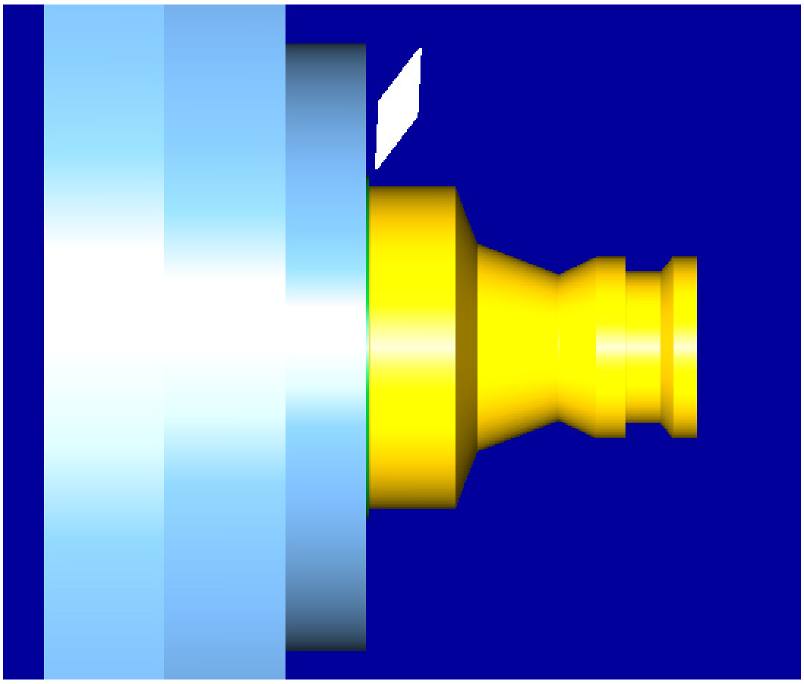


Figure 5.46: Final shape (yellow) and geometry of cutting tool (white)

Tooling:

The Mastercam software allows the selection of some tool features:

- Type
- Inserts
- Holders
- Parameters

As shown in the figure 5.47, the tool typology is “general turning tool”.

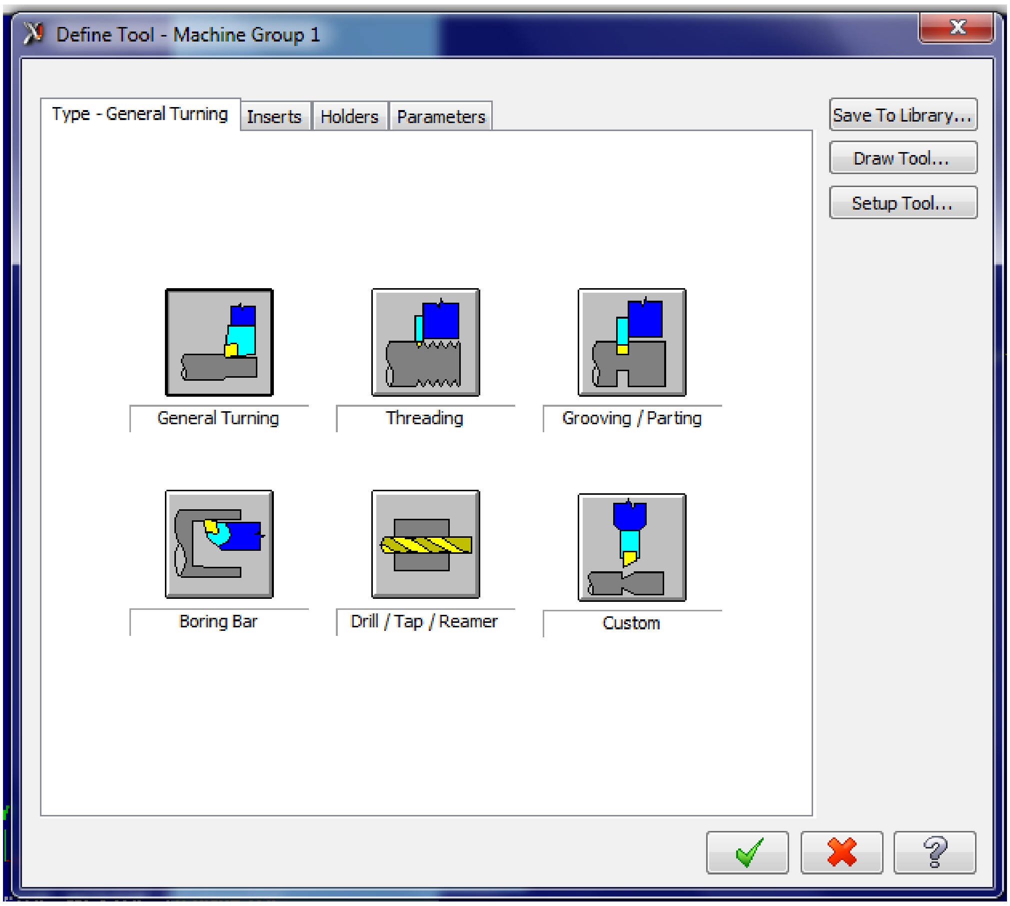


Figure 5.47: General tool information

The selected insert for both the operations was V- 35°-Diamond shape made of cemented carbide. A summary of the tool features is reported in the figure 5.48.

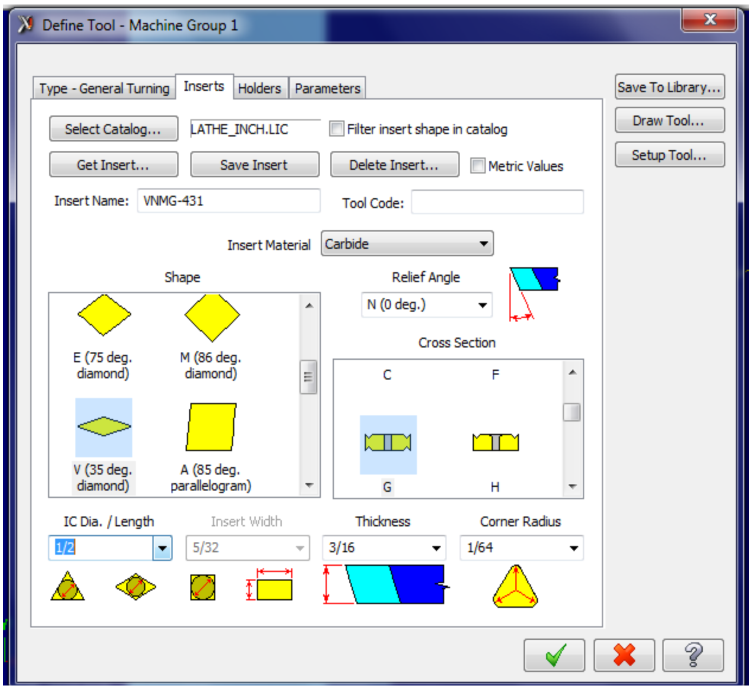


Figure 5.48: Summary of tool features

The tool holder adopted is a J-Shape -3 degrees side circle, as shown in the figure 5.49.

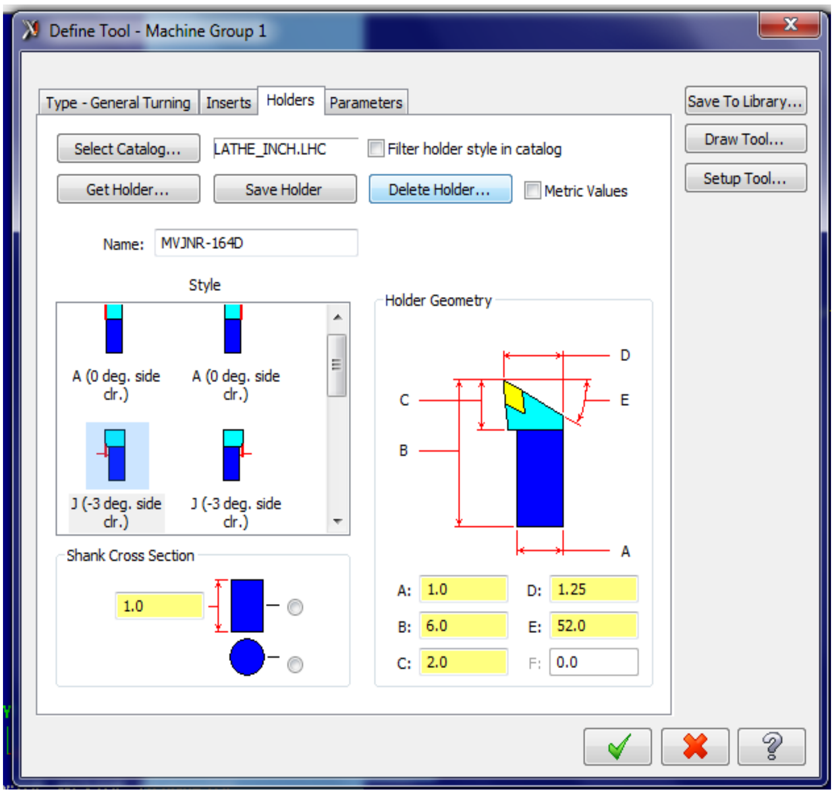


Figure 5.49: Holder information

The tool parameters are summarized in the figures 5.50.

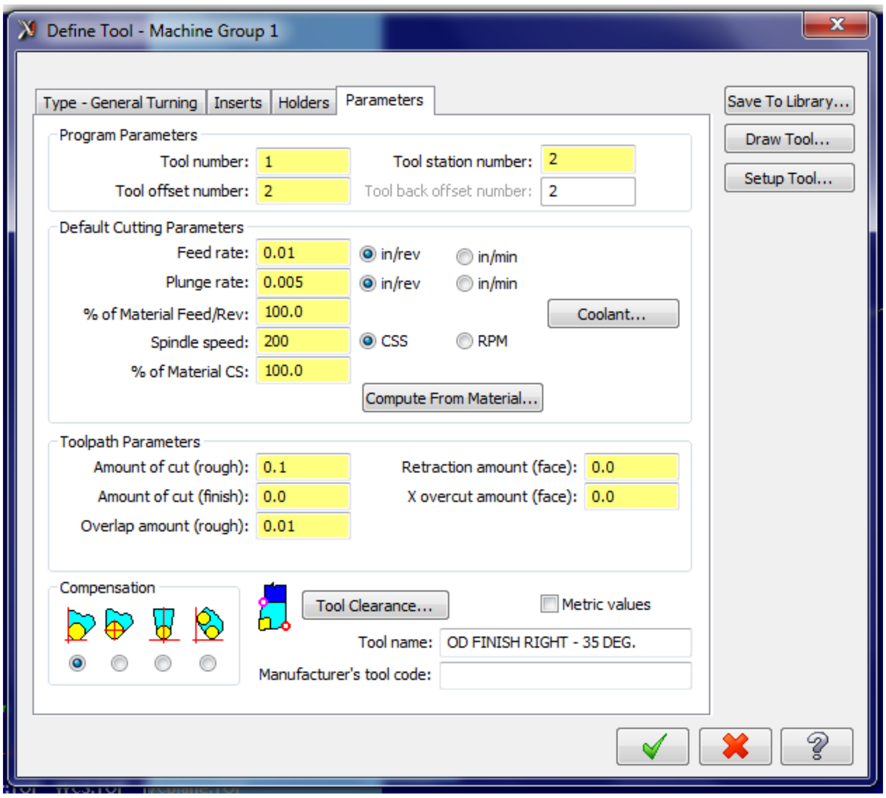


Figure 5.50: Cutting tool parameters

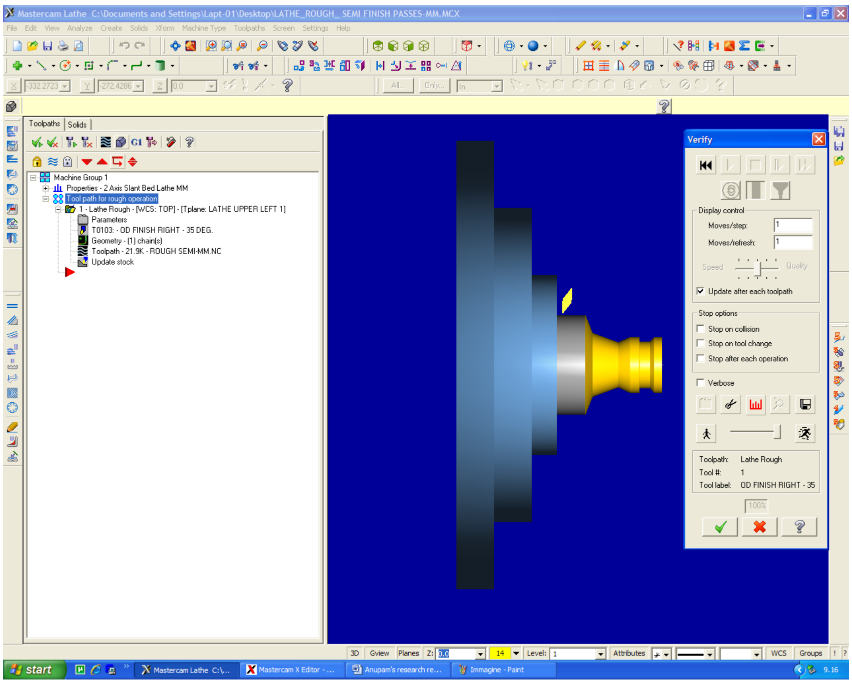


Figure 5.51: Simulation of Turning.

The simulation snap shot (figure 5.51) presents the final part after the rough and semi finish passes. In right side, project manager presents the details regarding the machine setup, operation parameters, tool insert holder, part geometry, tool path and stock. Another snap shot (figure 5.52) presents a top view of the tool path. Rough operation properties are defined as tool path parameter and rough parameter. Tool path parameter page defines the cutting tool, tool library, tool number, station number, offset number, feed rate, plunge feed rate, spindle speed, maximum possible spindle speed, home position, Tool origin coordinates, stock definition etc. The roughing parameters (Depth of cut, minimum depth of cut, stock to leave in X and Z direction, cutting method, semi finish pass details, rough direction and angle, lead in/ lead out details, stock recognition) are defined on rough parameter page.

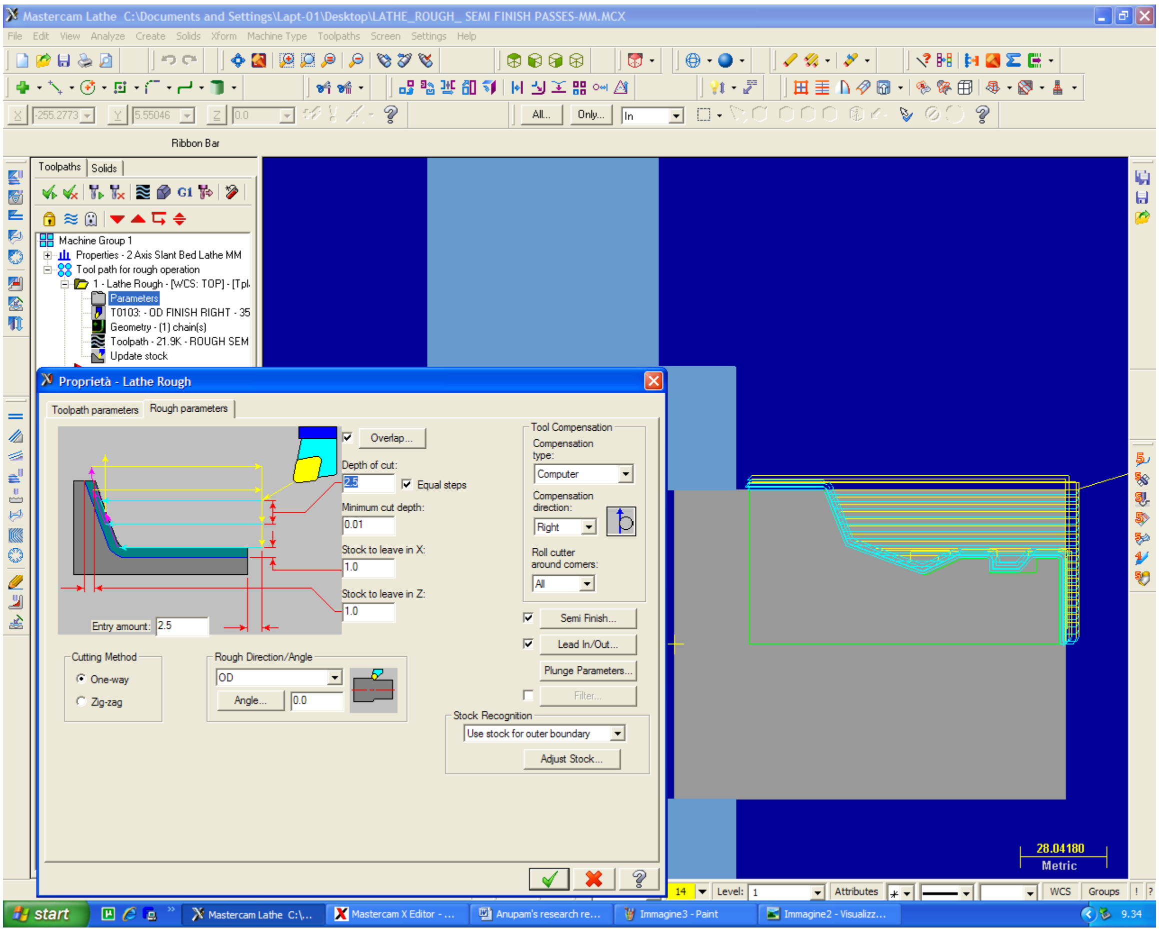


Figure 5.52: Simulation of Turning.

The operation accuracy, tool selection, tool path and collisions error can be analysed, and parameters can be adjusted. And after simulation finally obtained part can be compared with real part geometry to verify dimensional accuracy.

For the turning operation simulation, the CNC code was generated and reported below:

```
%
O0000
(PROGRAM NAME - ROUGH SEMI)
(DATE=DD-MM-YY - 28-11-11 TIME=HH:MM - 22:01)
(MCX FILE - C:\USERS\SARA\DESKTOP\MCX\LATHE\SAMPLES\INCH\LATHE 11 ROUGH
WITH SEMI FINISH PASSES.MCX)
(NC FILE - C:\MCAMX\LATHE\NC\ROUGH SEMI.NC)
(MATERIAL - NONE)
G20
(TOOL - 1 OFFSET - 2)
(OD FINISH RIGHT - 35 DEG.  INSERT - VNMG-431)
G0T0102
G97S184M03
G0G54X4.1432Z.3042
G50S3600
G96S200
G99G1X3.9553Z.27F.01
Z-2.9399
G3X4.0391Z-3.0136R.0857
G1Z-3.9956
X4.1491
X4.2905Z-3.9249
G0Z.3042
X3.9495
G1X3.7615Z.27
Z-2.9005
X3.9307Z-2.9339
G3X3.9753Z-2.9469R.0856
G1X4.1167Z-2.8762
G0Z.3042
X3.7557
G1X3.5678Z.27
Z-2.8623
X3.7815Z-2.9045
X3.923Z-2.8338
G0Z.3042
X3.5619
G1X3.374Z.27
Z-2.8241
X3.5878Z-2.8662
X3.7292Z-2.7955
G0Z.3042
X3.3682
G1X3.1802Z.27
Z-2.7859
X3.394Z-2.828
X3.5354Z-2.7573
G0Z.3042
X3.1744
G1X2.9865Z.27
Z-2.7476
X3.2002Z-2.7898
```

X3.3417Z-2.7191
G0Z.3042
X2.9806
G1X2.7927Z.27
Z-2.7094
X3.0065Z-2.7516
X3.1479Z-2.6809
G0Z.3042
X2.7869
G1X2.5989Z.27
Z-2.6446
X2.622Z-2.6757
X2.8127Z-2.7134
X2.9541Z-2.6427
G0Z.3042
X2.5931
G1X2.4052Z.27
Z-2.3826
X2.6189Z-2.6716
X2.7604Z-2.6009
G0Z.3042
X2.3994
G1X2.2114Z.27
Z.0667
G3X2.3355Z-.0157R.0857
G1Z-.3138
Z-2.2883
X2.4252Z-2.4096
X2.5666Z-2.3389
G0Z.3042
X2.2056
G1X2.0176Z.27
Z.07
X2.1642
G3X2.2314Z.0631R.0857
G1X2.3728Z.1338
G0Z.3042
X2.0118
G1X1.8239Z.27
Z.07
X2.0376
X2.1791Z.1407
G0Z.3042
X1.8181
G1X1.6301Z.27
Z.07
X1.8439
X1.9853Z.1407
G0Z.3042
X1.6243
G1X1.4364Z.27
Z.07
X1.6501
X1.7915Z.1407
G0Z.3042

X1.4305
G1X1.2426Z.27
Z.07
X1.4564
X1.5978Z.1407
G0Z.3042
X1.2368
G1X1.0488Z.27
Z.07
X1.2626
X1.404Z.1407
G0Z.3042
X1.043
G1X.8551Z.27
Z.07
X1.0688
X1.2102Z.1407
G0Z.3042
X.8492
G1X.6613Z.27
Z.07
X.8751
X1.0165Z.1407
G0Z.3042
X.6555
G1X.4675Z.27
Z.07
X.6813
X.8227Z.1407
G0Z.3042
X.4617
G1X.2738Z.27
Z.07
X.4875
X.629Z.1407
G0Z.3042
X.2679
G1X.08Z.27
Z.1
Z.07
X.2938
X.4352Z.1407
G0X2.3855
X2.5234
Z-.2796
G1X2.3355Z-.3138
G3X2.2766Z-.3784R.0857F.005
G1X2.1566Z-.4305
Z-.8244F.01
X2.1642
G3X2.3355Z-.91R.0856
G1X2.4769Z-.8393
G0Z-.3876
X2.3645
G1X2.1766Z-.4218

```
X1.9777Z-.5083F.005
Z-.8244F.01
X2.1642
G3X2.1766Z-.8246R.0856
G1X2.318Z-.7539
G0X2.3855
X2.5234
Z-1.2336
G1X2.3355Z-1.2678
G3X2.3196Z-1.3038R.0857F.005
G1X2.1982Z-1.4349
Z-2.1027F.01
X2.3555Z-2.3154
X2.4969Z-2.2447
G0Z-1.3791
X2.4061
G1X2.2182Z-1.4133
X2.0609Z-1.5831F.005
Z-1.917F.01
X2.2182Z-2.1297
X2.3596Z-2.059
G0Z-1.5273
X2.2689
G1X2.0809Z-1.5615
X1.9236Z-1.7314F.005
X2.0809Z-1.9441F.01
X2.2223Z-1.8734
G0X2.4395
Z.1242
X.1389
G1X-.049Z.09
X2.1642
G3X2.3755Z-.0157R.1056
G1Z-.3138
G3X2.3028Z-.3935R.1057
G1X2.0177Z-.5174
Z-.8044
X2.1642
G3X2.3755Z-.91R.1056
G1Z-1.2678
G3X2.3559Z-1.3121R.1057
G1X1.9669Z-1.7323
X2.6533Z-2.6604
X3.9453Z-2.9153
G3X4.0791Z-3.0136R.1056
G1Z-3.9756
X4.1491
X4.2905Z-3.9049
G0Z.2342
X.2479
G1X.06Z.2
Z.06
X2.1642
G3X2.3155Z-.0157R.0756
G1Z-.3138
```

```
G3X2.2635Z-.3709R.0756
G1X1.9577Z-.5037
Z-.8344
X2.1642
G3X2.3155Z-.91R.0756
G1Z-1.2678
G3X2.3015Z-1.2996R.0756
G1X1.902Z-1.731
X2.6063Z-2.6834
X3.9233Z-2.9432
G3X4.0191Z-3.0136R.0756
G1Z-4.0056
X4.1491
X4.2905Z-3.9349
G0Z.2342
X.1879
G1X0.Z.2
Z.03
X2.1642
G3X2.2555Z-.0157R.0456
G1Z-.3138
G3X2.2241Z-.3482R.0456
G1X1.8977Z-.49
Z-.8644
X2.1642
G3X2.2555Z-.91R.0456
G1Z-1.2678
G3X2.247Z-1.287R.0456
G1X1.8371Z-1.7297
X2.5594Z-2.7064
X3.9013Z-2.9711
G3X3.9591Z-3.0136R.0456
G1Z-4.0356
X4.1491
X4.2905Z-3.9649
G0Z.2342
X.1279
G1X-.06Z.2
Z0.
X2.1642
G3X2.1955Z-.0157R.0157
G1Z-.3138
G3X2.1847Z-.3256R.0156
G1X1.8377Z-.4764
Z-.8944
X2.1642
G3X2.1955Z-.91R.0156
G1Z-1.2678
G3X2.1926Z-1.2744R.0156
G1X1.7722Z-1.7284
X2.5124Z-2.7294
X3.8793Z-2.999
G3X3.8991Z-3.0136R.0156
G1Z-4.0656
X4.1491
```

X4.2905Z-3.9949
G28U0.W0.M05
T0100
M30
%

5.5 Machining Process Simulation Support in Teaching Programs

In recent years, manufacturing education has attracted much attention for utilization of virtual simulation facilities to assist teaching programs. Large manufacturing production cells as well as little manufacturing activities can be simulated into virtual digital environment [6]. Computer-Aided manufacturing (CAM) simulation is one of such simulation areas that greatly influence the industry and manufacturing education [7]. Increase of Computer Numeric Control (CNC) machine application improving quality of products and optimizing the cost and the time of production, CAM became more important to extend the CNC education. CAM process simulation can perform realistic 3D simulation of entire CNC machines, just like they behave in the shop that can contribute as a virtual laboratory for machining experiments. CAM simulation can provide a realistic experience of working with integrated Computer-Aided Design and the Computer-Aided Manufacturing practices. During generation of virtual machining operation it provides opportunity for multi-axis computerized numerical control for complex surface machining and to study the generated NC-programs in parallel.

The wide growth of CNC application in industries encourages strengthening of student knowledge in CNC programming and process management. The CNC practices in industries are relatively more complicated than real applications as is taught during academic theory classes. It is essential to facilitate practical experience working with CNC machines. Because of limitation of CNC facilities and environment, it has always been difficult to employ intense practical classes in universities. Wherever, virtual CNC machine and process simulation environment provides as alternative way to support CNC knowledge extension programs.

This research describes the wide utility of CAM simulation which can take an active part to strengthen concurrent CNC Knowledge extension. CAM simulation can help to integrate multistage of design and manufacturing curricula bringing them together in a virtual environment. The work presents manufacturing of an automobile component showing different level of design and manufacturing complexity. The step-wise CAM simulation development has been illustrated reducing the manufacturing complexity and supporting teaching programs. Facilities to create entire CNC machine environment, design part calibration, dynamic part creation, process and tool knowledgebase, error detection and CNC program generation are critical issues of CAM machining simulation. Simulation of tool paths and machine operations is desirable to detect collision errors and precise machining with cost and time savings [8,9, 10].

A major challenge in CAM based manufacturing education is, how to overcome the problems associated with practical learning experience at the optimum time of their study. Since practical work is an essential component of engineering education [7]. But, it becomes more necessary if CAD and CAM integration are getting upgraded regularly in industries. Table 5.4 below summarizes the important aspects of a successful machining process planning, advantages of CAM simulation as well as its co-related education aspect.

Important aspects of a successful Machining process planning	**Advantages form CAM simulation**	**Co-related Education Aspect**
Mass production market is trending toward job production. Customer demands more varieties in products.	CAD Design generation/ integration with several CAD software	• Part design aspects, • Availability of existing design format, • Transformation and compatibility of one format to another
Shape, size, work-piece holding techniques change from machine to machine	Work-piece setup and mounting on machine	• Work-piece shape and design aspects, • Realization of Work piece design to optimizes the machining operations in accordance with available tools
Technical details of a machine tool. Shape, size, position, orientation and movements of entities (mounting table, fixture, machining head, tool magazine etc.)	Machine setup	• Understanding of CNC machine with axis wise configuration and available environments, • Company wise CNC machine facilities comparison
Huge varieties in shape and size of cutting tools, insert and holders.	Tool magazine and tool library	• Tool distinction with machine process • Insert geometry • Tool handle shape and design • Insert tip geometry and compensation and cutting point

Right match between process and utilized tool	Types of machining processes and co-relation with tool	• Understanding of tool availability at available CNC Machine
Type of machine, Tool material, work-piece material, process, require quality finish, allowance, facilities to machine control, machine capabilities	Machining technologies	• Machining parameter • Orientation of tool • Tool path design
Machine complexity	Dynamic machining process simulation	• Error detection • When-if trial to check several configuration • Co-ordination between operations
Close view of machining process	Process verification	• Tool path constrains • Tool resource constrains • Material constrains • Machine constrains • Part constrains • Machining allowance constrains
Save machine downtime and verification of the Tool path movement during operation.	CNC program generation using verified machining process simulation, and any further modifications are easy	• Path of tool movement, • optimized path selection, • tool lead-in, tool lead-out positioning • Understanding of G- code format and editing

Table 5.4: Advantages and aspects of CAM simulation

5.6 Results and Discussions

In general, the research objectives in machining process verification and optimization are focused on sub-areas of machining process enhancement. Examples are represented by fixtures analysis and design, process parameters setting and optimization, tolerance setting, enhancements in NC programming and editing, scheduling of machining processes, etc. The researches are useful but to find a concrete enhancement, the research must be applied in all-embracing technical context at a machining tool environment together. Machining process simulation in 3D virtual environment can provide an alternative platform to implement and verify the research work that is going on in sub-areas of machining process enhancements.

The following tasks can be performed through a machine process simulation:

- Give an overview of complete details of machining process.
- Provide a way to realize, describe and visualize a machining process in detail with all technical competences.
- Easily analyze facilities at every step of machining process.
- Provide data base and process report for decision making
- Support knowledge transfer and storage
- 3D visualization facility to verify the process.
- Easier NC program generation and editing
- Minimize machine downtime by providing an offline virtual platform for NC code generation, process verification and optimization.

By performing these tasks, the application of CAM and machining process simulation provides benefits in terms of flexibility and efficiency, such as [11]:

- Greater supervision of the production
- Fast response to changes in market demand
- Greater flexibility
- Product variety
- Small lot-sizes
- Distributed processing capability

References

[1] Chang T C, Wysk R A and Wang H P (2006) Computer-Aided Manufacturing, 3rd ed. Prentice-Hall, Upper Saddle River, New Jersey

[2] Mehrabi M.G., Ulsoy A.G., Koren Y. (2001) Manufacturing Systems and Their Design Principles. In: The Mechanical Systems Design Handbook - Modeling, Measurement, and Control, Editor(s): Hurmuzlu Y., Nwokah O.D.I., CRC Press LLC, pp. 2-11

[3] Groover M.P. (2000) Automation, Production Systems, and Computer Integrated Manufacturing, 2nd ed., Prentice Hall, Englewood Cliffs, NJ.

[4] Yeung M K (2003) Intelligent process-planning system or optimal CNC programming - a step towards complete automation of CNC programming. Integrated Manufacturing Systems 14(7):593-598

[5] Koenig D T (1990) Computer Integrated Manufacturing - Theory and Practice, 1st ed. Taylor & Francis, New York

[6] Caggiano, A., Keshari, A., Teti, R., 2009, Analysis and Reconfiguration of a Manufacturing Cell through Discrete Event Simulation, 2nd IPROMS International Researchers Symposium, Ischia, 22-24 July, ISBN 978-88-95028-38-5: 175-180

[7] Quan, Li, 2005.Teaching Multi-axis Complex Surface Machining via Simulation and Projects, Proceedings of the 2005 American Society for Engineering Education Annual Conference & Exposition

[8] Vidal, A., Alberti, M., Ciuran, J., Casadesus, M., 2005, Decision support system for optimizing the selection of parameters when planning milling operations, International Journal of Machine tools and Manufacture, Vol. 45, 201-210

[9] Yeunga, C., Altintas, Y., Erkorkmaz, K., 2006, Virtual CNC system. Part I. System Architecture, International Journal of Machine tools and Manufacture, Vol. 46, 1107-1123

[10] Balic, J., 2006, Intelligent CAD/CAM system for CNC programming- An Overview, Advances in Production Engineering and Management, ISSN: 1854-6250, 13-22

[11] Post A L (2003) Computer-Aided Manufacturing. Encyclopedia of Information Systems 1:187-203

Bibliography

Chapter 1

[1] Teti, R., Jemileniak, K.,O‟Donnel, G., Dornfeld D., 2010, Advanced monitoring of machining operations, Annals of the CIRP Vol 59/2 pp 717-739.

[2] Byrne, G., Dornfeld, D., Inasaki, I., Ketteler, G., König, W., Teti, R., 1995, Tool Condition Monitoring (TCM) – The Status of Research and Industrial Application, Annals of the CIRP Vol. 44/2 pp. 441 – 567.

[3] Jemielniak, K., 1999, Commercial Tool Condition Monitoring Systems, The International Journal of Advanced Manufacturing Technology, 15 pp. 711-721.

[4] Allchin, D. 2001. "Error Types". Perspectives on Science 9 (1): 38–58.

[5] Hon, K.K.B., 2005, Performance and Evaluation of Manufacturing Systems, CIRP Annals 54/2, pp 139-154.

[6] Munzinger, C., Fleischer, J., Broos, A., Hennrich, H., Wieser, J., Ochs, A., Schopp, M., 2009, Development and implementation of smart maintenance activities for machine tools, CIRP Journal of Manufacturing Science and Technology, Volume 1, Issue 4, 2009, Pages 237-246.

[7] Martinsen, K., Holtskogb, H., 2011, Social aspects of Process Monitoring in Manufacturing Systems, CIRP Annals Manufacturing Technology, Annals 2011 - Vol. 60/1.

[8] Wikan Sakarinto, Hiroshi Narazaki, and Keiichi Shirase, 2011, A decision support system for capturing CNC operator knowledge, International Journal of Automation Technology, Vol.5. No.5.

Chapter 2

[1] Jawahir, I.S., van Luttervelt, C.A., 1993, Recent Developments in Chip Control Research and Applications, Annals of CIRP, 42/2, pp. 659-693.

[2] Spaans, C., 1970, A Systematic Approach to Three Dimensional Chip Curl, Chip Breaking and Chip Control, SME Paper, MR 70-241.

[3] Sukvittayong, S., Inasaki, I., 1991, Identification of Chip Form in Turning Process, ISME Series III, 34 (4), pp. 553-560.

[4] Nakayama, K, 1984, Chip Control in Metal Cutting, Bulletin JSPE, 18 (2), pp. 97-103.

[5] Moriwaki, T., Mori, Y., 1992, Sensor Fusion for In-process Identification of Cutting Process Based on Neural Network Approach, IMACS/SICE Int. Symp. on Robotics, Mechatronics and Manufacturing Systems, Kobe, Japan, pp. 245-250.

[6] Andreasen, J.L., De Chiffre, L., 1993, Automatic Chip-Breaking Detection in Turning by Frequency Analysis of Cutting Force, Annals of CIRP, 42/1, pp. 45-48.

[7] Dornfeld, D.A., Pan, C.S., 1985, A Study of Continous/Discontinus Chip Formation Using Acoustic Emission, J. Applied Metalwork, 4 (1), pp. 18-29.

[8] Segreto, T., Teti, R., Applications of Intelligent Sensor Monitoring for Machining Processes, 8th Int. Conf. and Exhibition on Laser Metrology, Machine Tool, CMM & Robotic Performance, 25-28 June 2007, Cardiff, Wales, pp. 388-399.

[9] Teti, R., Buonadonna, P., D'Addona, D., 2001, Chip Form Monitoring via Cutting Force Signal Processing, V AITeM Conf., Bari, 18-20 Sept., pp. 21-30.

[10] Kohonen, T., 1999, Self-Organizing Maps, Springer, Berlin, Heidelberg.

[11] D’Addona, D., Keshari, A., Teti, R., 2008, Spectrum estimation and processing of cutting force sensor signals for chip form monitoring and classification, 4th I*PROMS NoE Virtual International Conference on Innovative Production Machines and Systems - IPROMS 2008, 1-14 July, pp.555-560.

[12] Minutes of the STC-O CIRP Co-Operative Work Meeting, CIRP Jan. Meeting, Paris, 24-26 Jan. 2001.

[13] ISO 3685, 1993, Tool-Life Testing with Single-Point Turning Tools, Annex G: 41.

[14] Teti, R., Jawahir, I.S., Jemielniak, K., Segreto, T., Chen, S., Kossakowska, J., 2006, Chip Form Monitoring through Advanced Processing of Cutting Force Sensor Signals, Annals of CIRP, 55/1, ISBN 0080450490, ISSN 007-8506 (CIRP Annals), ISSN 1660-2773 (CD Rom): pp 75-80

[15] Merkl, D., Rauber, A., 1997, Alternative Ways for Cluster Visualization in Self-Organizing Maps, Workshop on Self-Organizing Maps – WSOM ’97, Espoo, June 4-6: 106-111.

[16] Merkl and Rauber, 1997. Alternative ways for cluster visualization in self-organizing maps, Proc. of WSOM'97, Workshop on Self-Organizing Maps, Espoo, Finland, June 4-6, pp.106-111.

[17] Masters, T., 1993, Practical Neural Network Recipes in C++, Academic Press, San Diego, CA

[18] Vesanto, J., Himberg, J., Alhoniemi, J. Parhankangas, E., 2000, SOM Toolbox For Matlab5, http://www.cis.hut.fi/projects/somtoolbox/

Chapter 3

[1] Rahman, M., Wang Z.G., Wong, Y.S., 2006, A Review of High-Speed Machining of Titanium Alloys, JSME Int. J. Ser. C: Mech. Syst. Mach. Elem. Manuf., Vol. 49: 11-20.

[2] Teti, R., 2007, Difficult to Machine Materials, 2nd Mftg. Eng. Soc. Int. Conf. – CISIF/MESIC '07, 9-11 July, Madrid, CD ROM

[3] Segreto, T., Teti, R., 2007, Applications of Intelligent Sensor Monitoring for Machining Processes, 8th Int. Conf. on Lamdamap, 25-28 June, Cardiff: 388-399.

[4] Teti, R., Jawahir, I.S., Jemielniak, K., Segreto, T., Chen, S., Kossakowska, J., 2006, Chip Form Monitoring through Advanced Processing of Cutting Force Sensor Signals, Annals of CIRP, 55/1: 75-80.

[5] Rubio, E.M., Teti, R., Baciu, I.L., 2006, Advanced Signal Processing in Acoustic Emission Monitoring Systems for Machining Technology, 2nd Int. Virtual Conf. on IPROMS, 3-14 July: 189-192.

[6] Segreto, T., Teti, R., Neugebauer, R., Harzbecker, C., 2008, Sensor Monitoring Based Optimisation during Turning of Titanium Alloys, Proceedings of Virtual International Conf. on Innovative Production Machines and Systems - IPROMS2008, 1-14 July: 547-554.

Chapter 4

[1] Keshari, A., D'Addona, D. Teti, R., Capece Minutolo, F. 2011, Projection based Image Processing for Automatic Tool Wear Detection, 10th AITEM Conference, 12-14 sept, Naples, Italy, ISBN 978-88-906061-0-1: 89-90

[2] Tool Wear, Wikipedia, the free encyclopedia <http://en.wikipedia.org/wiki/Tool_wear>

[3] Chapter 6: E.J.A. Armarego and R.H. Brown, The Machining of Metals, Prentice-Hall, Inc., 1969

[4] Chapter 9: David A. Stephenson and John S. Agapiou, Metal Cutting Theory and Practice, Marcel Dekker, Inc., 1997

[5] Chapter 23: Cutting Tool Technology, pp. 543-548 Mikell P. Groover, Fundamentals of Modern Manufacturing, John Wiley & Sons, Inc., 2007

[6] Modern Metal Cutting, A practical Handbook, Sandvik Coromant

[7] Byrne, G., Dornfield, D., Inasaki, I., Ketteler, G., Koenig, W., Teti, R.,1995. Tool condition monitoring (TCM) - The status of research and Industrial application, Annals of the CIRP, vol. 44/2, pp. 541-567.

[8] Wang, Y., Ji, S., Zhang, L., Jin, S., Chen, Y., 2008, Detection of tool wear condition based on the computer image processing, Key Engineering Materials, vol. 375-376, pp 553-557.

[9] Teti, R., 1993. Sensor signal frequency analysis for metal cutting process monitoring, 1st AITEM Conference, Ancona, Italy, 22-24 Sept., pp. 55-64.

[10] Teshima, T., Shibasaka, T., Takuma, M., Yamamoto, A., 1993. Estimation of Cutting Tool Life by Processing Tool Image Data with Neural Network, Annals of the CIRP, vol. 42/1, pp. 59-62.

[11] D'Addona, D., Teti, R., 2010. Monitoring of cutting tool wear through image analysis, 6th IPROMS Virtual Conference, 15-26 Nov.

[12] D'Addona, D., Teti, R., 2011. Cutting Tool Image Data Processing for Automatic Tool Wear Recognition Through Artificial Neural Networks, International Conference on Industrial Engineering and Systems Management - IESM 2011, 25-27 May, Metz, France.

Chapter 5

[1] Chang T C, Wysk R A and Wang H P (2006) Computer-Aided Manufacturing, 3rd ed. Prentice-Hall, Upper Saddle River, New Jersey

[2] Mehrabi M.G., Ulsoy A.G., Koren Y. (2001) Manufacturing Systems and Their Design Principles. In: The Mechanical Systems Design Handbook - Modeling, Measurement, and Control, Editor(s): Hurmuzlu Y., Nwokah O.D.I., CRC Press LLC, pp. 2-11

[3] Groover M.P. (2000) Automation, Production Systems, and Computer Integrated Manufacturing, 2nd ed., Prentice Hall, Englewood Cliffs, NJ.

[4] Yeung M K (2003) Intelligent process-planning system or optimal CNC programming - a step towards complete automation of CNC programming. Integrated Manufacturing Systems 14(7):593-598

[5] Koenig D T (1990) Computer Integrated Manufacturing - Theory and Practice, 1st ed. Taylor & Francis, New York

[6] Caggiano, A., Keshari, A., Teti, R., 2009, Analysis and Reconfiguration of a Manufacturing Cell through Discrete Event Simulation, 2nd IPROMS International Researchers Symposium, Ischia, 22-24 July, ISBN 978-88-95028-38-5: 175-180

[7] Quan, Li, 2005.Teaching Multi-axis Complex Surface Machining via Simulation and Projects, Proceedings of the 2005 American Society for Engineering Education Annual Conference & Exposition

[8] Vidal, A., Alberti, M., Ciuran, J., Casadesus, M., 2005, Decision support system for optimizing the selection of parameters when planning milling operations, International Journal of Machine tools and Manufacture, Vol. 45, 201-210

Yeunga, C., Altintas, Y., Erkorkmaz, K., 2006, Virtual CNC system. Part I. System chitecture, International Journal of Machine tools and Manufacture, Vol. 46, 1107-1123

[10] Balic, J., 2006, Intelligent CAD/CAM system for CNC programming- An Overview, Advances in Production Engineering and Management, ISSN: 1854-6250, 13-22

[11] Post A L (2003) Computer-Aided Manufacturing. Encyclopedia of Information Systems 1:187-203