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STABILITY LOBES DIAGRAM IDENTIFICATION AND SURFACE ROUGHNESS MONITORING IN MILLING PROCESSES

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DOCTORAL THESIS

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Projectes d'Innovació Tecnològica en l'Enginyeria del Producte i Procés

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supervisor: Joaquim de Ciurana i Gay

2009

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Als meus.

Mr. Chatterbox how long will you live?
Always to receive but never to give
Always carry news all over the place
Mr. Chatterbox you are a big disgrace

Bob Marley and The Wailers, 1970

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He après moltes coses aquests quatre anys de doctorat, i no només d'enginyeria. Han estat quatre anys molt intensos. Crec que tothom hauria de fer la seva Tesi Doctoral. Jo, sens dubte, repeteixo.

Summary Sumari

La millora de la productivitat i la qualitat són indubtablement dues de les principals exigències del sector productiu modern i factors clau per la competitivitat i la supervivència. Dins aquest sector, la fabricació per arrancada de material juga encara avui en dia un paper protagonista tot i l'aparició de noves tècniques de conformat per addició. Indústries com l'aeronàutica, l'automobilística, la del motlle o l'energètica, depenen en bona part de les prestacions de les màquines-eina.

Aquesta Tesi aborda dos aspectes rellevants quan es tracta de millorar de la productivitat i la qualitat del sector productiu: el problema del fimbrament, més conegut per la denominació anglosaxona *chatter*, i la monitorització de la rugositat superficial en el mecanitzat a alta velocitat.

Productivity and quality improvement are undoubtedly two of the main demands of the modern manufacturing sector and key factors for competitiveness and survival. Within this sector, material removal processes play, still nowadays, a principal role despite the emergence of additive manufacturing techniques. Industries such as aerospace, automotive, molds and dies or energy largely depend on machine tools performance for improved productivity and quality.

This Thesis is focused on two important aspects when it comes to improving productivity and quality of the manufacturing sector: chatter problem, and surface roughness monitoring in high speed milling.

Preface

Globalization has brought new challenges and requirements to the manufacturing sector. Industries are being continuously forced to improve productivity and quality and to reduce costs by increasing material removal rates and the flexibility, capabilities and performance of machine tools. Although the emergence of a significant number of other manufacturing techniques, the material removal process is still the most widely used technique for producing the final shape of manufactured products and, it appears that it will remain important for the time being.

Technologies involved in machining operations have advanced greatly the last decades and machines have experienced significant changes such as the incorporation of numerical control. Every year it is possible to observe in fairs, conferences and of course, in the market, how production capabilities increase thanks to the development of new concepts, devices, materials, tools, coatings, structures, etc. Accuracy, flexibility and productivity are enhanced constantly with innovative solutions that permit to achieve the market demands and raise them into higher levels. At the end, all these improvements are possible thanks to the generation of knowledge. The understanding of the metal cutting fundamentals has become a key factor in the last decades but this is not an easy task due to complexities of the chip formation mechanism.

The research trends in recent years, due to the advances in computers and sensors, seem to be focused on the on-line monitoring, measuring and controlling the machining process. Several kinds of sensors and signal processing techniques have been developed for direct or indirect diagnosis of aspects such as the workpiece condition (surface roughness, integrity, and dimensional accuracy), detection of tool wear and breakage, chatter identification, analysis of machine components condition, etc.

The evolution of science, technology and technique, and the pressure of competitive markets have stimulated the rising of the manufacturing frontiers. However, despite all these advances, chatter vibration has been, for the last sixty years, a common limitation on metal removal process when it comes to improving productivity and part quality. This phenomenon has been a popular topic for academic and industrial research. The chatter problem has generated a great deal of literature since the late 1950s. Tobias and Fishwick (1958), Tlusty and Polacek (1963) and Merrit (1965) presented the first research works regarding this phenomenon. Chatter arises given certain combinations of spindle speed and axial depth of cut. The border between a stable cut, i.e. without chatter, and an unstable one, i.e. with chatter, is described as a function of these two cutting parameters and can be visualised in a chart called stability lobe diagram (SLD). Once SLD is known, it is possible to select optimal cutting parameters to ensure chatter-free cutting operations.

The overarching aim of this Thesis arises with the trends and limitations of the present metal removal sector and it is twofold. First, it provides two novel experimental methodologies for identifying the stability lobes diagram in milling operations. Secondly, surface roughness generation is investigated in ball end milling operations and a surface roughness monitoring application is developed based on artificial neural networks.

The Thesis is organized as follows:

Chapter 1 presents the general domain of the Thesis, establishes the historical and conceptual framework and exposes the interest, motivation and objectives persecuted in this work.

Chapter 2 reviews the fundamentals of metal cutting mechanics, machine tool vibrations, and surface topography generation. Mechanics of two-dimensional orthogonal cutting is introduced first. The laws fundamental chip formation and friction between the rake and flank faces of a tool during the cutting are explained. Then, are reviewed the generalities of free, forced and self-excited (i.e. chatter) vibrations and presented the principal research lines on chatter phenomenon. After that, the complexities of surface topography generation are exposed and the main research works on this topic reviewed.

Chapter 3 presents an experimental methodology for Stability Lobe Diagram identification in milling operations. The methodology is based on empirical tests where, thanks to the inclined plane workpiece shape it is possible to gradually increase the axial depth of cut in the feed direction. The inclined plane method presented in this chapter permits to obtain a *metallic SLD* physically machined onto the workpiece.

Chapter 4 presents an experimental procedure that permits to determine the Stability Lobe Diagram of a milling process by applying sound mapping methodology. If the SLD is considered as a region and this region is divided into several zones with a mesh, a diagram can be constructed by applying a sound mapping method.

Chapter 5 analyzes the influence of the geometric characteristics of ball end mill cut on the surface generation process. The crest height (h) and the surface roughness average parameter (Ra) are calculated as function of cutting tool radius (R) and radial depth of cut

(Ae) considering surface angularity. Equations for the material removal rate (MRR) calculation are also developed and finally, the theoretical approach is compared with experimentation.

Chapter 6 presents the development of a surface roughness monitoring application based on artificial neural networks for ball end milling operations. Five full factorial series of experiments were carried out in order to obtain data that was used to train the artificial neural network. In the design of experiments geometrical cutting factors, dynamic factors, part geometries, lubricants, materials and machine tool were considered. Vibration was captured on-line with two piezoelectric accelerometers placed following the X and Y axes of the machine-tool.

Finally, Chapter 7 presents conclusions and outlook.

The body of this Thesis consists of the following four papers:

Paper A: Quintana, G., Ciurana, J., and Teixidor, D. (2008). A new experimental methodology for identification of stability lobes diagram in milling operations. International Journal of Machine Tools and Manufacture.

Paper B: Quintana, G., Ciurana, J., Ferrer, I., and Rodríguez, C. A. (2009). Sound mapping for identification of stability lobe diagrams in milling processes. *International Journal of Machine Tools and Manufacture.*

Paper C: Quintana, G., Ribatallada, J., and Ciurana, J. (2010). Surface roughness generation and material removal rate in ball end milling operations. *Materials and Manufacturing Processes.*

Paper D: Quintana, G., Ciurana, J., and Ribatallada, J., (2009). Surface roughness monitoring application based on artificial neural networks. *Proceedings of the 12Th CIRP Conference on Modelling of Machining Operation, San Sebastián-Donosti, Spain.*

Contents

List of symbols

Ae	Radial depth of cut [mm]
Ap	Axial depth of cut [mm]
$\mathbf{A_s}$	Area of the shear plane [mm^2]
F	Friction force [N]
$\mathbf{F_c}$	Cutting force [N]
$\mathbf{F_n}$	Normal force on the shear plane [N]
$\mathbf{F_t}$	Thrust force [N]
$\mathbf{F_{tj}}$	Tangential cutting force acting on the tooth j [N]
$\mathbf{F_{rj}}$	Radial cutting force acting on the tooth j [N]
F(t)	External force acting on a system [N]
$\mathbf{F_s}$	Shearing force [N]
$\mathbf{F_0}$	Initial force acting on a system [N]
h	Chip width [mm]
$\mathbf{h_0}$	Initial chip width [mm]
N	Normal force [N] or Number of teeth
R	Resultant force coming from the workpiece and action on the chip [N]
R'	Resultant force coming from the cutting tool (compensated by R) [N]
$\boldsymbol{\alpha}$	Rake angle of the Merchant Circle [radians]
$\boldsymbol{\mu}$	Friction coefficient
$\boldsymbol{\tau}$	Friction angle [radians]
$\boldsymbol{\Phi}$	Shear angle [radians]
$\boldsymbol{\Phi_j}$	Instantaneous angular immersion of tooth j [radians]
$\boldsymbol{\Omega}$	Spindle speed [rpm]

List of acronyms

AMB	Active Magnetic Bearing
ASCAMM	Associació Catalana d'Empreses de Motlles i Matrius
ASERM	Asociación Española de Rapid Manufacturing.
ASME	American Society of Mechanical Engineers
CAPP	Computer Aided Process Planning
CIRP	College International pour la Recherche en Productique
CNC	Computer Numerical Control
DDE	Delay Differential Equation
DOF	Degree of Freedom
EDM	Electrical Discharge Machining
FFT	Fast Fourier Transform
FRF	Frequency Response Function
GREP	Grup de Recerca en Enginyeria de Producte, Procés i Producció
HSM	High Speed Machining, High Speed Milling
MDOF	Multiple degree of freedom system
MMRR	Maximum material removal rate
MQL	Minimum quantity of Lubricant
MRR	Material Removal Rate
NC	Numerical Control
NEXT IP	Next Generation Production Systems Integrated Project
NN	Neural Network
ODE	Ordinary Differential Equation
PPC	Production Planning Control

SD method	Semi-discretization method.
SDOF	Single Degree of Freedom
SLD	Stability Lobes Diagram
SME	Society of Manufacturing Engineers
UdG	University of Girona
ZOA	Zeroth Order Approximation

Chapter 1. Introduction

Chapter 1 presents the general domain of the Thesis, establishes the historical and conceptual frame and exposes the interest, motivation and objectives persecuted in this work.

1.1 Historical and conceptual framework

Machining is applied to a wide range of materials to create a great variety of geometries and shapes, practically without restrictions on complexity. Typical workpiece materials are: aluminium alloys, cast iron, titanium, austenitic stainless or hardened steels, copper, carbon graphite and also plastics, woods and plastic composites. Regarding the complex geometries and shapes, two types of surfaces are usually defined: ruled surfaces, (e.g. for blades) and sculptured surfaces or free-form surfaces (e.g. for moulds and dies). This enormous number of combinations is able to meet the specific manufacturing requirements of a wide range of manufacturing industries, such as automotive, aerospace or dies and moulds (López de Lacalle and Lamikiz, 2008). Technologies involved in machining operations advance in parallel with developments in materials, computers and sensors. A blank is converted into a final product by cutting extra material away by turning, drilling, milling, broaching, boring, and grinding operations conducted on Computer Numerically controlled (CNC) machine tools (Altintas, 2000).

Since the pioneering work of Henry Maudslay[1] and others in the 1800's, the capabilities of metal cutting machine tools have continuously improved. This evolutionary process continually defines new levels of performance as the "standard". Businesses that refuse to adopt the new standard typically stagnate or go out of business. Those operating within the standard operate principally as producers of commodity goods in a highly competitive marketplace. Those operating above the standard operate, as a whole, at above-average profit margins (Arnone, 1998). Figure 1 shows the first machine built by Joseph R. Brown in 1862.

The first relevant investigation in the field of metal cutting was carried out by Taylor (1907). However, High Speed Machining (HSM) was firstly introduced by Dr. Eng. Carl. J. Salomon who carried out numerous experiments between 1924 and 1931 in Hannover, Germany, and registered the German patent no.523594 (Salomon, 1931). Fifty years later, in the 1980s a movement started to further increase cutting speeds, partly by introducing new types of tool materials such as CBN (cubic boron nitride) for machining hard steels and chilled irons, Si_3N_4 (silicon nitride), for three to four times more cutting speed on cast iron than with the carbides, but primarily and especially in the application to end milling of aluminium by developing spindles that could rotate much faster while retaining relatively good stiffness. This movement is known as high speed machining and is especially important in milling (Tlusty, 2000).

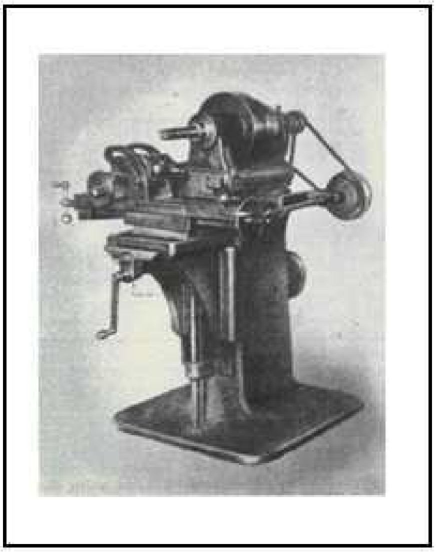

Figure 1: First milling machine built by Joseph R. Brown in 1862. Source: (Aldabaldetrecu, 2006)

Despite the long path travelled since 1931, authors have not established a clear and concise definition for High Speed Machining:

[1] Henry Maudslay (1771-1831) was a British machine tool innovator, tool and die maker, and inventor. He is considered a founding father of machine tool technology (Cantrell and Cookson, 2002).

- High speed machining is loosely defined as the use of higher spindle speeds and axis feed rates to achieve high material removal rates without a degradation of part accuracy or quality. An exact definition encompassing speeds and feeds is elusive because it is heavily dependent upon the type of component being machined. We can only define high speed machining in relative terms; by comparing it to the performance regularly achieved via conventional methods and standard machining centres. Typically we would expect feed rates and speeds at least 50% higher than those conventionally used (Tlusty, 2000).

- High Speed Machining definition is related with increasing cutting speed, spindle speed, feed rate..., depending on the process and the part material and cutting tool combination (Echepare and Esteban, 1999).

- High speed machining (HSM) generally refers to end milling or ball nose end milling at high rotational speeds (10 000-100 000 rev./min) (Urbanski et al., 2000).

- The term 'high speed milling' (HSM) is generally used to describe end milling with small diameter tools (≤10 mm) at high rotational speeds (≥10,000 rpm) (Toh, 2005).

- High-speed machining is defined as machining using average spindle speeds greater than 1047rad/s (10,000rpm), which can generate surface speeds in excess of 6m/s. This high-speed process produces heterogeneous plastic flow with severely localized stresses that results in extreme rates of plastic deformation (up to $10^6 s^{-1}$), high thermal gradients (100C/mm), and high heating rates (10^5C/s) (Campbell et al., 2006).

- As a result of advances in cutting tool and machine tool technologies, machining is being performed at ever increasing cutting speeds and feed rates. The term 'high speed machining' (HSM) have come into common use in recent years to describe end milling, at high rotational speeds (Dewes and Aspinwall, 1997).

- In (Schulz and Moriwaki, 1992), the definition of high-speed machining is based on the workpiece material. For instance, (see Figure 2) a cutting speed of 500m/min is considered high-speed machining for cutting alloy steel whereas this speed is considered conventional in cutting aluminium (Fallbohmer et al., 2000).

HSM acronym is indistinctly used for machining operations, in general, (i.e. High Speed Machining) or, more specifically, for milling operations (i.e. High Speed Milling). In this Thesis, the acronym HSM is also used along the text with these two meanings. The reader will easily understand the specific one depending on the context.

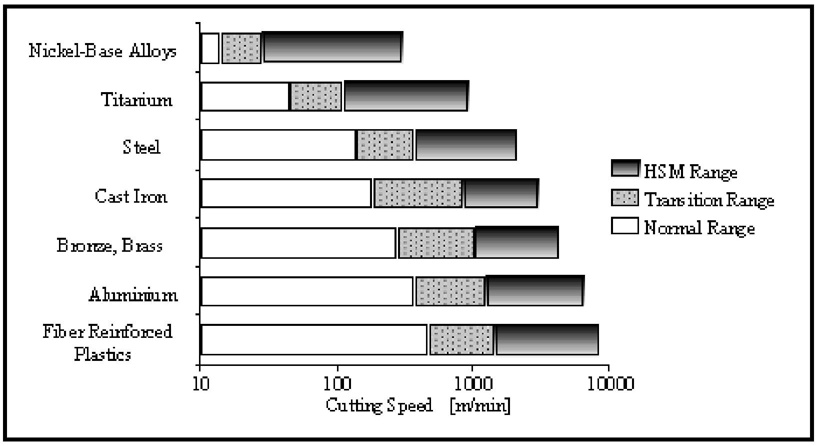

Figure 2: High speed machining cutting speeds range for various typical materials (Schulz and Moriwaki, 1992)

Last 10 years a constant innovation regarding manufacturing systems and specifically machining processes has been attended. Lots of advances can be summarized in the idea of approaching to a "more scientific machining" which means a machining process based on deep knowledge and not only on the use of tables, schemes and diagrams obtained from old and widely-known methodologies such as trial-error. Conjunction between experience and scientific knowledge has permitted to increase productivity and part quality of several manufacturing processes (López de Lacalle, et al., 2004). Markets pressure has stimulated the rising of new machining conceptions with increasing relevance (e.g. high speed machining, high performance cutting, high precision machining). Consolidation of these concepts in nowadays industry has been possible due to advances in process fundamentals, knowledge and, continuous innovations in materials, coatings, instrumentation, sensors and computers. The recent years trends seem to be focused on the on-line monitoring, measuring and controlling the machining process. Several kinds of sensors and signal processing techniques have been developed for the direct or indirect diagnosis of several aspects such as the workpiece condition e.g. surface roughness, integrity, and dimensional accuracy; detection of tool wear and breakage, chatter recognition, analysis of machine components condition, etc.

But, advancing has not been an easy task. Numerous and varied factors of high speed milling influence the quality of the final part and its manufacturing economy (Vivancos et al., 2005). Among these factors are the part and tool materials, the shape of the tool and the toolholder, the cutting conditions, the behaviour of the machine tool and the control performance, the type of interpolation used in generating CNC programmes and the use of refrigerants (Albertí et al., 2007). Moreover, operator plays still nowadays, an important role in the metal removal process and experience is a key factor Investigations have focused on the optimization of the machining time and quality considering the cutting parameters (Li et al., 2007), toolpath which can be linear, circular or polynomial interpolation (Helleno and Schützer, 2006; Schützer et al., 2006) machining strategies (Toh, 2005; Toh, 2006), cost (Albertí et al., 2005), tool wear and tool life (Fallbohmer et al., 2000; Ozel, 2003), the influence of toolholder (Albertí et al., 2007) and the effect of spray cutting fluids (Lopez de Lacalle et al., 2006). Amongst all these topics, chatter has been a principal matter of interest for the last decades. The dynamic behaviour of the system composed by the machine-tool, the toolholder, the cutting tool and workpiece material can be a critical issue when the frontier between stable and unstable cutting is very low. Chatter is still a common limitation for productivity and quality enhancement in metal removal processes and has motivated a great deal of research since the late 1950s when Tobias and Fishwick (1958) and Tlusty and Polacek (1963) developed the first theories explaining the uprising of chatter as a regenerative phenomenon. Later on, Merrit (1965) presented a feedback model explaining the system as a closed loop interaction between the structural dynamics and the cutting process. Very early on, it was observed that chatter arises given certain combinations of spindle speed and axial depth of cut. As a function of these two cutting parameters, the border between a stable cut, (i.e. without chatter), and an unstable one, (i.e. with chatter), can be visualised describing a lobbing effect frontier, in a chart called stability lobe diagram (SLD). Once the SLD is identified, it is possible to select optimal chatter-free cutting parameters while increasing material removal rates. For this reason, the identification of these diagrams has been and still is a valuable topic of academic and industrial research as will be explained in Chapter 2.

Machining is nowadays, after years and years of evolution, a mature production technique. Thanks to all these advances and despite all these limitations, machining (in particular, metal cutting) is still the fundamental manufacturing technique and it is expected to remain so for the next few decades. Moreover, it is predicted that ultra-precision machining will take an even more significant role among other manufacturing techniques. According to the *College International pour la Recherche en Productique* (CIRP), machining accounts for approximately half of all manufacturing techniques, which is a reflection of the achieved accuracy, productivity, reliability and energy consumption of this technique (Wiercigroch and Krivtsov, 2001b). López de Lacalle, Sánchez and Lamikiz give an interesting observation in their book entitled "Mecanizado de Alto Rendimiento", High Performance Cutting (López de Lacalle et al., 2004). They say that material removal processes are clearly anti-economic because money is spent to remove material from a part where money was previously spent to add material. For this reason, material removal processes can have, in the late future, an expiration date.

In fact, production systems are attending to the emergence of new concepts on manufacturing technologies. These new technologies can be used as alternatives or to complement HSM. These are Rapid Prototyping, Rapid Tooling and Rapid Manufacturing technologies that include techniques such as Dieless Forming, Direct Metal Laser Sintering (DMLS), Electrical Discharge Machining, (EDM) Electron Beam Melting (EBM), Fused Deposition Modelled (FDM), Selective Laser Sintering (SLS) and Stereolitography (SLA) (Ciurana et al., 2006). For sure, it will be interesting to observe the evolution and progresses of all these technologies the following years.

1.2 Interest and motivation

1st of February, 2006 University of Girona, UdG and ASCAMM Foundation signed a scientific collaboration agreement in the field of investigation and formation of researchers in innovative manufacturing technologies.

This Thesis is carried out on one hand, in the frame of the Research Group on Product, Process and Production Engineering (GREP) main research lines and on the other hand, in the context of ASCAMM Technology Centre research interests.

GREP, Research Group on Product, Process and Production Engineering (GREP, 2009) was set up in 1998 by University of Girona faculty members. The group is currently carrying out research on aspects related to the fields of the product, the process and the production. Concerning the product, GREP investigates to improve and to innovate the mechanical design of products and machines and the calculation of machine elements. Regarding the process, GREP works for selection and optimisation of the production process, development of CAPP applications (Computer Aided Process Planning), PPC applications (Production Planning Control) and the simulation of production processes. In the field of the production, GREP carries out research for production management systems improvement, design of computer tools for the improvement of production planning systems and introduction and maintenance of integrated management systems (quality, environment and health and safety).

GREP research interest focuses along the following lines:

- Design and introduction of a computer aided process planning (CAPP) system for planning and programming product manufacturing routes based on the technical characteristics (geometry, materials, etc.) of a given product (Albertí et al., 2005; Quintana et al., 2008; Quintana et al., 2009; Quintana et al., 2010; Quintana et al., 2008; Romeu and Ciurana, 2004).

- Study and introduction of production planning control (PPC) systems taking into account different management variables (work orders, stocks, machine loading, etc.) (Ciurana et al., 2003; Ciurana et al., 2006; Vidal et al., 2005).

- Integration of CAPP and PPC into a manufacturing firm taking into account technical parameters (implements, tools, etc.) and management parameters (programmed stops, tool changeovers, etc.) (Ciurana et al., 2003; Ciurana, Romeu et al., 2003; Ciurana et al., 2008; Quintana et al., 2007).

ASCAMM Technology Centre (ASCAMM, 2009) is located in Cerdanyola del Vallès (Barcelona). Was founded in 1987 by the Catalan Association of Dies and Moulds Makers and turned into a non-profit foundation in 1996 with the mission of helping industrial businesses to improve their competitiveness by technological innovation and knowledge transfer in the fields of industrial design and production, especially for plastic, metal and light alloy products and tooling.

ASCAMM Foundation participates in numerous Spanish and European R+D+i projects. Next Generation Production Systems, NEXT (Integrated Project IP-011815) involves 25 partners, 80 institutions and a budget of 24 M€ and is the biggest initiative ever undergone in Europe, in the production systems area. NEXT intends to determine the machines of the future and the sector's new business models that signify an important technological, industrial and social advance in Europe, so contributing to the transformation of the manufacturing industry is demanding faced with the new challenges that arise: delocalization, low manufacturing costs in emerging economies

The objective of the NEXT integrated project is to bring the manufacturing industry to new frontiers that make possible an important technological, industrial and social advance in Europe, through the development of a new generation of machines and new business models for the sector. NEXT is the only IP approved within the 6th R&D Framework Programme in the production area (Fatronik, 2009).

NEXT is structured in five objective-tracks: three technical tracks, one track for economic research and one track for education and dissemination:

- **Track 1 - Green Machine:** The aim is to get machines that consider environmental aspects through their entire life-cycle: use of recycled materials for machine elements (>50%), reduction of energy consumption (25% at least) at machine use, zero waste produced, dismantling and recycling of 100% machines and working in non-pollutant machining processes.

- **Track 2 - User-centric Autonomous Machine:** Establishing the base of a new generation of autonomous and "user-friendly" machines that will support a much more efficient and comfortable way of working (e.g. automatic recognition of manufacturing tasks and process conditions, ergonomic aspects, improve maintenance aspects).

- **Track 3 - Manufacturing Breakthrough:** Process oriented high performance production equipment. Design and build the most excellent process-controlled production machines. The aim is to get up to 5x improvement in machine productivity, as well as an order of magnitude improvement in machine accuracy, compared to current available machines.

- **Track 4 - Economic Objective:** Machine tool users are increasingly demanding a full life cycle service from their suppliers. This Track objective is to provide powerful new business models to support a full collaboration service between end users and machine tool builders characterised by: innovative value propositions, organisational changes, payment and financing methods related to output and availability, customised machine system configurations. Companies aiming to improve significantly their global competitiveness will have a set of customised tools and methods to develop and support their strategic business relationships.

- **Track 5 - Dissemination and Training Objective:** The dissemination task will target both academic and professional training, by the generation of new contents arising from the research and establishing the means to reach the target audiences, focusing specially in machine using and building SME's all over Europe. Transferring the research results to interested industrial partners, both users and producers of machines, where training and skill development will be provided.

1.3 Objectives

Once introduced the general domain of this Thesis, presented the historical and conceptual frames and, exposed the interest and motivation of this work; the objectives of this Thesis are established. They arise with the exposed limitations and trends of the nowadays metal removal sector and GREP and ASCAMM interests and are twofold. First, regarding the chatter problem, it provides two experimental methodologies for identifying the stability lobe diagram in milling operations. Secondly, concerning the monitoring and diagnosis trends, it focuses on surface roughness generation in ball end milling operations and a surface roughness monitoring application is developed based on artificial neural networks.

Machine tool operators often select conservative cutting parameters for several reasons, such as, avoiding chatter occurrence, ensuring quality requirements and avoiding to dump non-valid final parts having to restart the manufacturing process with the looses in time, energy and money that entails.

The first objective of this Thesis deals with the great relevance of chatter in nowadays industrial and academic research. In spite of the huge amount of investigation carried out regarding the chatter problem, in small workshops operators are still not used, for several reasons, to apply the existent methodologies designed to reduce, suppress or avoid the chatter occurrence and its negative consequences. There is an important lack of knowledge, in workshops, regarding chatter troubles. Operators are not familiar with large analytical methods. These methodologies are usually too much sophisticated and operators are not enough prepared to apply them. Modal examination requires trained personnel to perform tests, validate data and interpret frequency response functions. Although exist several efficient approaches that offer good SLD predictions the frequency response functions generation is not always easy especially in the case of small tools testing because it is difficult to correctly strike the tool. Moreover, in most of cases workshops are not capable or simply do not consider to acquire the necessary equipment to perform modal tests (i.e. impact hammers, piezoelectric transducers, software, sensors, etc.). For these reasons, it seems especially interesting to develop simple experimental methodologies to be easily applied in small and medium-sized workshops without the mentioned restrictions.

The second objective deals with the rising needs of ensuring surface quality in terms of roughness average while maintaining or increasing productivity. It is highly demanded in metal cutting production and a topic in constant evolution. For this reason it has been interesting for ASCAMM to carry out this investigation inside the NEXT generation production systems project. Surface roughness has a great influence on several mechanical characteristics of finished parts such as dimensional accuracy, friction coefficient, wear, thermal and electric resistance, fatigue limit, corrosion, post-processing requirements, appearance and cost. It is widely used as an index of quality and a technical requirement in mechanical products and is usually measured off-line when the part is already machined and time, energy and money have been spent on it. For these reasons, thanks to advances in computers and sensors, it seems especially interesting to develop an application for surface roughness monitoring in milling operations. With this application, production and quality control can be carried out simultaneously maximizing productivity and ensuring quality requirements.

Achieving the objectives established will permit machine tools operators to improve the parameters selection optimizing productivity while ensuring quality requirements.

Chapter 2. State of the art

Chapter 2 reviews the fundamentals of metal cutting mechanics, machine tool vibrations, surface topography generation and artificial neural networks. Mechanics of two-dimensional orthogonal cutting is introduced first. The laws fundamental chip formation and friction between the rake and flank faces of a tool during the cutting are explained. Then, are reviewed the generalities of free, forced and self-excited (i.e. chatter) vibrations. After that, the complexities of surface topography generation are exposed and the main research works on this topic reviewed.

2.1 Fundamentals of metal cutting

The final shapes of most mechanical parts are obtained by machining operations. Bulk deformation processes, such as forging and rolling, and casting processes are mostly followed by a series of metal removing operations in order to achieve parts with desired shapes, dimensions, and surface finish quality. The cutting operations are used to remove material from the blank. The subsequent grinding operations provide a good surface finish and precision dimensions to de part. The most common cutting operations are turning, milling, and drilling followed by special operations such as boring, broaching, hobing, shaping, and form cutting. However, all metal cutting operations share the same principles of mechanics, but their geometry and kinematics may differ from each other (Altintas, 2000).

Several relevant authors review the fundamentals of metal cutting in their publications (Altintas, 2000; Ganguli et al., 2005b; Kalpakjian and Schmid, 2001; López de Lacalle, et al., 2004; Tlusty, 2000; Wiercigroch and Budak, 2001).

In general, the cutting process is a result of the dynamic interactions between the machine tool, the cutting tool and the workpiece. Therefore, its mathematical description should take into account its kinematics, dynamics, geometry of the chip formation and workpiece mechanical and thermo-dynamical properties. Mechanics of the cutting process and chip formation is recognized even more now than ever before as the key issue in the development of machining technologies. The complexity of the cutting process is due to the interwoven physical phenomena such as elasto-plastic deformations in the cutting zones, variable friction between the tool and the chip and the workpiece, heat generation and transfer, adhesion and diffusion, and material structural and phase transformations, to name but a few (Wiercigroch and Budak, 2001).

Although cutting operations are commonly three dimensional and geometrically complex, the simple case of two-dimensional orthogonal cutting is usually used to explain the general mechanics of metal removal. In orthogonal cutting, material is removed by a cutting tool that is perpendicular to the direction of relative tool-workpiece motion.

Figure 3 shows schematic representations of orthogonal and oblique cutting processes where the cutting velocity (v) is perpendicular to the cutting edge in orthogonal cutting, whereas in oblique cutting, it is inclined at an acute angle to the plan normal to the cutting edge (Altintas, 2000).

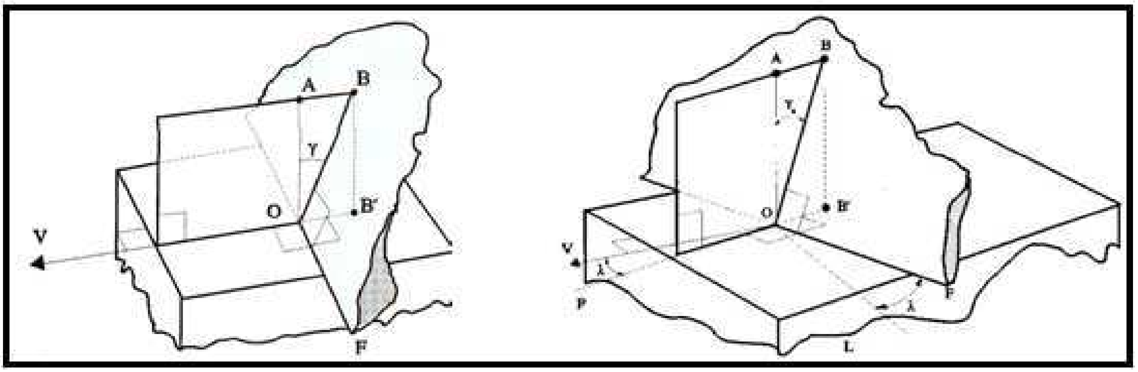

Figure 3: Geometries of orthogonal and oblique cutting processes.

Three deformation cutting zones are distinguished in the chip generation process (Figure 4):

- **Primary shear zone:** As the edge of the tool penetrates into the workpiece, the material ahead of the tool is sheared over the primary shear zone to form a chip.

- **Secondary shear zone:** The shared material, the chip, partially deforms and moves along the rake face of the tool, which is called the secondary deformation zone or secondary shear zone.

- **Tertiary zone:** Is the friction area, where the flank of the tool rubs the newly machined surface.

Along the twentieth century researchers have tried to develop an adequate model to explain metal removal phenomena and predict three fundamental aspects: chip shape, forces and cutting temperatures. However nowadays does not exist a totally accepted model (López de Lacalle, et al., 2004).

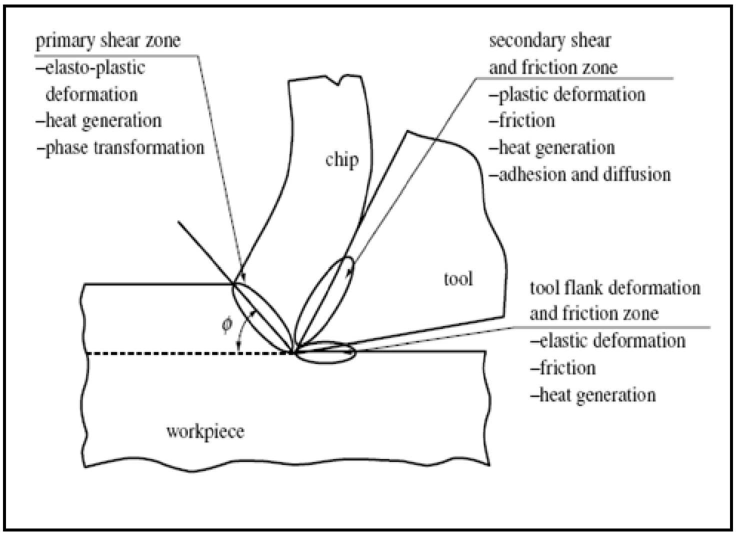

Figure 4: Deformation zones and physical phenomena. Source: (Wiercigroch and Budak, 2001)

One basic model of chip formation was developed by Merchant (1944). Merchant's force diagram is an orthogonal cutting model that assumes the shear zone to be a thin plane. This circle is restricted to a model of orthogonal two-dimensional metal cutting (see Figure 5).

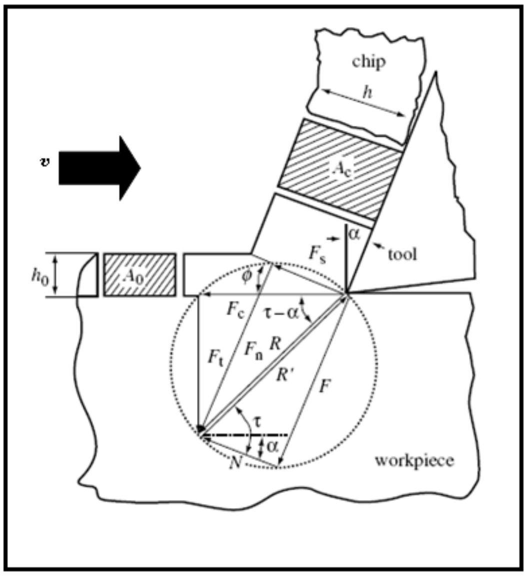

Figure 5: Merchant's force diagram. Source: (Merchant, 1944)

Where,

v: cutting velocity

F_c: cutting force

F_t: thrust force

F_s: shearing force

F: friction force

F_n: normal shear force

N: normal force to the rake face

R: resultant force coming from the workpiece and action on the chip

R': resultant force coming from the cutting tool (compensated by R)

Φ: shear angle

α: rake angle

τ: friction angle

h: chip width

h_0: initial depth of cut

Cutting parameters such as feed, cutting velocity and depth of cut have a relevant influence on the chip formation mechanism. Any change in these parameters modifies instantaneously the value of the normal force (N), the friction force (F) and the relative velocity between the chip and the workpiece (**v**) effecting the dynamics of the system (Wiercigroch and Budak, 2001).

The important force relationships derivable from the geometry of Figure 5 are:

$$\mu = \frac{F}{N} = \tan\tau \qquad \text{Eq. 1}$$

Where, μ is the friction coefficient between the chip and the tool.

The resultant force coming from the workpiece (R) is compensated by the resultant force coming from the cutting tool (R') and is formed from the cutting (F_c) and thrust (F_t) forces.

$$R = R' = \sqrt{F_c^{\,2} + F_t^{\,2}} \qquad \text{Eq. 2}$$

$$R = R' = \sqrt{F_c^{\,2} + F_t^{\,2}} \qquad \text{Eq. 3}$$

$$F = F_t \cos\alpha + F_c \sin\alpha \qquad \text{Eq. 4}$$

$$F_s = F_c \cos\phi - F_t \sin\phi \qquad \text{Eq. 5}$$

The key variable in Merchant's approach is the shear angle, Φ. By knowing this angle and a few constant process parameters, the force R can be calculated from,

$$R = \frac{F_s}{\cos(\tau - \alpha + \phi)} \qquad \text{Eq. 6}$$

Where $F_s = \sigma_s A_s$ and A_s is the cross-section of the shear plane, σ_s is the shear flow stress and α and τ are the rake and friction angles, respectively. The cross-section can be also expressed in terms of the shear angle (Φ) as $A_s = {wh_0}/{\sin\phi}$, which leads to:

$$R = \frac{\sigma_s w h_0}{\cos(\tau - \alpha + \phi)\sin\phi} \qquad \text{Eq. 7}$$

This leads to the following equations to evaluate the cutting and thrust forces:

$$F_c = R\cos(\tau - \alpha) = \frac{\sigma_s w h_0 \cos(\tau - \alpha)}{\cos(\tau - \alpha + \phi)\sin\phi} \qquad \text{Eq. 8}$$

$$F_t = R\sin(\tau - \alpha) = \frac{\sigma_s w h_0 \sin(\tau - \alpha)}{\cos(\tau - \alpha + \phi)\sin\phi} \qquad \text{Eq. 9}$$

Merchant's approach assumes that the cutting-process mechanics can be entirely explained by the shear angle (Φ). The optimum shear angle (Φ) is calculated following the principle of minimum energy.

$$\phi = \frac{1}{4}\pi - \frac{\tau}{2} + \frac{\alpha}{2} \qquad \text{Eq. 10}$$

Merchant developed an elegant model based on the shear angle (Φ) and despite of the fact that this approach has not correlated too well with the experimental results, this research left a significant impact in the field (Wiercigroch and Budak, 2001).

2.2 Machine tools vibrations

2.2.1 Generalities

Stephen Albert Tobias (Tobias, 1961) exposes in May 1961 in the preface of his book *Schwingungen an Werkzeugmaschinen*: “Machine tool development in recent decades has created an increasing number of vibration problems. Machine tool designers in early development phases are worried about vibration characteristics; production engineers know that vibrations diminish tool life, generate unacceptable surface finish of the parts and which results in a reduction of productivity”.

Nowadays, authors persist in referring to vibrations as a limiting factor, one of the most important machining challenges and of course, an aspect to be improved:

- Machine tool vibrations play an important role in hindering productivity during machining. Excessive vibrations accelerate tool wear and chipping, cause poor surface finish, and may damage the spindle bearings (Altintas, 2000).

- High-speed machining increased working speeds and accelerations produce excitation of oscillations and cause dynamic problems. These problems affect the tool life (tool wear and tool failure), produce shoddy end surface, reduce productivity, produces scrap parts and affect the environment (Solis et al., 2004).

But vibration phenomena have been observed, analyzed and used since very ancient times. Vibration knowledge appeared jointly with everyday vibration experiences such as sounds, music or pendulum oscillations and was limited by knowledge about mechanics, mathematics, physics and technology development of the moment. In the ancient world, there was substantial progress in vibration theory and an extended understanding of the basic principles of natural frequency, vibration isolation, vibration measurements, and resonance and sympathetic vibrations, with very limited use in engineering. This body of knowledge had very limited use, however, due to the low level of production technology and machinery speeds. Moreover, many branches of mathematics were already extensively developed, but calculus and computational mathematics were at too early a stage to allow for analytical treatment of vibration (Dimarogonas, 1996). For these reasons, first investigations referring machine tool vibrations and instabilities appeared at the beginning of the 20th century as the result of metal removal processes improvement. In the 20th century machine tools experienced a considerable evolution to become more powerful, precise, rigid and automatic. This fact was stimulated by the general industry development especially in the case of, aerospace, moulds and automotive industries with, for instance, the mass production of the Ford T in 1908 (Aldabaldetrecu, 2006). But with all these improvements in the manufacturing sector, it appeared also, new limitations and challenges. Machines and structures are not rigid bodies, but rather, are systems of elastic components that respond to external of internal forces with finite deformations. In addition, there are relative motions between the components, giving rise to internal forces. Due to these internal and external forces, the machine or structure moves. This motion, as a result of internal and external forces, is subject of dynamics and vibration (Seto, 1970).

Metal cutting processes can entail three different types of mechanical vibrations that arise due to the lack of dynamic stiffness of one or several elements of the system composed by the machine tool, the tool holder, the cutting tool and the workpiece material. These three types of vibrations are known as free vibrations, forced vibrations and self-excited vibrations (Tobias, 1961). Free vibrations occur when the mechanical system is displaced from its equilibrium and then is allowed to vibrate freely. In metal removal operations, free vibrations appear, for example, due to a collision between the cutting tool and the workpiece because of an incorrect tool path definition. Forced vibrations appear due to external harmonic excitations associated, for example, with unbalanced bearings or cutting tools or also can be transmitted by other machine-tools through the workshop floor. Free and forced vibrations can be avoided, reduced or eliminated when the cause of vibration is identified. Engineers have developed and can implement several different widely known methodologies to mitigate and reduce their occurrence. Self-excited vibrations extract the energy to start and grow from the interaction between the cutting-tool and the workpiece during the machining process. This type of vibration brings the system to instability and is the most undesirable and the least controllable vibration. For this reason, chatter has been a popular topic for academic and industrial research. In the following section are introduced the chatter generalities and are compiled the main advances and developments carried out with the aim of preventing, avoiding, reducing, suppressing or controlling its occurrence.

2.2.2 Chatter vibrations in cutting

From the very beginning, metal cutting has had one troublesome problem in increasing productivity and accuracy, namely chatter. In 1907, Taylor stated that chatter is the “most obscure and delicate of all problems facing the machinist” (Taylor, 1907). Chatter is a self-excited vibration that can occur during machining operations and becomes a common limitation to productivity and part quality. This phenomenon has several negative effects such as:

- Poor surface quality,
- Unacceptable inaccuracy,
- Excessive noise
- Disproportionate tool wear,
- Machine tool damage,
- Reduced material removal rate (MRR),
- Increased costs in terms of production time,
- Waste of materials,
- Waste of energy,

- Environmental impact of dumping non-valid final parts and having to repeat the manufacturing process.

Chatter is almost unavoidable specially in those cases where long slender end mills or highly flexible thin-wall parts, such as air-frame or turbine engine components, are involved (Wiercigroch and Budak, 2001). In workshops, machine tool operators often select conservative cutting parameters to avoid chatter occurrence. This common practice usually results in a productivity decrease. Chatter is a highly complex phenomenon due to the rotating tool, multiple cutting teeth, periodical cutting forces and chip load directions in multi-degree-of-freedom structures. Predicting its occurrence is still the subject of much research, even though the regenerative effect, the main cause of chatter, was identified more than 50 years ago. It is well established that the occurrence of chatter is dependent on three factors: cutting conditions, work piece material properties and the dynamics of machine tool system (Movahhedy and Gerami, 2006). Chatter can occur in milling operations, but also in other machining processes such as in turning (Al-Regib et al., 2003; Baker and Rouch, 2002; Chiou and Liang, 1998; Chiou and Liang, 2000; Clancy and Shin, 2002; Deshpande and Fofana, 2001; Devillez and Dudzinski, 2007; Olgac and Hosek, 1998; Pan et al., 1996; Rao and Shin, 1999; Tansel et al., 2006; Tarng et al., 2000), drilling (Arvajeh and Ismail, 2006a; Arvajeh and Ismail, 2006b; Dilley et al., 2005; Ema and Marui, 2003; Roukema and Altintas, 2006), boring (Atabey et al., 2003; Edhi and Hoshi, 2001; Ema and Marui, 2000; Wang and Fei, 1999; Wang and Fei, 1999; Wang and Fei, 2001), broaching (Axinte et al., 2004) and grinding (Gonzalez-Brambila et al., 2006; Gradisek et al., 2003; Mannan et al., 1999). However, this Thesis focuses in the chatter occurrence in milling processes.

2.2.2.1 Chatter mechanisms

Nowadays, chatter is classified in two categories: primary and secondary chatter. Primary chatter can be caused by the cutting process itself (i.e. by the friction between tool and workpiece, by thermo-mechanical effect on the chip formation or by mode coupling). Secondary chatter may be caused by the regeneration of waviness of the workpiece surface. This is the so-called regenerative chatter and is the most important cause of chatter So that, depending on the chatter mechanism, it is possible to distinguish between frictional chatter, thermo-mechanical chatter, mode coupling chatter and regenerative chatter (Faassen, 2007).

- ***Frictional chatter*** occurs when rubbing on the clearance face excites vibration in the direction of the cutting force F_c and limits in the thrust force F_t direction (Wiercigroch and Krivtsov, 2001a; M. Wiercigroch and Krivtsov, 2001b).

- ***Thermo-mechanical chatter*** occurs due the temperature and strain-rate in the plastic deformation zone (Wiercigroch and Budak, 2001).

- ***Mode coupling chatter*** exists if vibration in the thrust force direction generates vibration in the cutting force direction and vice versa (Tlusty and Polacek, 1963; Tlusty, 2000; Tobias, 1961). This results in simultaneous vibration in the cutting and thrust force directions. Physically, it is caused by a number of sources such as friction on the rake and clearance surfaces, chip-thickness variation, shear angle oscillations and regeneration effect (Wiercigroch and Budak, 2001).

- ***Regenerative chatter*** is the most common form of self-excited vibration. It can occur often as the majority of metal cutting operations involve overlapping cuts which can be a source of vibrations amplification. Due to the cutter vibrations a wavy surface is left on the surface (See Figure 6). In milling the next tooth in cut attacks this wavy surface and generates a new wavy surface. The chip thickness hence, the force on the cutting tool varies due to the phase difference between the wave left by the previous teeth (in turning is the surface left in the previous revolution) and the wave left by the actual one (Altintas, 2000; Foulds and Neumann, 2003; M. Wiercigroch and Budak, 2001). This phenomenon can greatly amplify vibrations becoming dominant and building up chatter (Faassen et al., 2003). Figure 7 shows the phase difference influence on the chip thickness (R. P. H. Faassen, 2007). If the relative phase difference is zero, the dynamic chip thickness is also zero (Figure 7a). If the relative phase is π, the dynamic chip thickness variation is maximum (Figure 7c). Consequently, the force on the cutter depends, amongst others, on the displacement of the previous tooth.

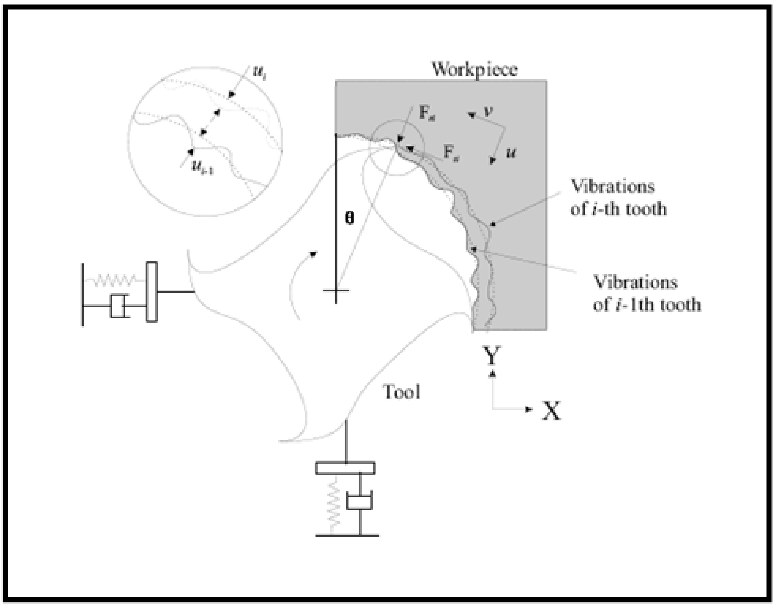

Figure 6: Regeneration of waviness in a milling model. Source: (Ganguli et al., 2005a)

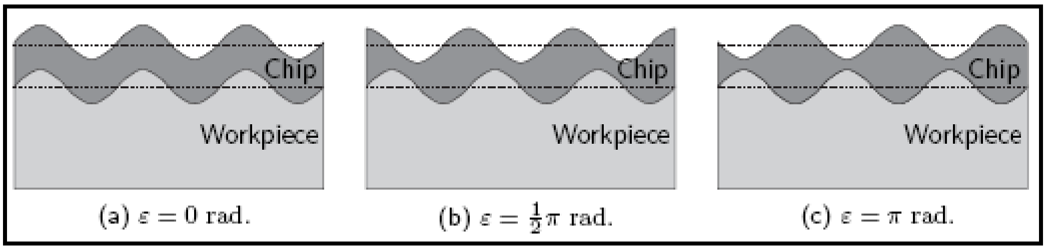

Figure 7: Effect of phase of subsequent tooth passing on chip thickness. Source: (Faassen, 2007)

2.2.2.2 Stability lobe diagrams

The border between a stable cut (i.e. no chatter) and an unstable cut (i.e. with chatter) can be visualized in terms of the axial depth-of cut as a function of the spindle speed. This is a stability lobes diagram (SLD), see Figure 8. Using these diagrams it is possible to find the specific combination of machining parameters, which results in the maximum chatter-free material removal rate (Faassen et al., 2003). The idea is to seek regions of stability within lobes as shown in Figure 8 taking advantage of the lobbing effect.

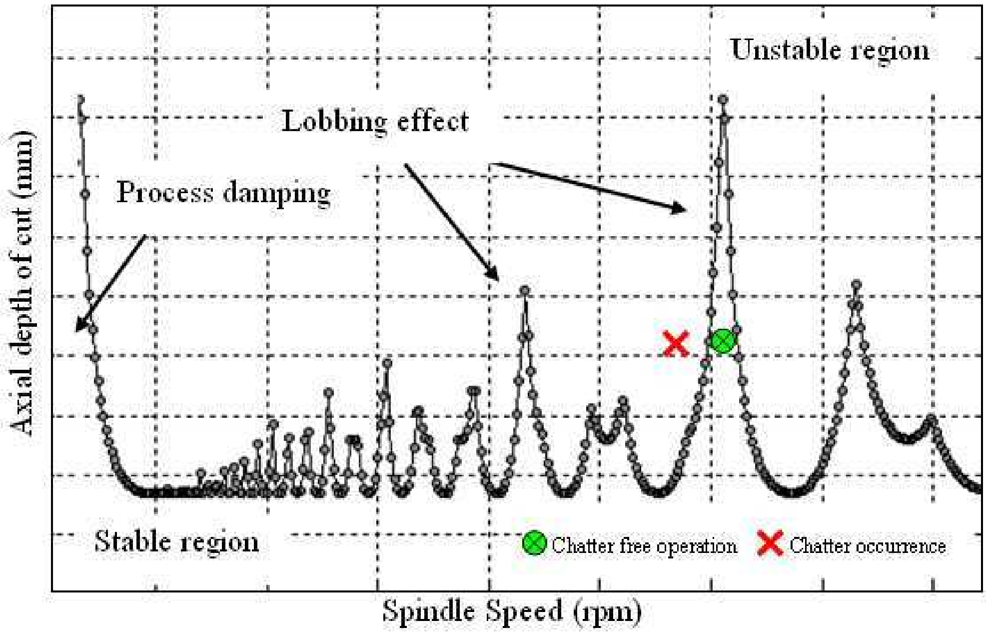

Figure 8: Stability lobes diagram.

At high speeds, the stabilizing effect of process damping diminishes, making the process more prone to chatter (See Figure 8). Process damping usually occurs at low spindle speeds and provides stability due to the short undulations left on the part's surface by high-frequency vibrations. These surface waves interfere with the cutting tool flank face and dampen the cutting tool vibration.

The construction of a SLD requires previous information about, for example, the frequency response function, FRF, of a cutting tool, tool holder, machine tool and workpiece material combination. But modelling the milling process for identifying the SLD is not an easy task due to the multi-degree-of-freedom structures, multiple cutting teeth, variable cutting forces and chip-load directions complicate the analysis and the calculation. Next is briefly introduced a well-known analytical model for chatter prediction provided by Altintas and Budak (1995). This method, known as zeroth order approximation (ZOA), makes stability predictions using the zeroth order Fourier term to approximate the cutting force variation and can achieve reasonably accurate SLD predictions for processes where the cutting force varies relatively little, i.e. considerable radial immersions and large number of teeth. First, is provided a milling model, then, the cutting forces formulation and, finally, the chatter limits calculation.

Figure 9 shows a schematic representation of the milling process considering 2 degrees of freedom, 2DOF. Cutting forces affect the structure in the feed (X) and normal (Y) directions, causing dynamic displacements in *x* and *y*, respectively. Considering ϕ_j the instantaneous angular immersion of tooth *j*, as shown in Figure 9, and a spindle angular speed of Ω (rad/s), the immersion angle varies with time as $\phi_j(t) = \Omega t$. The resulting chip thickness Eq. 11 consists of a static part $[st\sin\phi_j(t)]$, attributed to rigid body motion of the cutter (*st* is the feed rate per tooth), and a dynamic component caused by the vibrations of the tool at the present tooth period $[-x(t)\sin\phi_j(t) - y\cos\phi_j(t)]$ and the previous tooth period $[-x(t-T)\sin\phi_j(t) - y(t-T)\cos\phi_j(t)]$.

$$h(\phi_j) = st\sin\phi_j(t) - [-x(t)\sin\phi_j(t) - y\cos\phi_j(t)] + [-x(t-T)\sin\phi_j(t) - y(t-T)\cos\phi_j(t)] \quad \text{Eq. 11}$$

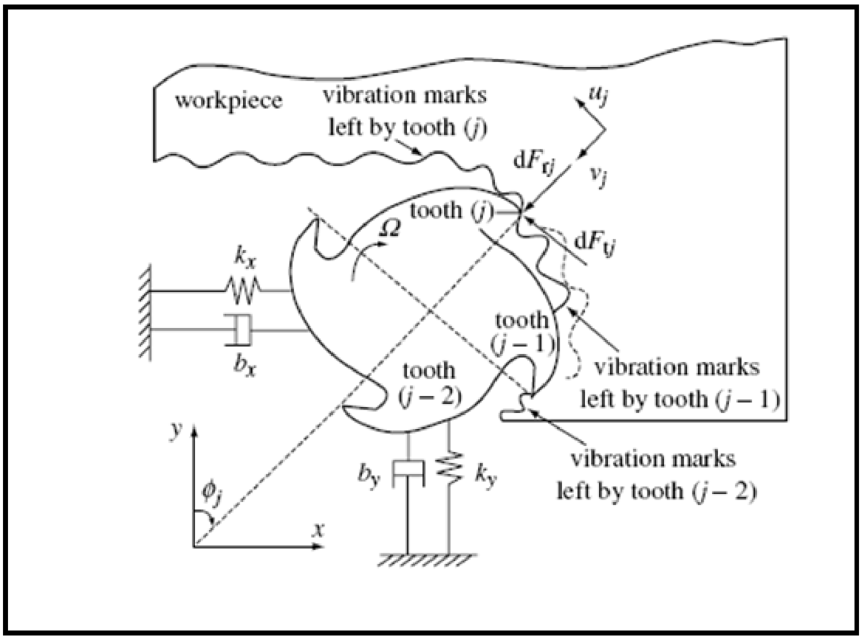

Figure 9: Cross sectional view of an end mill. Source: (Altintas, 2000)

The static component of the chip thickness $st\sin\phi_j(t)$ is removed from Eq. 11 because it does not contribute to the dynamic chip load regeneration mechanism. Considering ($\Delta x = x - x_0$) and ($\Delta y = y - y_0$) where (x,y) and (x_0,y_0) represent the dynamic displacements of the cutter structure at the present and previous tooth periods, respectively. The function $g(\phi_j)$ is a unit step function that determines whether the tooth is in or out of cut.

$$h(\phi_j) = [\Delta x \sin\phi_j + \Delta y \cos\phi_j]\, g(\phi_j) \qquad \text{Eq. 12}$$

The tangential (F_{tj}) and radial (F_{rj}) cutting forces action on the tooth j are proportional to the axial depth-of-cut (a) and chip thickness (h). Cutting coefficients K_t and K_r are constant.

$$F_{tj} = K_t a h(\phi_j) \qquad \text{Eq. 13}$$

$$F_{rj} = K_r F_{tj} \qquad \text{Eq. 14}$$

After resolving the cutting forces in the *x* and *y* directions, summing the cutting forces contributed by all teeth and expanding into Fourier series the resulting time domain expression, the dynamic milling expression is reduced to the following.

$$\left[F(t)\right] = \frac{1}{2} a K_t \left[A_0\right]\left[\Delta(t)\right] \qquad \text{Eq. 15}$$

This approach uses the average component of the Fourier series expansion in [A_0] which is valid only between the entry (ϕ_{st}) and exit (ϕ_{ex}) angles of the cutter (i.e., $g(\phi_j) = 1$) and the cutter pitch angle $\phi_p = 2\pi / N$ being N, the number of teeth.

$$\left[A_0\right] = \frac{1}{\phi_p} \int_{\phi st}^{\phi ex} \left[A(\phi)\right] d\phi = \frac{N}{2\pi} \begin{bmatrix} \alpha_{xx} & \alpha_{xy} \\ \alpha_{yx} & \alpha_{yy} \end{bmatrix} \qquad \text{Eq. 16}$$

Where the integrated functions of the time-invariant but immersion-dependent directional cutting coefficient matrix [A_0] are,

$$\alpha_{xx} = \frac{1}{2}\left[\cos 2\phi - 2K_r\phi + K_r \sin 2\phi\right]_{\phi_{st}}^{\phi_{ex}} \qquad \alpha_{yx} = \frac{1}{2}\left[-\sin 2\phi + 2\ \ \phi + K_r \cos 2\phi\right]_{\phi_{st}}^{\phi_{ex}}$$

$$\alpha_{xy} = \frac{1}{2}\left[-\sin 2\phi - 2\phi + K_r \cos 2\phi\right]_{\phi_{st}}^{\phi_{ex}} \qquad \alpha_{yy} = \frac{1}{2}\left[-\cos 2\phi - 2K_r\phi - K_r \sin 2\phi\right]_{\phi_{st}}^{\phi_{ex}}$$

The use of the average Fourier coefficient [A_0] shows good agreement for cutters with a large number of teeth and considerable radial immersions. For cutters with few teeth and low radial immersions a prohibitively number of Fourier terms is needed to capture the cutting force variation.

The chatter-free boundary (i.e. SLD) is usually presented in a chart of the maximal depth of-cut vs. spindle speed. Once identified the transfer function matrix $[\phi(i\omega)]$ between the cutter-workpiece in the contact zone,

$$[\phi(i\omega)] = \begin{bmatrix} \phi_{xx}(i\omega) & \phi_{xy}(i\omega) \\ \phi_{yx}(i\omega) & \phi_{yy}(i\omega) \end{bmatrix} \qquad \text{Eq. 17}$$

Where $\phi_{xx}(i\omega)$ and $\phi_{yy}(i\omega)$ are the direct transfer functions in the x and y directions and $\phi_{xy}(i\omega)$ and $\phi_{yx}(i\omega)$ are the cross transfer functions. Defining the dynamic milling equation in the frequency domain as,

$$[F]e^{i\omega_c t} = \frac{1}{2} aK_t \left[1 - e^{-i\omega_c T}\right][A_0][\phi(i\omega_c)][F]e^{i\omega_c t} \qquad \text{Eq. 18}$$

Which has a nontrivial solution if its determinant is zero:

$$\det\left[[I] - \frac{1}{2} aK_t (1 - e^{-i\omega_c T})[A_0][\phi(i\omega_c)]\right] = 0 \qquad \text{Eq. 19}$$

And simplifying the notation by defining the oriented transfer function matrix as,

$$[\phi_0(i\omega_c)] = \begin{bmatrix} \alpha_{xx}\phi_{xx}(i\omega_c) + \alpha_{xy}\phi_{yx}(i\omega_c) & \alpha_{xx}\phi_{xy}(i\omega_c) + \alpha_{xy}\phi_{yy}(i\omega_c) \\ \alpha_{yx}\phi_{yx}(i\omega_c) + \alpha_{yy}\phi_{yx}(i\omega_c) & \alpha_{yx}\phi_{yy}(i\omega_c) + \alpha_{yy}\phi_{yy}(i\omega_c) \end{bmatrix} \qquad \text{Eq. 20}$$

And the eigenvalue of the characteristic equation as,

$$\Lambda = \Lambda_R + \Lambda_I = \frac{N}{4\pi} aK_t (1 - e^{-i\omega_c T}) \qquad \text{Eq. 21}$$

The resulting characteristic equation becomes,

$$\det\left[[I] + \Lambda[\phi_0(i\omega_c)]\right] = 0 \qquad \text{Eq. 22}$$

And the final expression for chatter-free axial depth of cut is for a given chatter frequency ω_c is,

$$a_{\lim} = -\frac{2\pi\Lambda_R}{NK_t}(1+\kappa^2) \qquad \text{Eq. 23}$$

Considering two orthogonal degrees of freedom in feed (X) and normal directions (i.e. $\phi_{xy} = \phi_{yx} = 0$), the eigenvalue is calculated as a quadratic function.

$$a_0\Lambda^2 + a_1\Lambda + 1 = 0$$ Eq. 24

Where,

$$a_0 = \phi_{xx}(i\omega_c)\phi_{yy}(i\omega_c)(\alpha_{xx}\alpha_{yy} - \alpha_{xy}\alpha_{yx}),$$
$$a_1 = \alpha_{xx}\phi_{xx}(i\omega_c) + \alpha_{yy}\phi_{yy}(i\omega_c).$$

And,

$$\kappa = \frac{\Lambda_I}{\Lambda_R} = \frac{\sin\omega_c T}{1-\cos\omega_c T}$$ Eq. 25

The corresponding spindle speeds (n) are found as following,

$$T = \frac{1}{\omega_c}(\in + 2k\pi) \rightarrow n = \frac{60}{NT}$$ Eq. 26

Thus, once identified the transfer function (FRF) of the machine tool system, the SLD can be calculated for a specified cutter, workpiece material and radial immersion and the workshop operator can select combinations of axial depth-of-cut and spindle speed that ensure chatter-free operations.

This analytical method for stability lobes prediction was enhanced by Altintas to a three dimensional model (Altintas, 2001).

2.2.3 Strategies for ensuring stable machining processes

In general, researchers talk about *detecting, identifying, avoiding, preventing, reducing, controlling, or suppressing* chatter occurrence. The revision of the great deal of literature regarding the chatter problem brings to classify the several existing methodologies into two main groups.

The first main group is composed by all those methodologies that are based on ensuring a stable machining process by selecting cutting parameters combinations in the stable zone of the SLD and making the most of the lobbing effect. The second main group includes those methodologies that try to avoid chatter occurrence by modifying the stability frontier through changing the system behaviour.

Figure 10 presents the main lines of research on chatter vibrations.

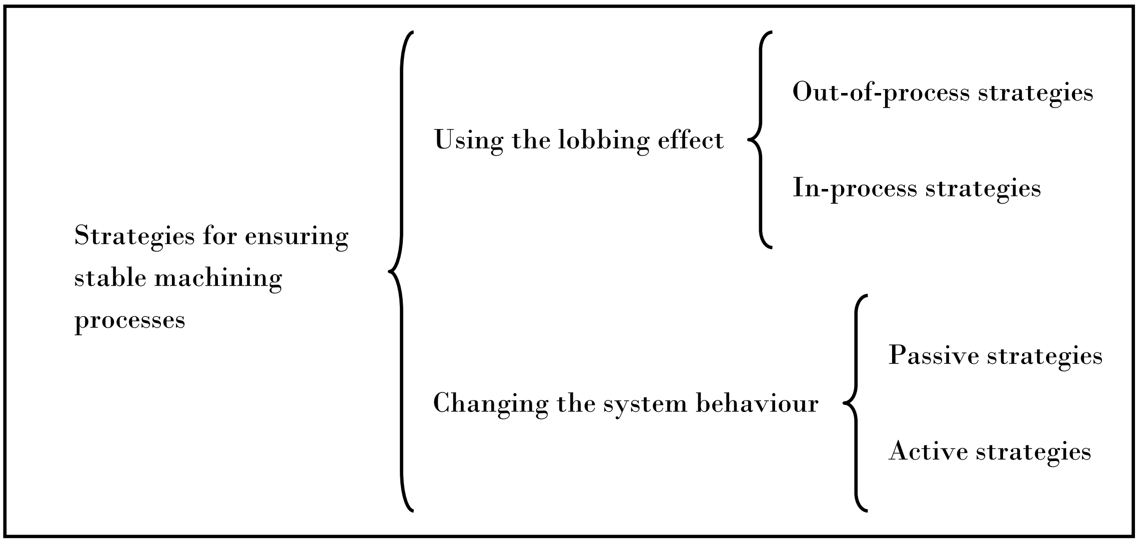

Figure 10: Research lines focussed on chatter vibration.

Regarding the first main group, it is possible to distinguish between the out-of-process and the in-process methodologies. The first subcategory includes those methods that pretend to predict the situation of the stability boundary of the cutting process to select stable cutting parameters combinations. The SLD identification is done out-of-process before the beginning of the manufacturing process. The second subcategory includes those methods that permit to detect chatter during the metal cutting process to correct the parameters. In the former case is required to calculate the stability frontier before the beginning of the machining operation. In the second one, it is necessary to identify chatter occurrence in-process, as soon as the phenomenon arises, to modify the cutting parameters until a stable cut is ensured.

Concerning the second main group, it is possible to distinguish between the passive and active methodologies. The first subcategory is composed by those strategies that are based on modifying certain machine tool elements to passively change the behaviour of the system composed by the machine-tool, the cutting-tool and toolholder. The second subcategory includes those methodologies that are based on certain elements capable to modulate the quantity of work provided, absorbing or supplying energy with the aim of actively raising or, at least, changing, the stability frontier.

In the following sections are presented in more detail the chatter research lines.

2.2.3.1 Out-of-process strategies for stability lobe diagram identification

This research line is focused on avoiding chatter phenomenon without modifying the characteristics of the system composed by the machine-tool structure, the tool holder and cutting tool. The aim is to select optimal cutting parameters by seeking stable regions between the lobes of the stability chart. At low spindle speeds the stabilizing effect of the process damping is dominant and chatter, usually, does not appear. At higher spindle speeds, the effect of process damping diminishes but the stability limits are higher which can be used to substantially increase the chatter-free material removal rate. The main requirement to be able to carry out this strategy is to identify the complete SLD or, at least, the SLD in the working speeds range.

To identify the SLD it is necessary to predict or model the system behaviour by characterising or simulating the response of the machine tool, tool holder, cutting tool system.

The first approaches, as mentioned in previous sections, were presented by Tobias and Fishwick (1958) and Tlusty and Polacek (1963). They identified the regeneration mechanism and developed mathematical models in form of delay differential equations (DDEs). Merrit (1965) presented a feedback model of the system, explaining it as a closed loop interaction between the structural dynamics and the cutting process. The zeroth order approximation method of Altintas and Budak (Altintas and Budak, 1995; Altintas, 2000) presented in the previous section is an indispensable reference, however, other researchers have attempted to predict SLD using analytical methods. Insperger and Stépán (2002 and 2004) applied the semidiscretization (SD) method, to convert the DDE into a series of autonomous ordinary differential equations (ODEs) with known solutions. Gradišek et al. (Gradisek et al., 2005) compared the stability boundaries predicted by ZOA and SD methods and stated that the two methods obtain similar predictions of SLD for high radial immersions but, for low radial immersions, predictions present considerable differences. Analytical investigations led to the implementation of the bifurcation methods, i.e. Hopf bifurcation and period doubling or Flip bifurcation, for stability prediction in milling (Fofana, 2002; Fofana, 2003). There are also investigators who use finite element analysis (FEA) or the finite element method (FEM) for stability simulation and prediction (Brecher and Esser, 2006; Brecher et al., 2006; Brecher and Esser, 2007; Gagnolet al., 2007; Le Lan et al., 2006; Mann et al., 2005). With this methodology it is possible to predict the machine-tool behaviour or the behaviour of some components in the design stage, before it is constructed with the advantages that it entails. Movahhedy and Mosaddegh (2006) include in their model the gyroscopic effects of the spindle rotating to obtain the FRF. At high rotating speeds, the gyroscopic effect on the spindle dynamics becomes more relevant affecting the stability borders of the system. Insperger et al. (2008) take into consideration the role of the tool runout on the process stability. Gonzalo et al. (2006) focus their work in the simulation of thin walled parts machining in aluminium. Campa et al. (2007) solve the problem of the variable dynamics of a thin walled part through the calculation of a 3D stability lobes where the third dimension is the tool position along the part.

The transfer function of a multi-degree-of-freedom system can be identified by structural dynamic tests. The structure is excited with an impact hammer instrumented with a piezoelectric force transducer and the resulting vibrations are measured with displacement, velocity or acceleration sensors. Exist some commercial solutions such as the CutPro® software that simplifies the test and offers automatic predictions of the SLD (Manufacturing Automation Laboratories Inc. CUTPRO 8.0, 2009). Sims et al. (2005) describe the use of piezoelectric sensors and actuators to predict milling SLDs. This approach offers more control over the excitation signal than an impact hammer and is more suitable for small tools where it is impossible to accurately strike the tool tip. Abele et al. (2006 and 2007) use an active magnetic bearing (AMB) to identify the spindle tool system's frequency response function (FRF). This method allows a non-contact measurement to be made while the spindle is running. The substructure coupling techniques allow the dynamics of the spindle and the tool to be studied separately then combine them to obtain the system's global response. Consequently, once the spindle dynamics have been studied theoretically or experimentally, it is possible to estimate the response at the tool tip for different tools (Movahhedy and Gerami, 2006; Park et al., 2003).

2.2.3.2 In-process strategies for chatter recognition

The estimation of lobes explained above is the off-line approach to prevent unstable machining. If the lobes are fine calculated, the user can select cutting conditions for stable machining and at the same time have a very large axial depth of cut, in other words with a high removal rate. However, this approach implies a complete analysis of machine dynamics, which is difficult for industrial users to carry out, and requires an in-depth knowledge of the machining process and material (López de Lacalle et al., 2008). Moreover, in some cases, (e.g. where there are more than three axes or for thin-walled workpieces) the SLD of the system cutting tool, machine tool and workpiece is continuously changing and it is difficult to make predictions in advance and schedule the correct parameters to ensure stable operations (Soliman and Ismail, 1997). The methods based on chatter recognition do not need SLD identification. For such cases, researchers have developed methods consisting of online chatter detection, by monitoring a certain signal. It is normal to use different types of sensors or instruments to obtain process information.

Liao and Young (1996) propose an on-line spindle speed regulation method to control chatter when it starts to occur. Current vibration is monitored and new spindle speed is computed and readjusted in real time. Varying spindle speed and tooth passing frequency disturbs the regeneration mechanism. Faassen et al. (2006) propose to detect chatter online on its onset before it is completely developed. Early chatter detection allows operators to interfere in the process, thus avoiding chatter occurrence. Faassen et al. expose that the method presented can be applied using various sensors, however, for practical reasons these authors prefer the use of accelerometers. Doppenberg et al. (2006) use the detection algorithm presented in (Faassen et al., 2006) to suggest a chatter controller that forces the machining process into a region of chatter-free operation by adjusting the spindle speed when the onset of chatter is identified.

The milling sound emerging from the mechanical vibrations produced in the interaction zone between the cutting tool and the workpiece has also been used to detect chatter and control its occurrence (Delio et al., 1992; Schmitz et al., 2001, 2002 and 2003; Weingaertner et al., 2006). It has been demonstrated that a microphone is an excellent sensor to be used with this objective and comparisons made with other sensors such as dynamometers, displacement probes and accelerometers have given good results regarding unstable milling identification (Delio et al., 1992). Schmitz et al. (2001, 2002 and 2003) proposed a methodology for chatter recognition through statistical evaluations of the milling sound variance with a synchronously sampled (one sample per spindle revolution) signal.

Kuljanic et al. (2008 and 2009) developed a multisensor chatter detection system for application in industrial conditions. First, they compare several sensors, such as rotating dynamometer, accelerometers, acoustic emission and electrical power sensors, determine which signals are most sensitive to chatter onset.

A software program called Harmonizer™ by Metalmax® (Manufacturing Laboratories. Harmonizer, 2009) scans the sound of the cutting process with a microphone and chatter is detected if the energy of the measured sound signal exceeds a certain threshold.

2.2.3.3 Passive chatter avoidance

In contrast with those methods that pretend to avoid chatter occurrence by situating the machining process in the stable zone of the SLD, to obtain high MMRs, exists another research line with the aim of enlarging the stable zone of the SLD by raising the stability frontier. Here it is possible to find methodologies based in improving the design of the machine tool to change its behaviour against vibration or, the use of extra devices that can absorb extra energy or disrupt the regenerative effect. This research line is focused in ensuring chatter-free operations by damping, reducing and controlling the phenomena with the use of passive strategies.

Wang and Lee (1996) proposed to change the dynamic behaviour of the machine tool system by carrying out a redesigning procedure of the weakest component of the structure. They performed several cutting tests and the analysis of the process vibration showed that the spindle was the main feeble component. Marui et al. (1998), increased the damping capacity of a cutting tool system with inner friction plates. Semercigil and Chen (2002) suggested the use of a passive vibration controller, an impact dampers to reduce the excessive vibrations of an end-mill cutter. Kim et al. (2006) introduced a mechanical damper into a cylindrical hole in the centre of a standard end-milling cutter to dissipate chatter energy in the form of friction work.

The use of no-standard cutting tool i.e. variable pitch and variable helix milling tools has been proposed to increase the stable limit depth of cut by disrupting the regenerative effect

(Budak, 2003a; Budak, 2003b; Shirase and Altintas, 1996; Sims et al., 2008; Turner et al., 2006).

In industrial environments it is possible to find tools with integrated dampening like the Sandvik® Coromant's CoroMill 390. Also, the dynamic behaviour of the spindle system can be enhanced by reducing the tool overhang/diameter ratio or using monoblock tools, where shank and toolholder are the same body (Quintana et al., 2008).

2.2.3.4 Active chatter elimination

Active systems for chatter elimination are basically distinguished from the passive methods because they have the capacity of monitoring the dynamic state of the machine-tool system, diagnosing a certain occurrence and actively execute those decisions that change, if necessary, the system to a more adequate situation. Therefore, active vibration reduction systems are usually composed by monitoring, diagnosis and execution elements. This kind of strategy is becoming more important thanks to the advances in the recent years, in fields such as computers and sensors. With these strategies the SLD is actively raised or, at least, changed. To perform it is necessary the use of certain elements capable to modulate the quantity of work provided, absorbing or supplying work.

Olgac and Hosek (1998) present a practical approach to chatter elimination method based on root locus plot analysis and uses a device for active vibration suppression namely delayed resonator. Dohner et al. (2004) make an active control approach for mitigating chatter actively rising the stability lobes diagram. Ganguli et al. (2005, 2005a, 2006, 2007) propose the use of an active damping system to enhance the stability limits of the system based on an accelerometer to measure the machine tool vibrations and an electromagnetic proof mass dampers also called Active Mass Damper (AMD). Chiou et al. (2003) propose an algorithm for controlling machining chatter by changing the response function of the structure and its modal properties using active electrostatic and piezo-electric spindle bearing support.

Al-Regib et al. (2003) present a method for programming spindle speed variation for chatter suppression. They propose a sinusoidal spindle speed variation S^3V to disrupt the regenerative effect. Zatarain et al. (2008) present the general theory for the analysis in frequency domain of any speed variation strategy. Zhang et al. (2009) present a systematic stability analysis of spindle speed variation (SSV) based on a machining chatter model of non-linear delay differential equation, verify the results with numerical simulations and experiments and propose a formula for selecting the SSV amplitude.

In some cases, researchers blend or combine different strategies into a single approach or contribution and therefore, the classification into one of the above-described groups, is not possible. Ismail and Ziaei (2002) implement an algorithm that combines off-line scheduling of parameters and on-line spindle speed ramping. Faassen et al. (2003) use Harmonizer® for the experimental validation of the proposed D-partitioning model, which considers the spindle speed dependencies. Bediaga et al. (2009) develop a strategy that detects chatter emergence and in, accordance with SLD, determines if taking the machine to a stable spindle speed or changes to continuous spindle speed variation. Industrial implementation of the strategy and the chatter detection and diagnosis algorithm is carried out using a portable digital assistant (PDA).

2.3 Surface roughness

2.3.1 Generalities and definitions

Surface topography is the result of the material removal process due to relative motion between tool and part. It is quantified by the vertical deviations of a real surface from its ideal form. Surface properties play an important role in the performance of a finished part. They have an enormous influence on several relevant characteristics of the final product such as (Groover, 2004):

- Dimensional accuracy,
- Friction coefficient,
- Wear,
- Thermal resistance
- Electric resistance,
- Fatigue limit and behaviour
- Corrosion,
- Post-processing requirements,
- Appearance
- Cost.

For this reason, it is necessary to be able to describe surface properties accurately. Objective values of surface characteristics permit an objective evaluation of its behaviour and quality as surface characteristics largely determine, in principal, how the finished part will interact with its environment. But describing a surface is not an easy task due to the great number of different features that can generate a unique surface (See Figure 11). All surfaces have their own characteristics that, in general, can be defined by four elements: roughness, waviness, lay and flaws (Kalpakjian and Schmid, 2001).

- **Roughness** refers to the small, finely spaced deviations from the nominal surface that are determined by the material characteristics and the process that formed the surface.

- **Waviness** is defined as the deviations of much larger spacing; they occur due to work deflection, vibration, heat treatment, and similar factors. Roughness is superimposed on waviness.

- **Lay** is the predominant direction or pattern of the surface texture. It is determined by the manufacturing method used to create the surface, usually from the action of a cutting tool. Symbols for surface lays are shown in Figure 12.

- **Flaws** are irregularities that occur occasionally on the surface; these include cracks, scratches, inclusions, and similar defects in the surface.

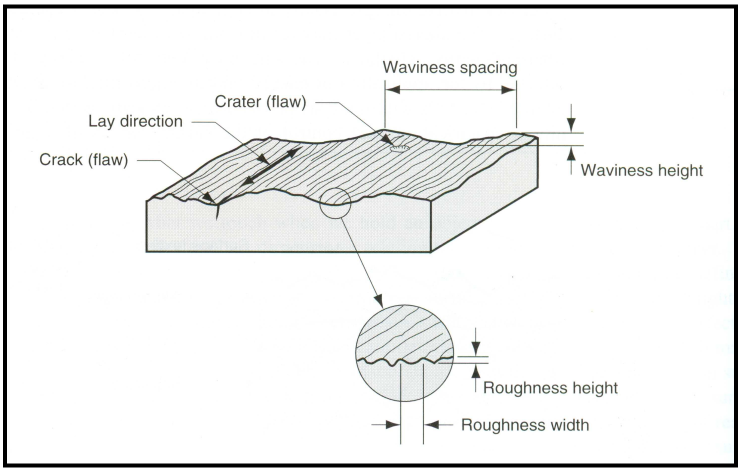

Figure 11: Surface texture elements. Source: (Groover, 2004)

Lay symbol	Surface pattern	Description
=		Lay is parallel to line representing surface to which symbol is applied.
⊥		Lay is perpendicular to line representing surface to which symbol is applied.
X		Lay is angular in both directions to line representing surface to which symbol is applied.
M		Lay is multidirectional.
C		Lay is circular relative to center of surface to which symbol is applied.
R		Lay is approximately radial relative to the center of the surface to which symbol is applied.
P		Lay is particulate, nondirectional, or protuberant.

Figure 12: Surface lays symbols and patterns. Source: (Groover, 2004)

All these characteristics, roughness, waviness, lays and flaws, represent what is known as surface texture. But surface texture as a combination of an objective description and quantification of the roughness, waviness, lay and flaws does not completely describe surfaces properties. Other changes exist that can occur during the manufacturing process that affect the subsurface layer and influence the performance of the finished part or product. These changes define what is called the *surface integrity* and include alterations of the workpiece surface such as impurities absorption, alloy depletions, cracks, craters, hardness changes, heat-affected zones (HAZ), inclusions, laps, folds, seams, plastic deformations, recrystallization, residual stresses, selective chemical attacks, etc. (Groover, 2004). However, for this reason, sometimes surface description can be a little bit more subjective. It is usual to employ indistinctly the terms *surface roughness* and *surface finish*. These two terms can be normally confused. Surface roughness is a measurable characteristic based on the roughness deviations. Surface finish is a more subjective term denoting smoothness and general quality of a surface. Surface finish is often used as a synonym of surface roughness.

Several standards have been developed, for instance (ISO-4287, 1997; ISO-4288, 1996), with the aim of analyzing, identifying and rigorously define, measure and quantify surface characteristics in order to permit an objective evaluation of the surface quality. ISO-4287 (1997) and ISO-4288 (1996) are both about dimensional and geometrical product specifications and verification and are focused mainly on surface texture. ISO-4287 introduces terms, definitions and establishes the surface texture parameters and ISO-4288 defines rules and procedures for the assessment of surface texture parameters defined in ISO 4287.

Surface texture is specified in engineering drawings by means of symbols (see Figure 13). The normalized symbol for surface texture designation looks like a square root sign and contains information about the maximum waviness height, the maximum waviness width, the maximum and the minimum Ra, the cut off length, the lay symbol and also, the maximum roughness spacing (Kalpakjian and Schmid, 2001).

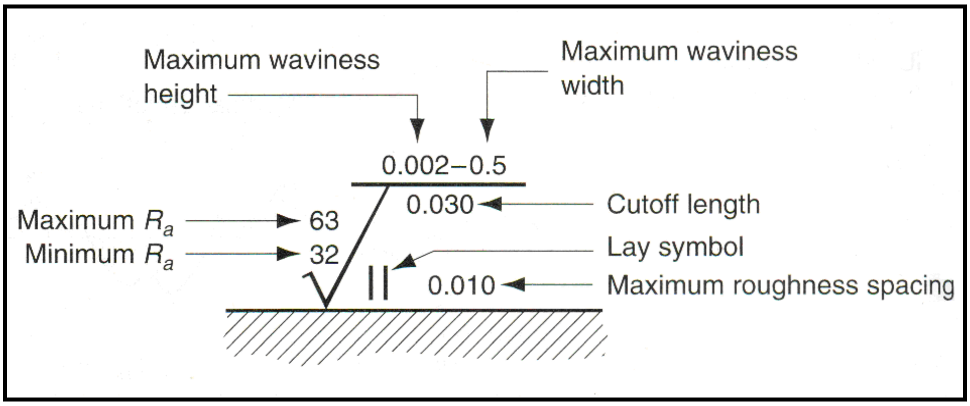

Figure 13: Surface texture symbols in engineering drawings. Source: (Groover, 2004)

The most commonly used measure of surface texture is surface roughness average (Ra) (Correa et al., 2009). Surface roughness average can be defined as the average of the vertical deviations from the nominal surface over a specified surface length. An arithmetic average is generally used, base on the absolute values of the deviations, and the roughness value is referred to by the name *average roughness*. In equation form,

$$Ra = \int_0^{Lm} \frac{|y|}{Lm} dx \qquad \text{Eq. 27}$$

Where Ra is the arithmetic mean value of roughness also known as C.L.A. Centre Line Average; y is the vertical deviation from the nominal surface converted to absolute value and Lm is the specified distance over which the surface deviations are measured. An approximation of Eq. 27 is given by

$$Ra = \sum_{i=1}^{n} \frac{|y_i|}{n} \qquad \text{Eq. 28}$$

Where Ra is the arithmetic mean value again; y_i are the vertical deviations converted to absolute values and identified by the subscript i, and n is the number of deviations included in Lm. Micrometers are the commonly used unit to express surface roughness.

Figure 14 shows the mentioned parameters. The reference horizontal line, usually called central line, is situated where the sum of areas above it is equal to the sum of areas below it.

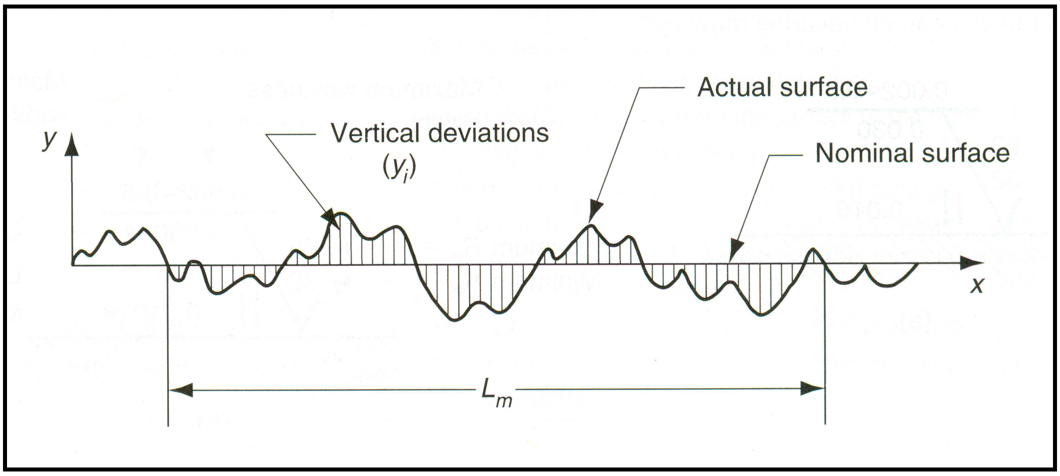

Figure 14: Actual and nominal surfaces. Source: (Groover, 2004)

It should be mentioned, that beside roughness average parameter (Ra), there exist, other surface roughness measures, such as Rc, Rq or Rt, that can be preferred, over Ra, in some other applications. Nevertheless, this Thesis focuses in the calculation and prediction of Ra parameter because, as above-mentioned, it is the most commonly used parameter in industry. In order to give a brief definition about these parameters, the following information has been extracted from (ISO-4287, 1997; ISO-4288, 1996):

- Rc: It is the arithmetical mean of the height of all profile elements (Zt) composed by peak(Zp) and valley pairs (Zv).

$$Rc = \frac{1}{n}\sum_{i=1}^{n} Zt_i \qquad \text{Eq. 29}$$

Where Zp is a peak projecting above the profile known as a "peak for profile element", Zv is a valley dropping below the lower count level also known as a "valley for profile element" and Zt is this peak and valley pair which appears continuously namely "profile element" (Zt=Zp+Zv).

- Rq: It is the square root of the arithmetical mean of the squares of profile deviations (y_i) from the mean line.

$$Rq = \left(\frac{1}{n}\sum_{i=1}^{n} Yi^2\right)^{\frac{1}{2}} \qquad \text{Eq. 30}$$

- Rt: It is the sum of height Yp of the highest point from the mean line and of depth Yv of the lowes point from the mean line.

$$Rt = Yp + Yv \qquad \text{Eq. 31}$$

Lot of research has been focused on surface generation considering several manufacturing processes, such as turning (Abouelatta and Mádl, 2001; Croletet al., 2006; Ozel and Karpat, 2005; Risbood et al., 2003; Thomas et al., 1996), milling (Ismail et al., 1993; Martellotti, 1945; Martellotti, 1941; Montgomery and Altintas, 1991), grinding (Brinksmeier et al., 2006; Liu et al., 2005; Ohmori and Nakagawa, 1995; Tönshoff et al., 1992), broaching (Kuljanic, 1975; Mo et al., 2005), drilling (Ogawa et al., 1997; Sanjay and Jyothi, 2006; Sanjay et al., 2006; Tsao and Hocheng, 2008; Zhang and Chen, 2009), electrical discharge machining (Markopoulos et al., 2008), wire electrical discharge machining (Gökler and Ozanözgü, 2000), laser machining (Ciurana et al., 2009), etc. In general, the manufacturing process determines surface characteristics. Some processes, due to their intrinsic principals are more capable to produce a good surface finish than others. This is the case, for instance of lapping or polishing processes.

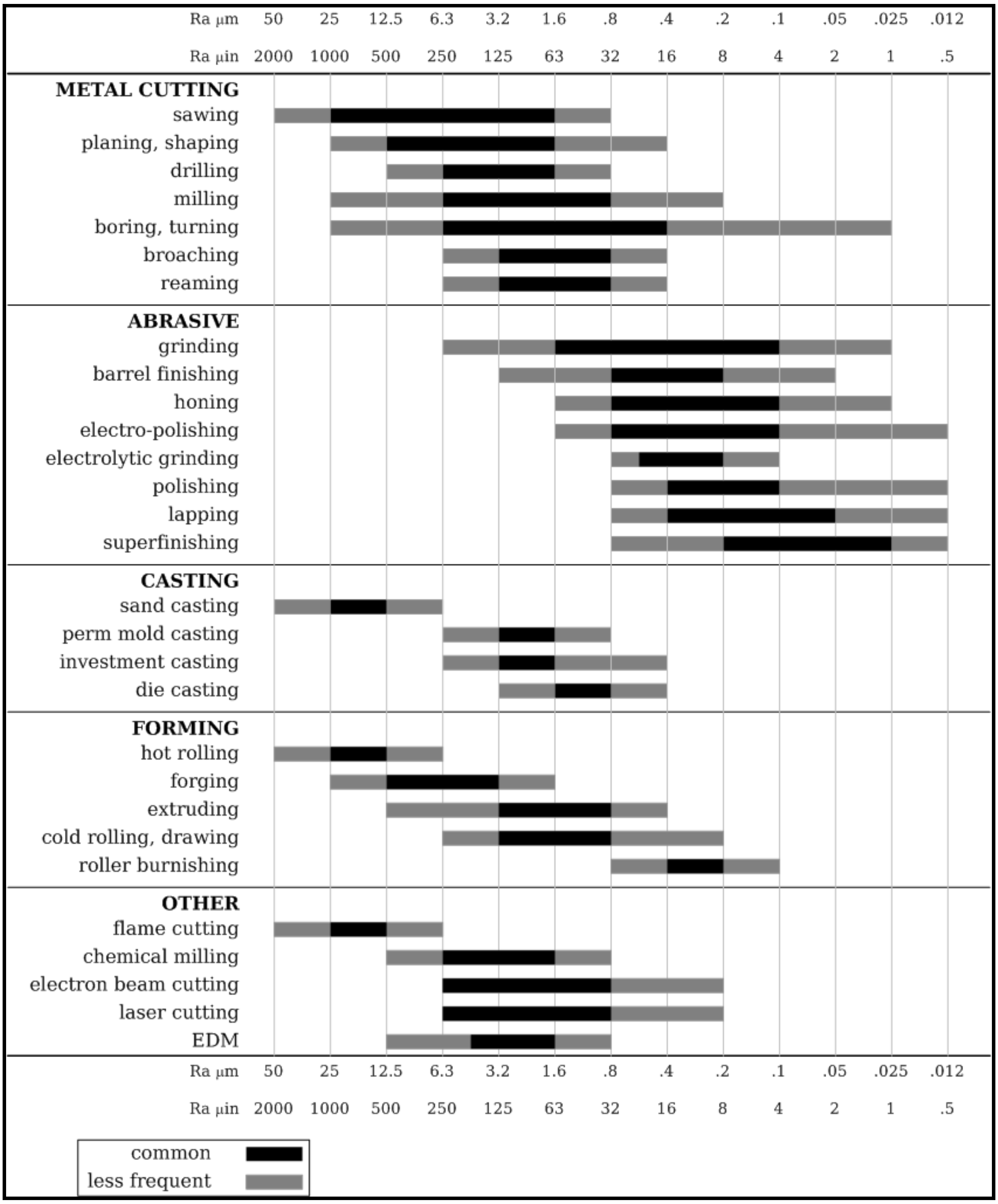

Figure 15: Actual and nominal surfaces. Source: (Oberg et al., 2004)

Figure 15 shows the usual surface roughness that can be expected from several manufacturing processes.

2.3.2 Surface roughness generation in milling operations

Milling consists in removing the excess material from the workpiece in the form of small individual chips. These chips are formed by the intermittent engagement with the workpiece of a plurality of cutting edges or teeth integral with or inserted in a cylindrical body known as the milling cutter. This intermittent engagement is produced by feeding the workpiece into the field dominated by the rotating cutter. Therefore, a finished surface consists of a series of elemental surfaces generated by the individual cutter edges. Milling chip is short and with variable thickness resulting from work translatory motion combination and cutter rotary motion (Martellotti, 1941). Surface topography is the result of the material removal process due to the relative motion between tool and part. Figure 16 shows a schematic milling process representation with ball end mill cutter. It is possible to observe that surface generation in ball end milling operations is highly influenced by the geometric characteristics of cutter.

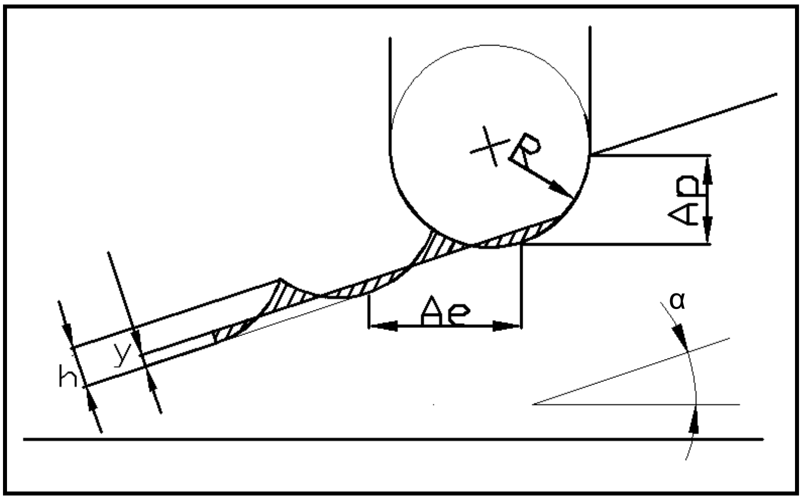

Figure 16: Surface roughness generation in ball end milling operations on inclined surfaces.

Surface topography can be analyzed considering it as the superposition of several order deviations from the nominal surface as shows Figure 17. First order deviations refer to the general form such as flatness, circularity, etc. Second order deviations refer to waviness. First and second order deviations are due to machine tool errors, workpiece deformation, setups and clamping errors, material inhomogenities, structural vibrations, etc. Third and fourth order deviations correspond to periodic grooves, cracks, etc. which are more related with process kinematics and chip formation. Fifth and sixth order deviations refer to workpiece material structure which is connected to physical and chemical mechanisms such as slip, diffusion, oxidation, residual stresses, etc.

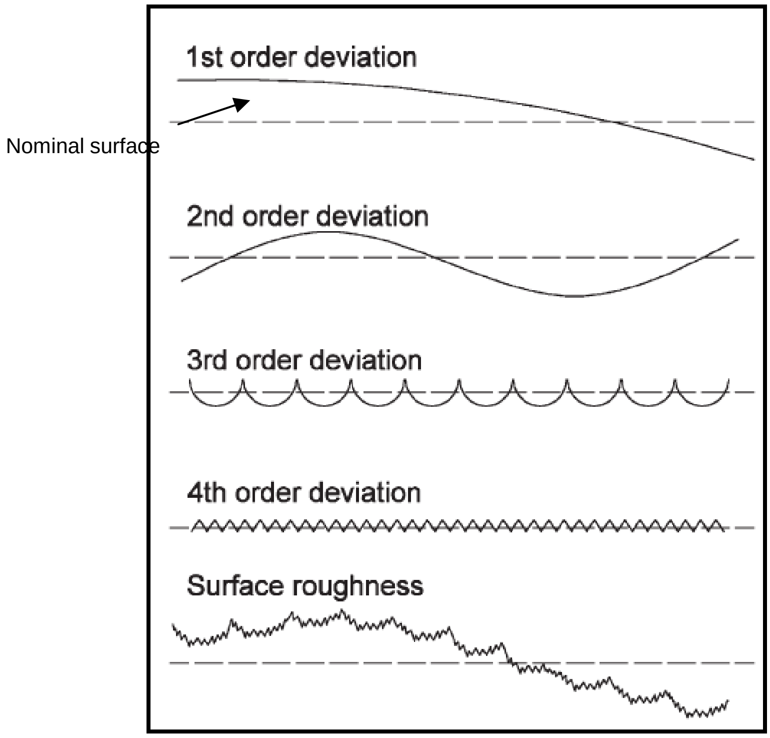

Figure 17: Surface form deviations. Source: (DIN4760 et al.)

In industry, surface roughness average parameter Ra, is the most extended index of product quality and in most cases a technical requirement for mechanical products as surface quality is of great importance for the functional behaviour of a part (Benardos and Vosniakos, 2003). Surface roughness is usually measured off-line when the part is already machined. Quality is evaluated out-of-process, resulting in losses as there is no alternative to remove defective parts from the production line and time and money have been spent on them (Correa et al., 2008).

For this reason it is interesting to understand the surface generation process in order to determine those process parameters that permit to ensure the required product quality in terms of surface roughness, while maximizing productivity. But it is not an easy task due to the dependent nature of the surface roughness formation mechanism and the numerous uncontrollable factors influencing it. In workshops, operators tend to select conservative combinations of cutting parameters diminishing productivity with the aim of ensuring quality and avoid repeating the process. In moulds and dies industry, for instance, it is usual to apply manual finishing operations in order to achieve the required surface roughness. Although this procedure permits to produce the desired surface finish it is a time-consuming process which influences the accuracy of mould shape. Finishing process depends entirely on the experience, skill, and inspection ability of workers (Lee et al., 2006). Figure 18 shows the proportion of the total processing cost for the manual finishing process (more than a 15%) in a general mould manufacturing process (Schulz, 1995).

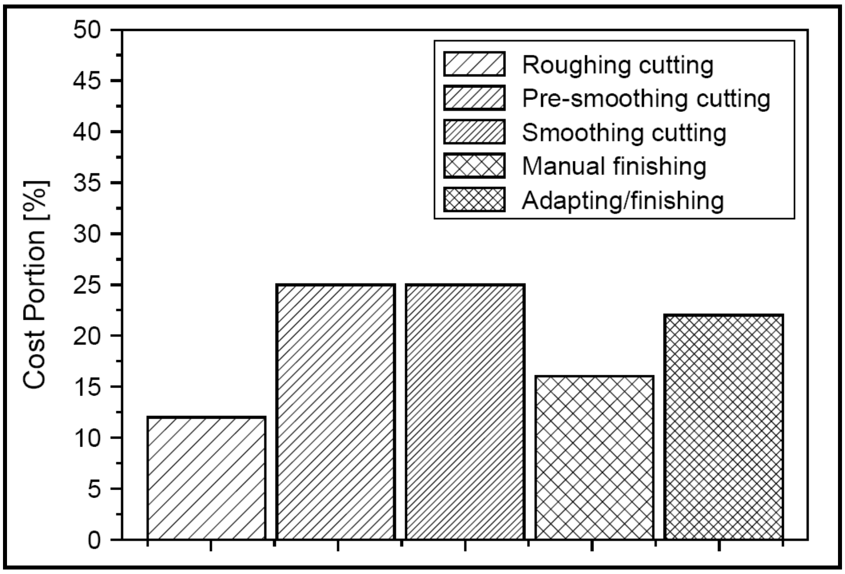

Figure 18: Processes cost portions in mould and die production. Source: (Schulz, 1995)

Although high roughness is usually undesirable, it is difficult and expensive to control in manufacturing. Decreasing the roughness of a surface will usually increase exponentially its manufacturing costs. This often results in a trade-off between the manufacturing cost of a component and its performance in application.

However, understanding the surface generation fundamentals, gives certain advantage in order to optimize the process parameters selection. But, surface roughness formation is influenced by a great number of factors. The set of factors that influence the surface roughness is compiled by Benardos and Vosniakos (2003) in a fishbone diagram (see Figure 19) that considers: machining parameters such as process kinematics, cooling fluid, stepover, depth of cut, tool angle, feed rate and cutting speed; the cutting tool properties such as the tool material, runout errors, tool shape and nose radius; the workpiece properties such as the length, diameter and hardness; and the cutting phenomena such as the cutting force variation, friction in the cutting zone, chip formation, vibrations and accelerations. Interactions among these factors are complex and make difficult understanding of cause-effect relationships necessary to implement surface roughness models.

Due to the enormous number of factors influencing surface roughness it is difficult to ensure that quality requirements will be achieved before the beginning of the manufacturing process. It is a topic that still depends very much on the operator expertise and manual finishing operations. For this reason, many research projects have been focused on surface roughness generation understanding and various methodologies and practices have been developed and are being employed to predict, in advance, the surface roughness. This permits to become more productive, reduce costs, re-processing parts and be more competitive. Next section presents and classifies numerous approaches proposed by researchers for surface roughness prediction.

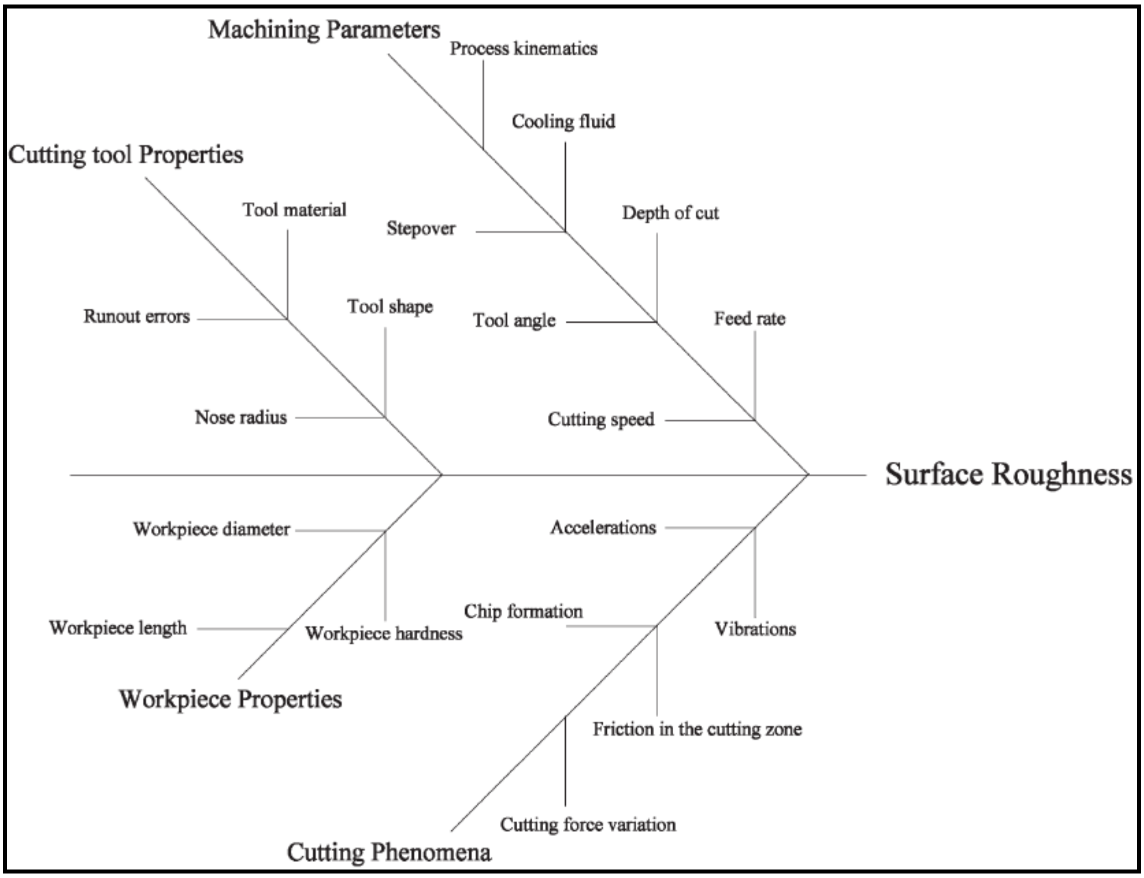

Figure 19: Parameters that affect the surface roughness. Source: (Benardos and Vosniakos, 2003)

2.3.3 Surface roughness prediction methods

In 2003, Benardos and Vosniakos present the last published review on surface roughness prediction (Benardos and Vosniakos, 2003). In this paper they propose to classify the research lines into four major categories which are: approaches based on machining theory; approaches based on experimental investigations; approaches based on designed experiments and; approaches based on artificial intelligence. In this Thesis, the surface roughness prediction methods are classified following the categories proposed by Benardos and Vosniakos as shown in Figure 20. However, it should be mentioned that, as stated in (Benardos and Vosniakos, 2003), the classification of papers is not easy due to great deal of literature that does not strictly follow a certain methodology. In many cases, researchers blend different strategies into a single approach and therefore a single classification is not perfectly accurate.

2.3.3.1 Machining theory approaches

This category includes approaches based on machining theory that are used to develop analytical models and/or computer algorithms to represent the machined surface. Certain aspects such as process kinematics, cutting tool properties, chip formation mechanisms, can be taken into consideration.

Surface roughness prediction strategies

- Machining theory approaches
- Experimental investigation approaches
- Designed experiments approaches
- Artificial intelligence approaches

Figure 20: Research lines focused on surface roughness prediction strategies.

The approach proposed by Martellotti in 1941, for peripheral milling operations is an essential reference. Martellotti (1941 and 1945) treated from a mathematical point of view peripheral milling operations to show that cutting tool path is an arc of trochoid. Trochoid arc is described by an equation that can be derived from the known cutting variables so that considering a rigid tool and a rigid workpiece system, maximum feed mark height could be easily calculated. Later on, Montgomery and Altintas (1991) proposed a model for peripheral milling processes considering the kinematics of the cutter and workpiece vibrations to predict the surface generation. Grzesik (1996) assumed that the differences between the theoretical and real surface roughness are mainly produced by adhesion at the rake-chip interface in turning operations. With this assumption, Grzesik improve a simple model for predicting the surface roughness of a turned surface. In (Lin and Chang, 1998), Lin and Chang establish a surface topography simulation model to simulate the surface finish profile in turning operations incorporating the effects of the relative motion between the cutting tool and the workpiece and the influence of tool geometry. Baek et al. (2001) analyze the effects of the inserts runout error and feedrate variation on the surface roughness for face-milling operations. A model was developed to calculate the optimal feedrate that permits to obtain a maximum material removal rate ensuring to accomplish with a given surface roughness constraint. Lee et al. (2001) presented a method for simulating the machined surface using the acceleration signal. The authors state that the vibration caused by high speed of the spindle in high speed milling deteriorates the geometric accuracy of the machined surface and, for this reason, they decide to take into consideration the vibration of the spindle system. Arizmendi et al. (2008 and 2009) presented two models for topography generation understanding. In (Arizmendi et al., 2008), is presented a model for the topography prediction of ball-end milled surfaces considering the tool parallel axis offset. In (Arizmendi et al., 2009), is proposed a model to predict the bands generated on surfaces machined by peripheral milling considering several tool setting errors which are cutter parallel axis offset and cutter axis tilt. Models predictions are compared with experimental results with good agreement.

When the approach is from a theoretical point of view, usually experiments are carried out with the goal of comparing the predicted calculations with the experimental results. In the case of topography generation, despite the strong background of the abovementioned methodologies the phenomena that lead to the formation of surface roughness are very complex and interacting in nature so a complete solution has not been found, yet. Therefore, the results obtained by these models are generally not accurate.

2.3.3.2 Experimental investigation approaches

This research line consists of those approaches that examine the effects of various factors through the execution of experiments and the analysis of the results obtained. The idea is to conduct experiments taking into consideration those parameters that are supposed to be the most influencing and, use the results obtained to analyze and quantify the effect of each studied factor on the observed characteristic. This is the most conventional approach. The main advantage is that it is easy to carry out and can provide very good results. The main drawback is that the obtained conclusions have little or no general applicability (Benardos and Vosniakos, 2003).

Jang et al. (1996) focused on the development of an online real-time roughness measuring technique by studying the effects of vibration in hard turning operations. The correlation between surface roughness and cutting vibration was studied. The results showed that surface roughness had specific frequency components that were determined by feed marks in the lower frequency range and by natural frequencies of spindle-workpiece system (measured with a displacement sensor), in the high frequency range. Coker and Shin (1996) presented an in-process monitoring and control system for surface roughness with ultrasonic sensing. An ultrasonic sensor connected to a PC, produced a pulse which was reflected by the workpiece surface and measured the amplitude of the returned signal. The main advantage of this technique is that cutting fluids and chips do not affect the measurement. Beggan et al. (1999) employ the analysis of the acoustic emission to predict surface quality in turning operations. Abouelatta et al. (2001) studied the relationship between tool wear, surface roughness and vibration in turning and derived mathematical regression models based on cutting parameters and machine tool vibrations. The variables considered were cutting speed, feed rate, depth of cut, tool nose radius, tool overhang, approach angle, workpiece length and diameter and the accelerations in radial and feed directions. Ghani et al. (2002) used vibration signals to monitor tool wear and verify the correlation between tool wear progression and surface roughness when turning nodular cast iron with a ceramic tool. Very aggressive experiments were carried out under various combinations of speed, feed and depth of cut leading to very short tool life: about 1.5min. Vibration was measured using two accelerometers attached to the toolholder. Crolet et al. (2006) analyzed the influence of vibrations on surface and roughness during a superfinish turning operation. Vivancos et al. (2004 and 2005) studied cutting parameters (cutting speed, feed per tooth, axial depth and radial depth of cut) influence on the roughness obtained in high speed milling of hardened die steels. Chang et al. (2007) proposed a method to predict surface roughness in-process by measuring spindle displacements with a sensor and using a linear regression model with high correlation near 95%. Grzesik (2008) studied the influence of tool wear on surface roughness in hard turning with different shapes of ceramic tools. After conducting experimentation, compared some predominant tool wear patterns produced on the two types of ceramic inserts and analyzed their influence on the alteration of surface roughness.

2.3.3.3 Designed experiments approaches

This category includes the approaches that use designed experiments. It is a different category from the one presented in the previous section because in this case it is used a systematic methodology for planning experimentation and analysis. The most used methodologies for the surface roughness prediction problem are the response surface methodology (RSM) (Myers and Montgomery, 2002) and the Taguchi techniques (Taguchi, 1993) for design of experiments (DoE). To give a brief explanation of these two methodologies, in RSM the factors that are considered to be the most relevant are used to build a polynomial model where the independent variable or target is the experiment's response. Taguchi methodologies for design of experiments are based on a series of steps to follow for the experiments to obtain an improvement of the product or process understanding.

Alauddin et al. (1995 and 1996)used RSM to develop two implementations of a surface roughness model for end milling operations with the aim of increasing material removal rates ensuring the surface quality requirement. Thomas et al. (1996) studied the effect of tool vibrations on surface roughness for lathe dry turning processes. In this extensive work six parameters were taken into account including workpiece and cutting tool length and a full factorial design was adopted. Yang and Tarng (1998) used the Taguchi method to find optimal cutting parameters for turning operations of S45C steel bars. Choudhury and Bartarya (2003) used RSM to show that the effect of feed is much more pronounced than the effects of cutting speed and depth of cut on the surface roughness in turning of high-strength steel. Thangavel and Selladurai (2008) studied the effect of turning parameters such as cutting seed, feed rate, depth of cut and tool nose radius on the surface roughness and developed a mathematical model relating surface roughness and these factors with RSM. Dhokia et al. (2008) provide a predictive model using a design of experiments strategy to obtain optimised machining parameters for a specific surface roughness assurance in ball-end machining of polypropylene. Gologlu and Sakarya (2008) considered the cutting speed, feed rate, depth of cut and step over to optimize pocket milling operation by means of using Taguchi design. Ho et al. (2009) present a system for surface roughness prediction in milling processes using hybrid Taguchi-genetic learning algorithm.

2.3.3.4 Artificial intelligence approaches

This category is composed by these approaches that use artificial intelligence (AI) methods. These methods are composed by artificial neural networks (ANN) models, genetic algorithms (GAs), fuzzy logic and expert systems and simulate the way in which human beings process information and make decisions. Roughly, ANN is a mathematical model or computational model that consists of an interconnected group of artificial neurons that simulate the structure of biological neurons to imitate human reasoning (Swingler, 1996). Fuzzy systems or neuro-fuzzy systems are based on fuzzy sets, without a clearly defined boundary (usually between 0 and 1) instead of only 0 or 1 in binary (Nauck et al., 1997). GAs are searching techniques used in computing to find exact or approximate solution to optimization problems. The idea is derived from the heuristic assumption that the best solution is located in regions of solution spaced containing high proportion of good solutions (Reeves and Rowe, 2003).

Lou et al. (1998) developed a prediction technique based in multiple regression prediction models for CNC end-milling with an accuracy of 90%. The authors found that the feed rate is the most significant machining parameter and the model presented includes also spindle speed and depth of cut. Tsai et al. (1999) presented an in-process system for surface recognition in end milling operations based on neural networks. The authors used an accelerometer to obtain vibration data from the machine tool and workpiece system. A CNC vertical machining centre was used to perform experimentation. The ANN model develop included the following input parameters: spindle speed, feed rate, depth of cut and vibration. Ho et al. (2002) proposed a method using an adaptive neuro-fuzzy inference system to predict surface roughness with the features of surface image (obtained with a digital camera and a PC) and some cutting parameters: cutting speed, feed rate, and depth of cut. In (Benardos and Vosniakos, 2002), the authors used ANN modelling with designed experiments for surface roughness prediction in face milling considering feed per tooth, axial and radial depths of cut, use of cutting fluid and the component of the cutting force along the feed direction. They showed that the use of ANN can be extremely accurate. Risbood et al. (2003) used neural networks to predict surface finish in turning processes considering the level of vibration of the tool holder. Brezocnik et al. (2003 and 2004) propose the use of a genetic algorithm approach to predict surface roughness in end-milling. Ozel and Karpat (2005) developed a predictive model for surface roughness base on artificial neural networks for finish hard turning operations. Abellán et al. (2006) compared the performance of three different modelling approaches: multiple regression analyses (MRA), artificial neural networks (ANN) and bayesian networks (BN). The authors proposed a multi-sensor system to predict surface roughness based on vibrations and spindle load signals for face milling operations on AISI 1045 carbon steel. Shie (2006) focuses on finding an optimal cutting parameters combination using neural networks for dry machining parameter of high-purity graphite in end-milling processes. Suresh et al. (2007) present an approach using RSM. Then, this model was taken as an objective function and was optimized with GA to obtain the machining conditions for a desired surface finish with minimum and maximum values.

Correa et al. (2008 and 2009) presented two models for roughness prediction in high speed milling processes developed through bayesian networks (BN) approach. Ramesh et al. (2008) use fuzzy logic for the selection of cutting parameters in turning titanium alloy considering cutting speed, feed and the depth of cut. The model presented can effectively predict the tool flank wear, surface roughness and specific cutting pressure in titanium alloys machining. Samanta et al. (2008 and 2009) use soft computing techniques or computational intelligence techniques to model surface roughness in end-milling processes considering multiple regression analyses, artificial neural networks and adaptive neuro-fuzzy system.

Chapter 3. Stability lobes diagram identification: Inclined Plane Methodology

Chapter 3 presents an experimental methodology for Stability Lobe Diagram identification in milling operations. The methodology is based on empirical tests where, thanks to the inclined plane workpiece shape it is possible to gradually increase the axial depth of cut in the feed direction. The inclined plane method presented in this Chapter permits to obtain a *metallic SLD* physically machined onto the workpiece.

This methodology was presented in an article entitled "*A new experimental methodology for identification of stability lobes diagram in milling operations*", published by the International Journal of Machine Tools and Manufacture in July 2008 (Quintana et al., 2008).

Guillem Quintana, Joaquim Ciurana and Daniel Teixidor. “A new experimental methodology for identification of stability lobes diagram in milling operations” *International journal of machine tools and manufacture*. Vol. 48, issue 15 (December 2008) : p. 1637-1645

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Abstract

Chatter is a self-excited vibration that can occur during machining operations. This undesirable phenomenon is one of the most common limitations when it comes to improving productivity and part quality. For this reason, several methods have been developed with the aim of preventing, avoiding, reducing, suppressing or controlling the occurrence of chatter.

A stability lobes diagram (SLD) shows the boundary between chatter-free machining operations and unstable processes, in terms of axial depth of cut as a function of spindle speed. These diagrams are used to select chatter-free combinations of machining parameters.

This paper presents an experimental method for identifying SLDs in milling operations. The methodology is based on empirical tests where the workpiece permits a gradual increase of the axial depth of cut in the feed direction, which represents the *y* coordinate of the SLD while the spindle speed (the *x* coordinate of the SLD) is increased between passes. This is possible thanks to the inclined plane shape presented by the workpiece. The cutting process is interrupted as soon as chatter is detected and the frontier between stable and unstable cutting, i.e. the stability lobes diagram, is identified. This permits to obtain the SLD physically machined onto the workpiece. The methodology is good for those small and medium enterprises which have no technical knowledge and sophisticated resources, because the SLD can be identified with a microphone and prepared workpiece.

At first, we present the results obtained when chatter is detected by the operator by analyzing the sound emission. Then, in order to eliminate the subjective component of the human hearing intervention, a computer application is presented. It permits to monitor the milling process sound and analyze its amplitudes and frequencies to identify chatter as soon as its occurrence starts. The results provided by the computer application are quite better.

Keywords: Milling processes; Stability lobes diagram

Chapter 4. Stability lobes diagram identification: Sound Mapping Procedure

Chapter 4 presents an experimental procedure that permits to determine the Stability Lobe Diagram of a milling process by applying sound mapping methodology. If the SLD is considered as a region and this region is meshed into several zones, a diagram can be constructed by applying a sound mapping method. In this work, milling process sound was captured with a microphone placed inside the machine-tool enclosure. Then, a 3D sound map was built by plotting the sound amplitude at frequencies around chatter frequency on the corresponding points of a mesh composed of 30 spindle speeds per 20 axial depths of cut. The chart obtained was the process SLD.

This methodology was presented in an article entitled "*Sound mapping for identification of stability lobe diagrams in milling processes*", published by the International Journal of Machine Tools and Manufacture in December 2008 (Quintana et al., 2009).

Guillem Quintana, Joaquim Ciurana, Inés Ferrer and Ciro A. Rodríguez. “Sound mapping for identification of stability lobe diagrams in milling processes”. *International journal of machine tools and manufacture*. Vol. 49, issue 3-4 (March 2009) : p. 203-211

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Abstract

This paper deals with milling sound information. In milling operations, cutting edge impacts excite vibrations due to the interaction between the cutter and the workpiece, and because of the system's lack of dynamic stiffness. It is possible to distinguish between free, forced and self-excited vibrations. During a milling operation these three different types of mechanical vibrations propagate through air and generate a sound that intrinsically contains information about the process.

A sound map is a graphical sound-level representation of a certain zone or region that is divided into points by means of a mesh. Sound maps have typically been used with social considerations in mind: to determine, for instance, noise levels in cities. The goal of this paper is to determine the stability lobe diagram (SLD) of a milling process by applying sound mapping methodology. Stability lobe diagrams show the stability frontier as combinations of spindle speeds (i.e. the abscissas axis) and radial depths of cut (i.e. the ordinate axis). In this investigation the SLD was obtained from a mesh of 30 spindle speeds per 20 axial depths of cut, resulting in a total of 600 experiments. A data acquisition platform was developed to collect the milling process sound through a microphone placed inside the machine-tool enclosure. Data were analysed off-line in order to recognise chatter frequencies.

A 3D sound map was built by plotting, on each corresponding point of the mesh described above, the sound amplitude at frequencies around chatter frequency. The difference between stable and unstable zones is shown. This is the stability lobe diagram. The extensive experimentation detailed in this work reasserts and confirms the current state of knowledge of the chatter phenomenon.

Keywords: Audio; Chatter; Milling; Sound; Stability

Chapter 5. Studying surface roughness generation in ball end milling operations

Chapter 5 analyzes the influence of the geometric characteristics of ball end mill cut on the surface generation process. The crest height (h) and the surface roughness average parameter (Ra) are calculated as function of cutting tool radius (R) and radial depth of cut (Ae) considering surface angularity. Equations for the material removal rate (MRR) calculation are also developed and finally, the theoretical approach is compared with experimentation.

This study was presented in an article entitled "*Surface Roughness Generation and Material Removal Rate in Ball End Milling Operations*", accepted for publication in Materials and Manufacturing Processes in March 2009 (Quintana et al.).

Surface Roughness Generation and Material Removal Rate in Ball End Milling Operations

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Abstract
Surface roughness plays an important role in the performance of a finished part. Surface roughness generated in machining operations is influenced by an enormous set of factors such as cutting parameters, cutting tool characteristics, workpiece properties or cutting phenomena. Cutting geometric characteristics, when ball end mill is used, clearly affect surface crests generated.
In this paper, is studied the influence of the geometric characteristics of ball end mill cut on the theoretical surface roughness obtained. The crests height on the surface (h) and roughness average parameter (Ra) are calculated as function of cutting tool radius (R) and radial depth of cut (Ae). Surface angularity is also considered. This work also analyses cutting parameters implication on material removal rate of ball end milling operations. The equations and specially the figures presented in this paper can be easily applied in workshops to improve quality and productivity of ball end milling operations.
Finally, experimentation carried out permits to observe and quantify the deviations of the theoretical approach.

Keywords: Ball end mill, Cutting parameters, Surface Roughness, Material Removal Rate.

1. Introduction

General manufacturing problem can be described as the achievement of a predefined product quality with given equipment, cost and time constraints. Unfortunately, for some quality characteristics of a product such as surface roughness it is hard to ensure that these requirements will be met. Surface roughness is a widely used index of product quality and in most cases a technical requirement for mechanical products. Achieving desired surface quality is of great importance for the functional behaviour of a part [1]. Surface properties play an important role as they influence dimensional accuracy, friction coefficient and wear, thermal and electric resistance, fatigue limit and behaviour, corrosion, post-processing requirements, appearance and cost [2]. Surface roughness is usually measured off-line when the part is already machined. Quality is evaluated out-of-process, resulting in losses as there is no alternative to remove defective parts from the production line [3]. For this reason it is interesting to determine those process parameters that permit to ensure the required product quality in terms of surface roughness, while maximizing productivity. But it is not an easy task due to the dependent nature of the surface roughness formation mechanism and the numerous uncontrollable factors influencing it. Usually conservative combinations of cutting parameters are selected by the operators.

The set of factors that influence the surface roughness is compiled by Benardos and Vosniakos [1] in a fishbone diagram that considers: machining parameters such as process kinematics, cooling fluid, stepover, depth of cut, tool angle, feed rate and cutting speed; the cutting tool properties such as the tool material, runout errors, tool shape and nose radius; the workpiece properties such as the length, diameter and hardness; and the cutting phenomena such as the cutting force variation, friction in the cutting zone, chip formation, vibrations and accelerations. Interactions among these factors are complex and make difficult understanding of cause-effect relationships necessary to implement surface roughness models.

Many investigations have been carried out about surface generation considering the influence of several parameters and phenomena that affect the roughness produced. Some analytical models are based on machining theory to calculate surface roughness [4-6]. However, other works are based on experimental approaches. Many research works have been developed in areas to use computational models to solve quality surfaces properties with process or machine parameters. Ramesh et al. [7] use a fuzzy rule-based model to predict surface roughness among other characteristics considering cutting speed, feed and depth of cut. Ozel and Karpat [8] developed a predictive model for surface roughness base on artificial neural networks for finish hard turning operations. Ciurana et al. [9] proposed a model based on neural networks to analyze process parameters influence on surface quality. Abellán et al. [10] compared three different modelling approaches performance: multiple regression analyses, artificial neural networks and bayesian networks. Their work had proposed a multi-sensor system to predict surface roughness based on vibrations and spindle load signals for face milling operations on AISI 1045 carbon steel. Risbood et al. [11] used neural networks to predict surface finish in turning processes considering tool holder vibration level. Ho et al. [12] used an adaptive network-based fuzzy inference system with hybrid Taguchi-genetic learning algorithm to predict surface roughness for the end milling process.

Vibration seems to have important influence on quality surface and it is especially studied in several works. Thomas et al. [13] studied the effect of tool vibrations on surface roughness for lathe dry turning processes. Jang et al. [14] studied the correlation between surface roughness and cutting vibration. Vibration signal is superimposed onto the kinematic roughness to develop an on-line roughness measuring methodology for hard turning operations. Brezocnik and Kovacic [15] proposed a method a genetic algorithm to predict surface roughness in end milling operations considering four independent variables –spindle speed, feed rate, depth of cut and vibrations. Peigne et al. [16] studied the influence of forced vibrations on surface roughness in comparison with self-excited vibrations.

Other works studied other influences on surface quality. Vivancos et al. [17, 18] studied cutting parameters (cutting speed, feed per tooth, axial depth and radial depth of cut) influence on the roughness obtained in high speed milling of hardened die steels. Toh [19] investigated three main cutter path strategies –raster, single-direction raster, and offset- with the aim of increasing axial depths of cut when high-speed rough milling hardened AISI H13. Ghani et al. [20] verified the change in workpiece surface finish due to the increasing tool wear while machining nodular cast iron with ceramic tools. Larue and Lapujoulade [21] focused their investigation on surface quality prediction in thin walled parts milling which becomes special interesting in aerospace and die and mould industry. Chang et al. [22] proposed a method to predict surface roughness in-process by measuring spindle displacements with a sensor and using a linear regression model with high correlation near 95%. Arizmendi et al. [23] presented a model to predict the bands generated on surfaces machined by peripheral milling considering several tool setting errors.

Beside methodologies and strategies adopted by researchers in order to study the surface roughness generation and the finishing techniques applied in industry, several standards have been developed [24,25]. ISO-4287 and ISO-4288 are both about dimensional and geometrical product specifications and verification and are focused mainly on surface texture. ISO-4287 introduces terms, definitions and establishes the surface texture parameters and ISO-4288 defines rules and procedures for the assessment of surface texture parameters defined in ISO 4287.

Manual finishing operation is still used in moulds industry. Although it permits to produce the desired surface finish it is a time-consuming process which influences the accuracy of mould shape. The finishing process success entirely depends on the experience, skill, and inspection ability of the workshop workers [26]. The proportion of the total processing cost for the manual finishing process is more than a 15% in a general mould manufacturing process [27].

In this paper surface generation is analyzed for ball end milling operations from a geometrical point of view of the cut. This kind of work has been carried out for other kind of milling operations, such as peripheral milling [4,5,23], but the authors do not have information about a similar study focused on ball end milling operations. The crests height left on the surface (h) and surface roughness average parameter (Ra) are calculated as function of cutting tool radius (R) and radial depth of cut (Ae) considering also, the surface angularity (α). This is possible as (R, Ae and α) are, from the geometrical point of view, the main actors of surface profile generation. Surface crest height and roughness average are parameters related with quality. Equations for the material removal rate (MRR) are also developed as MRR is a productivity indicator. Charts for the theoretical calculation of h, Ra and MRR are provided. In workshops, operators can easily apply the charts presented to calculate h, Ra and MRR approximations in order analyse the quality and productivity of ball end milling operations and improve parameters selection. Then experimentation is carried out on hardened AISI H13 steel to analyze and quantify theoretical approach deviations and differences between theory and practice.

2. Surface roughness in milling operations

Milling consists in removing the excess material from the workpiece in the form of small individual chips. These chips are formed by the intermittent engagement with the workpiece of a plurality of cutting edges. A finished surface consists of a series of elemental surfaces generated by the individual cutter edges [4]. Surface topography is the result of the material removal process due to relative motion between tool and part. It is possible to analyze surface topography considering it as the superposition of several order deviations from the nominal surface. First order deviations refer to the general form such as flatness, circularity, etc. Second order deviations refer to waviness. First and second order deviations are due to machine tool errors, workpiece deformation, setups and clamping errors, material inhomogenities, vibrations, etc. Third and fourth order deviations correspond to periodic grooves, cracks, etc.; which are more related with process kinematics and chip formation. Fifth and sixth order deviations refer to workpiece material structure which is connected to physical and chemical mechanisms such as slip, diffusion, oxidation, residual stresses, etc [28].

This paper is focused in ball end milling operations. Figure 1 shows a schematic milling process representation with ball end mill cutter. It is possible to observe how surface generation in ball end milling operations is highly influenced by the geometric characteristics of cut.

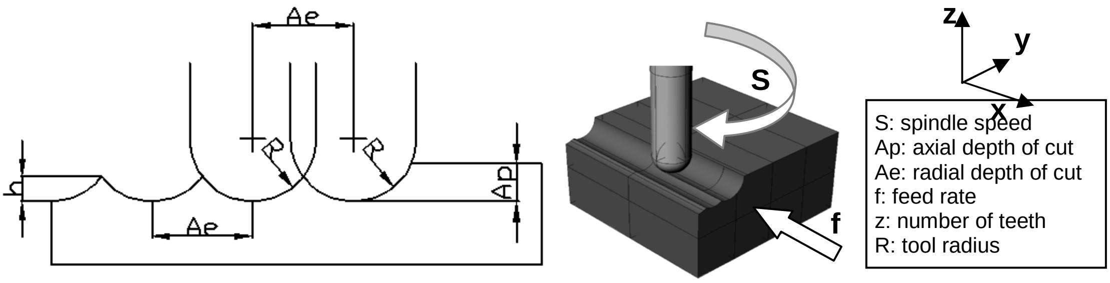

Figure 1. Surface roughness generation in ball end milling operations.

In this section is analyzed the surface generation in ball end milling operations considering the geometric aspects of the cut. First, second and third order surface deviations are considered. Crests generated due to the circular shape of the cutter and the radial step over between passes perform third order deviations on the nominal surface while feed angularity makes first and second order deviations. Crest height parameter (h) is analyzed as it is usually used in workshops to make easy calculations about surface characteristics. The approaches proposed by Martellotti in 1931 for peripheral milling operations are essential references of this topic and are reviewed in this research. Material removal rate (MRR) of ball end milling operations has been also calculated in order to observe relationship between quality and productivity.

2.1. Surface crests height (h)

Martellotti [4,5] treated mathematical point of view for peripheral milling operations to show that cutting tool path is an arc of trochoid. Trochoid arc is described by an equation that can be derived from the known cutting variables. Considering a rigid tool and a rigid workpiece system, maximum feed mark height can be calculated as shown in Equation 1:

$$h = \frac{F_z^2}{8\left[R \pm \frac{F_z \times z}{\pi}\right]} \qquad 1$$

Where h is maximum peak height from the lowest level, F_z is the feed per tooth, R the cutting tool radius and z the teeth number. Positive sign in the denominator is for upmilling and negative sign is for downmilling. This equation assumes equal tooth pitch around the cutter and zero run-out.

For ball end milling operations the maximum height of the crest is usually calculated in workshops following the approximated Equation 2.

$$h \approx \frac{Ae^2}{8R} \quad 2$$

This formula is based on cutting geometrical characteristics (see Figure 1). Observing the formula it is possible to determine that bigger is the relation Ae/R, the higher is the crest. Given a cutting tool radius (R) it is possible to reduce the crest height by diminishing the space between two consecutive passes (Ae). Otherwise, fixing Ae it is possible to reduce crest height by using bigger radius tool.

The approximated formula is widely used but it does not provide good approximations in some cases. Theoretical crest height in ball end milling operations can be exactly calculated following circumference equation in a x-y cartesian coordinate system where a circumference with centre in the point (a,b) and radius R is described as:

$$(x-a)^2 + (y-b)^2 = R^2 \quad 3$$

The crest height (h) can be calculated as:

$$h = R - \frac{\sqrt{4R^2 - Ae^2}}{2} \quad 4$$

Figure 2 permits to calculate the crest height in mm given a certain Ae/R value, following the curve of the corresponding tool radius (R).

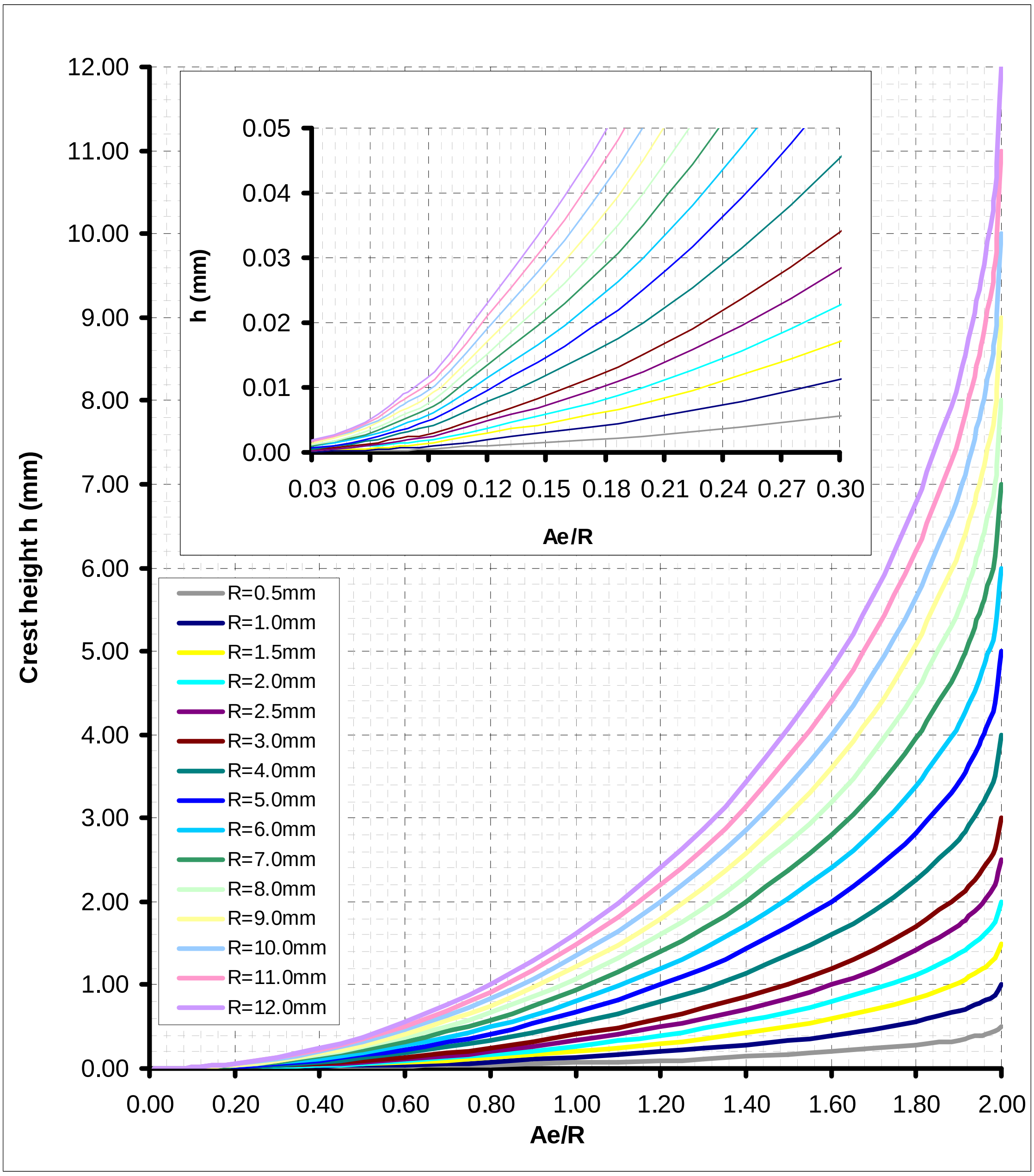

Figure 2. Surface crest height in mm.

For a certain Ae/R relationship, the exact crest height value (h) can be calculated as the product of a constant (k) multiplied by the cutting tool radius (R) as h=k·R with Equation 5. Considering the factor Ae/R, the results obtained applying the approximated formula, have been compared with the results provided by the exact formula in Figure 3 where the value of k factor can be observed multiplying R given a certain Ae/R rate.

$$h=\left(1-\frac{\sqrt{4-\left(\frac{Ae}{R}\right)^{2}}}{2}\right)\times R \qquad 5$$

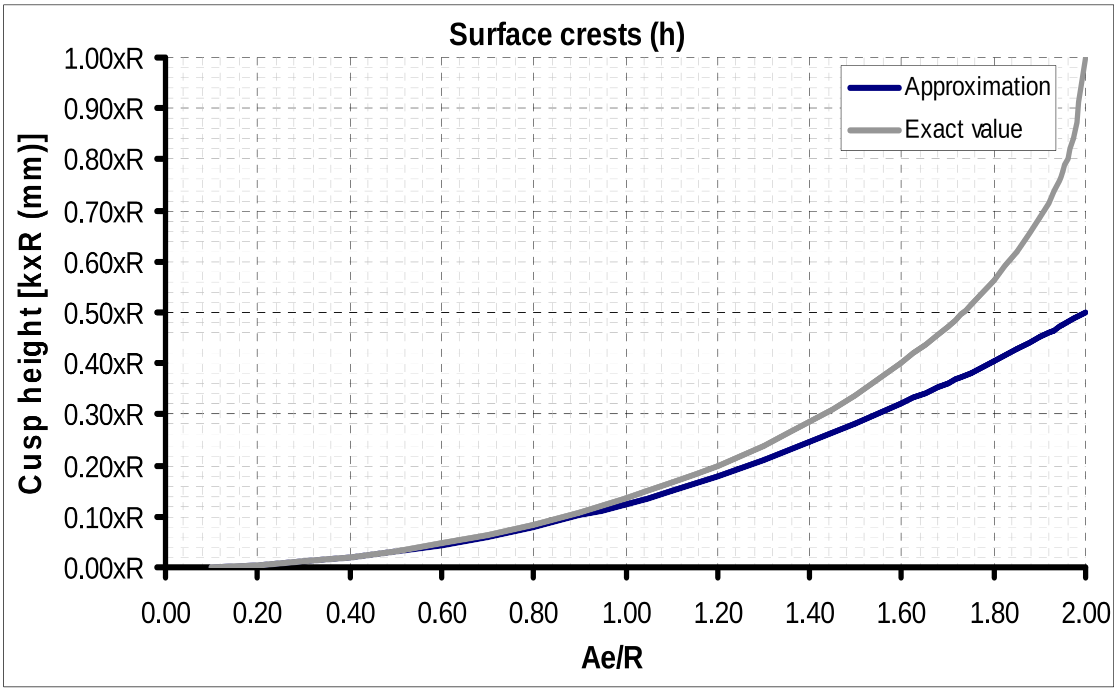

Figure 3. Comparison between exact and approximated calculations.

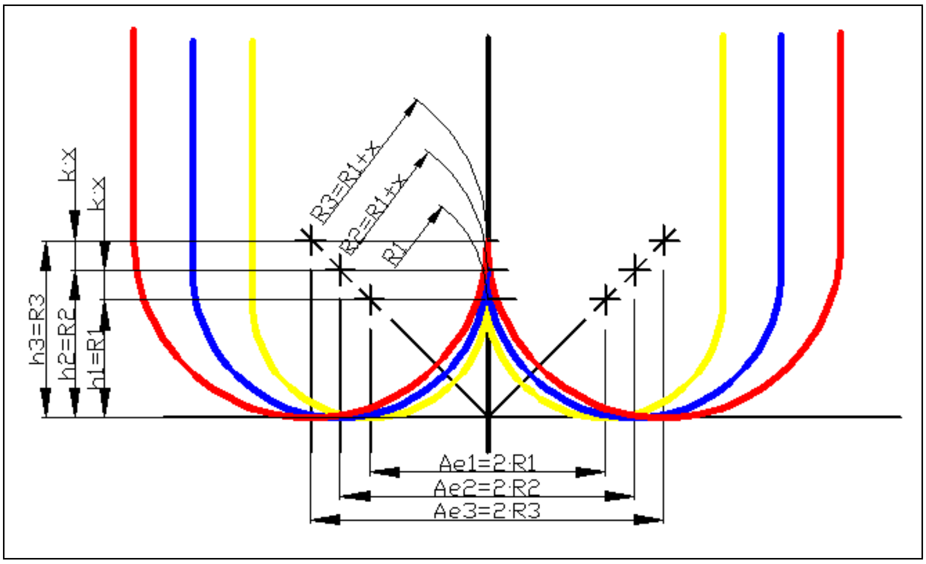

Figure 4. k factor geometrical representation .

The maximum possible Ae value is 2R. When Ae=2R crest height is h=R. Figure 4 shows the geometric description of the k factor presented in Equation 5. Figure 4 shows the specific case of (Ae/R)=2 which is a limit situation. For a certain Ae/R quotient it has been demonstrated that h=k·R; then for R1 it is possible to affirm that h1=k·R1; if R1 is increased a certain value (x) while the quotient Ae/R and so, k, are kept constant, it results in h2=k·(R1+x) or, what is the same, h2=k·R1+k·x. As k·R1=h1, it is demonstrated that h2=h1+k·x as is shown in Figure 4.

Absolute (ε) and relative (e) errors committed when the approximated formula is used have been calculated. The maximum error occurs when Ae=2R then it is when the absolute (ε) and relative (e) errors are bigger.

$$\varepsilon = \left| h_{approx} - h_{exact} \right| \qquad (6)$$

$$e = \left| \frac{h_{aprox} - h_{exact}}{h_{exact}} \right| \qquad (7)$$

In high speed milling Ae/R relationship has usually values around 0.1. At these conditions relative error is 0.0625% which can be an acceptable value. However, relative error increases very quickly (when Ae/R=0.2 the relative error e=0.2506%) until a 50% of relative error when Ae/R=2. (See Figure 5).

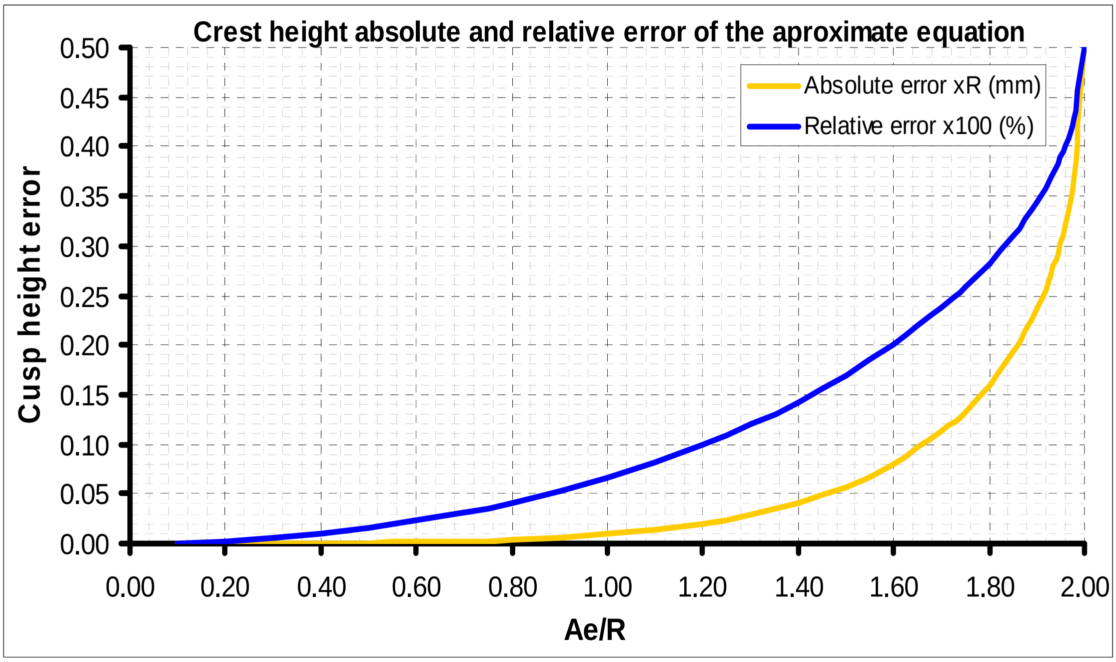

Figure 5. Comparison between exact and approximated calculations.

When inclined surfaces are analyzed then height of surface cusps left due to the axial depth of cut and the tool radius can be calculated as shown in Equation 8. Considering a certain Ae/R relationship, the exact crest height value (h) can be calculated again, as the product of a constant (k) multiplied by the cutting tool radius (R): h=k·R as shown in Equation 9.

$$h = R - \frac{\sqrt{4R^2 - \left(\frac{Ae}{\cos\alpha}\right)^2}}{2} \qquad (8)$$

$$h = \left(1 - \frac{\sqrt{4 - \left(\frac{Ae}{R \cdot \cos\alpha}\right)^2}}{2}\right) \times R \qquad (9)$$

As it is possible to observe, given a certain cutter radius and radial depth of cut, the bigger is surface inclination, the higher is surface crest. Figure 6 shows the surface crest height given a certain case of surface angularity. As it is possible to observe the maximum possible Ae/R relationship is (Ae/R)=2·cos(α) depending on the surface angle. This verifies that the maximum radial depth of cut (Ae) achievable is Ae=2R in the case of angle 0.

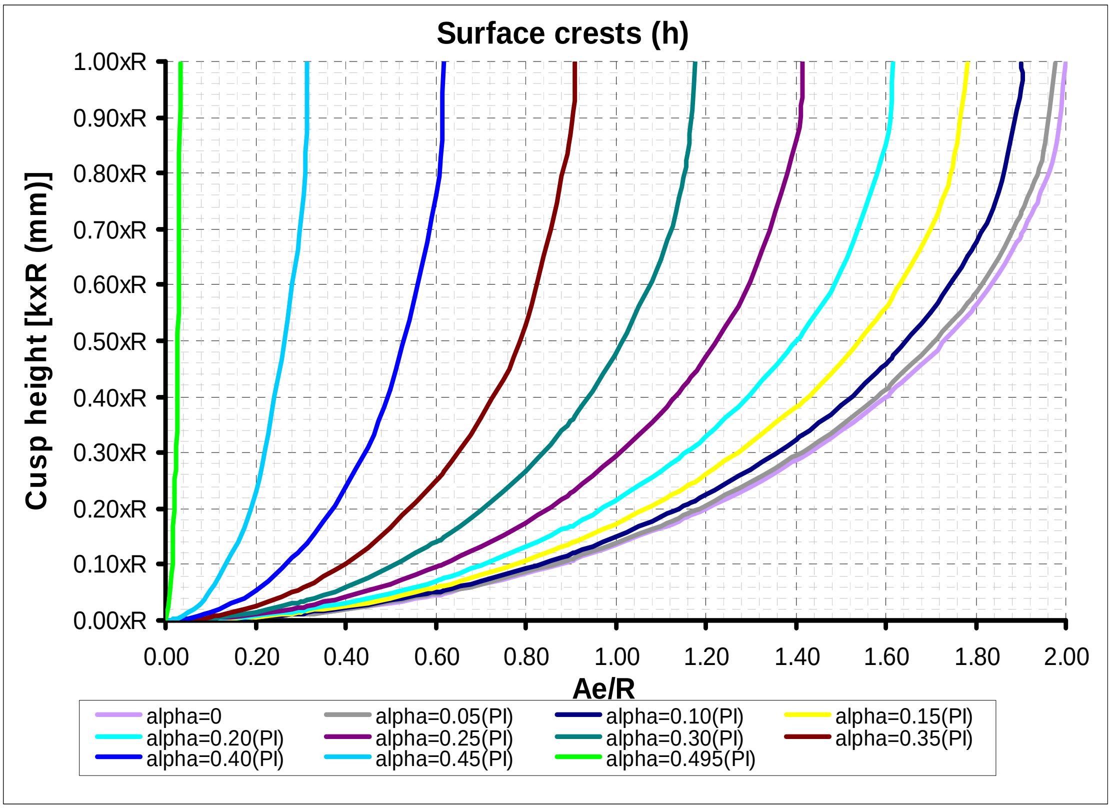

Figure 6. Surface crest and its angularity dependency.

2.2. Surface roughness (Ra)

Figure 7 schematically illustrates the cutting parameters that can generate the third order surface deviations in the case of ball end milling operations where *y* is the position of the central line and it is possible to observe that the sum of areas above the central line is equal to the sum of areas under the central line.

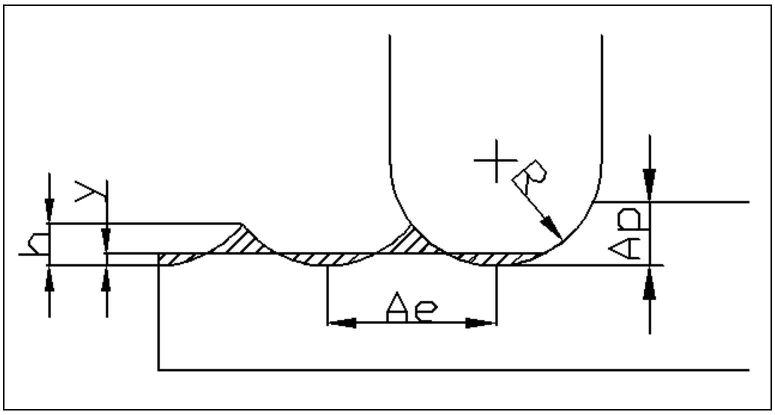

Figure 7. Surface roughness generation in ball end milling operations.

To calculate the theoretical roughness average (Ra) first of all is required to calculate the situation of the central line (y). Equation 10 permits to calculate y as function of h, R and Ae:

$$y = \frac{h}{2} + \frac{R}{2} - \frac{R^2}{Ae} \cdot \sin^{-1}\left(\frac{Ae}{2R}\right) \qquad 10$$

As it is possible to observe in Equation 11, the central line position (y) is a function that depends on surface crest height (h), cutting tool radius (R) and radial depth of cut (Ae). But, as *h* only depends on *R* and *Ae*, it is possible to conclude that *y* only depends on these two parameters. This is also observable in Figure 7. The position of the central line can be calculated with *Ae* and *R* as y=cR considering the rate Ae/R. In Equation 11 the *c* factor can be observed multiplying *R* given a certain Ae/R rate.

$$y=\left[1-\frac{\sqrt{4-\left(\frac{Ae}{R}\right)^{2}}}{4}-\frac{R}{Ae}\cdot\sin^{-1}\left(\frac{Ae}{2R}\right)\right]\times R \qquad 11$$

Once the position of the central line (y) is defined, theoretical roughness average parameter (Ra) can be calculated applying the circumference equation, shown in Equation 3, and roughness average parameter equation, shown in Equation 10. Ra can be calculated with Equation 12 as a function of cutting tool radius (R), axial depth of cut (Ae) and central line position (y).

$$Ra=\frac{2}{Ae}\cdot\left[R^{2}\cdot\cos^{-1}\left(\frac{R-y}{R}\right)-\left[(R-y)\cdot\sqrt{2\cdot R\cdot y-y^{2}}\right]\right] \qquad 12$$

Substituting the central line position (y) in Equation 12 it is possible to observe that *Ra* parameter only depends on *Ae* and *R*, and obviously, *Ae* has a maximum value Ae=2R. Equation 13 permits to calculate the value of the surface roughness average with the radial depth of cut (Ae) and the cutting tool radius (R).

$$Ra=\frac{2}{Ae}\cdot\left[R^{2}\cdot\cos^{-1}\left(\frac{\sqrt{R^{2}-\frac{Ae^{2}}{4}}}{2R}+\frac{R}{Ae}\sin^{-1}\left(\frac{Ae}{2R}\right)\right)-\left(\frac{R^{2}}{Ae}\cdot\sin^{-1}\left(\frac{Ae}{2R}\right)+\frac{\sqrt{R^{2}-\frac{Ae^{2}}{4}}}{2}\right)\cdot\right.$$
$$\left.\cdot\sqrt{-\frac{2R^{3}}{Ae}\cdot\sin^{-1}\left(\frac{Ae}{2R}\right)+2R^{2}-R\sqrt{R^{2}-\frac{Ae^{2}}{4}}-\left(-\frac{R^{2}}{Ae}\sin^{-1}\left(\frac{Ae}{2R}\right)+R-\frac{\sqrt{R^{2}-\frac{Ae^{2}}{4}}}{2}\right)^{2}}\,\right] \qquad 13$$

In Figure 8 surface roughness has been plotted vs. Ae/R. It is possible to calculate surface roughness considering a certain Ae/R relationship and a cutting tool radius (R) which describes the curves described by Equation 13.

Theoretical roughness average parameter (Ra) for inclined surfaces due to the axial depth of cut and the tool radius is described by Equation 15 and the situation of the central line (y) can be calculated applying Equation 14.

$$y=\frac{h}{2}+\frac{R}{2}-\frac{R^{2}\cdot\cos\alpha}{Ae}\cdot\sin^{-1}\left(\frac{Ae}{2R\cdot\cos\alpha}\right) \qquad 14$$

Equation 15 permits to calculate the theoretical surface roughness parameter Ra given a certain radial depth of cut (Ae), a certain cutting tool radius (R) and a certain surface inclination or angularity (α).

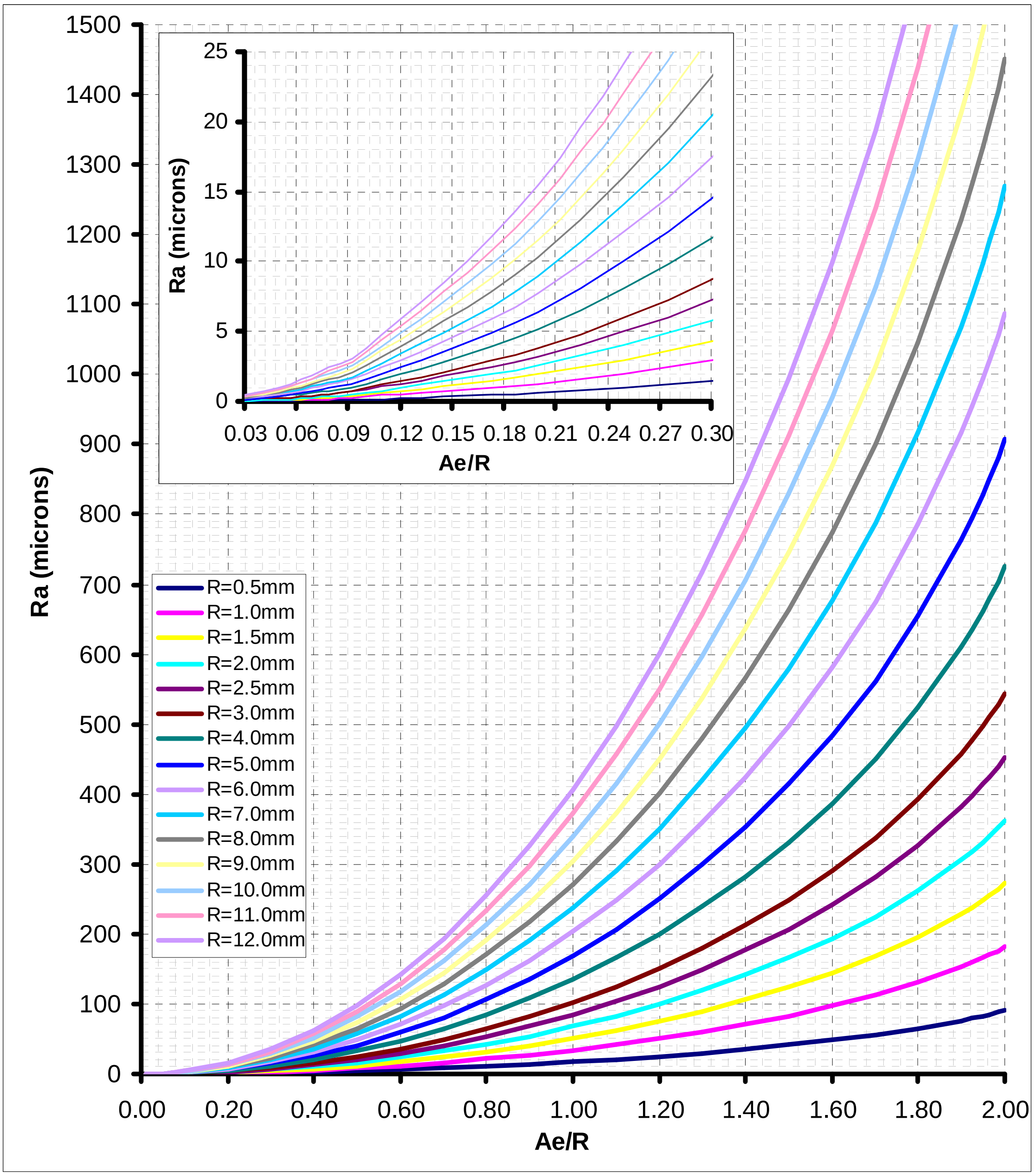

Figure 8. Theoretical *Ra*.

$$Ra = \frac{2\cdot\cos\alpha}{Ae}\cdot\left[R^2\cdot\cos^{-1}\left(\frac{\sqrt{R^2-\frac{Ae^2}{4\cdot\cos^2\alpha}}}{2R}+\frac{R\cdot\cos\alpha}{Ae}\sin^{-1}\left(\frac{Ae}{2R\cdot\cos\alpha}\right)\right)-\left(\frac{R^2\cdot\cos\alpha}{Ae}\cdot\sin^{-1}\left(\frac{Ae}{2R\cdot\cos\alpha}\right)+\frac{\sqrt{R^2-\frac{Ae^2}{4\cdot\cos^2\alpha}}}{2}\right)\cdot\right.$$

$$\left.\cdot\sqrt{-\frac{2R^3\cdot\cos\alpha}{Ae}\cdot\sin^{-1}\left(\frac{Ae}{2R\cdot\cos\alpha}\right)+2R^2-R\sqrt{R^2-\frac{Ae^2}{4\cdot\cos^2\alpha}}-\left(-\frac{R^2\cdot\cos\alpha}{Ae}\sin^{-1}\left(\frac{Ae}{2R\cdot\cos\alpha}\right)+R-\frac{\sqrt{R^2-\frac{Ae^2}{4\cdot\cos^2\alpha}}}{2}\right)^2}\right]$$

2.3. Material removal rate

Material removal rate, MRR, provides information about the process productivity. It is the volume of material that is took away in a certain time period due to the interaction between the cutting tool and the workpiece in the machining operation. For flat milling operations (see Figure 9), with the radial depth of cut (Ae), axial depth of cut (Ap) in mm and feed speed, (f), in mm/min, volume of material removed (MRR) in mm^3/min can be calculated as: $MRR = Ae \cdot Ap \cdot f$. Where (Ae·Ap) is known as transversal cutting section (Cs) [29].

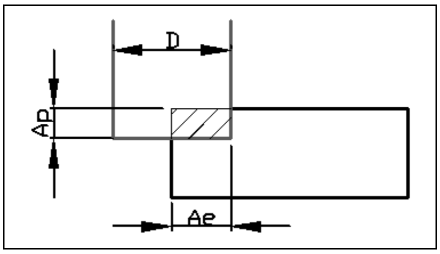

Figure 9. Material removal rate in flat end milling operations.

For ball end milling operations (see Figure 10), MRR depends on axial and radial depths of cut (Ap, Ae), the cutting tool radius (R) and the feed rate (f) as shows Equation 16, so MRR(Ae,R,Ap,f). The minimum Ap given a certain relation Ae/R must be, at least, equal to h as, otherwise, it would become a slotting operation. The maximum Ap value is R, which is the maximum crest height (h) possible. This is possible to be observed in Figure 10. h<Ap<R.

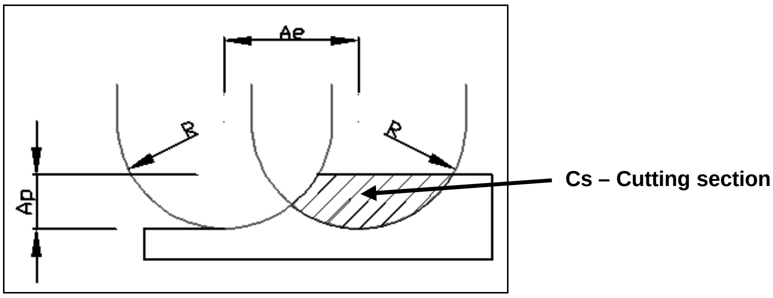

Figure 10. Material removal rate in ball end milling operations.

$$MRR = f\left[\left[Ae \cdot Ap\right] - \left[Ae \cdot R - \frac{Ae}{2}\left[\sqrt{R^2 - \left(\frac{Ae}{2}\right)^2}\right] - R^2 \cdot \sin^{-1}\left[\frac{Ae}{2 \cdot R}\right]\right]\right] \qquad 16$$

Where, the term multiplying the feed rate is the transversal cutting section shown in Figure 10. As above-mentioned, material removal rate can only be calculated for Ap>h and Ap<R. For the first limit case, when Ap=h the MRR is described by Equation 17 that has been built substituting Equation 4 in the term Ap of Equation 16 and simplifying.

$$MRR_{mín} = f\left[R^2 \cdot \sin^{-1}\left[\frac{Ae}{2 \cdot R}\right] - \frac{Ae}{4}\sqrt{4R^2 - Ae^2}\right] \qquad 17$$

For the second limit case, when Ap=R the MRR is described by Equation 18. Equation 18 has been built substituting the term Ap by R in Equation 16 and simplifying.

$$MRR_{\max} = f\left[R^2 \cdot \sin^{-1}\left[\frac{Ae}{2 \cdot R}\right] + \frac{Ae}{4}\sqrt{4R^2 - Ae^2}\right] \qquad 18$$

When Ae=2R, which is the limit case h=R, the root square of Equations 17 and 18 is 0 and so, $MRR_{min}=MRR_{max}$. In this case, $\sin^{-1}=(Ae/(2R))=\pi/2$, which is the area of a semicircle, the region of the cutting tool immersed in the workpiece, multiplied by the feed rate (Equation 19).

$$MRR_{Ae=2R} = f\left[R^2 \cdot \frac{\pi}{2}\right] \qquad 19$$

Figure 11 shows four views of Equation 16 plotted for the specific cases presented in Equations 17 and 18. It is possible to observe the cutter radius (R) with a maximum of 6mm and relation

Ae/R effect on the value of the cutting section. This values permits to calculate the MRR once multiplied by the feed rate chosen.

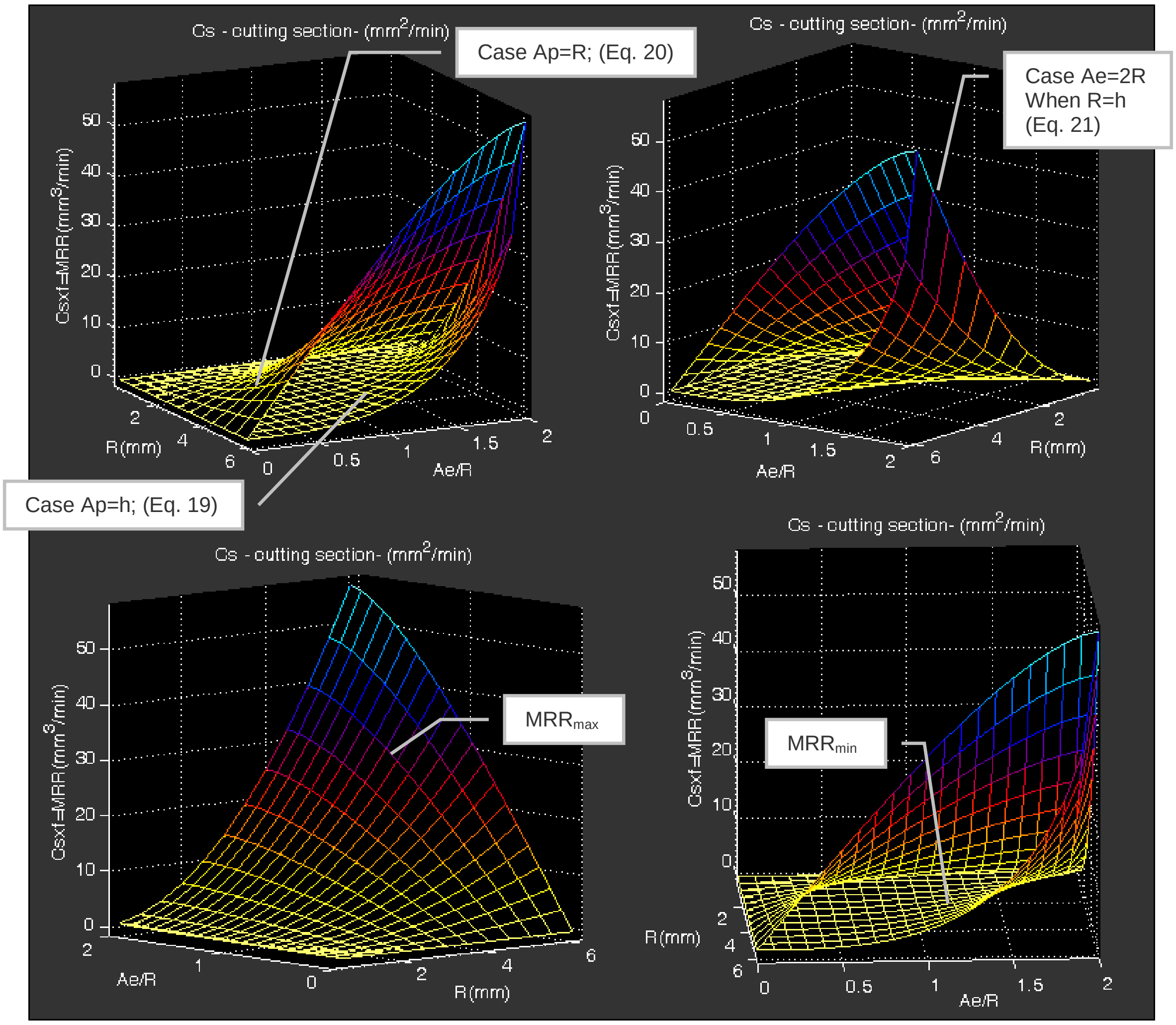

Figure 11. Material removal rate curves in ball end milling operations.

From the geometrical point of view, as the axial depth of cut (Ap) does not affect the surface roughness (see Equation 13), it can be increased to obtain higher material removal rate without affecting the theoretical surface roughness average. Material removal rate given a certain *Ae*, *R* and *f* results in a straight line that can be extracted from Equation 16 (MRR=f·Ae·Ap – constant) where the straight line slope is (f·Ae).

3. Design of Experiments and Experimental Set Up

Several experiments were carried out considering several cutting conditions. Surface roughness has been analyzed with a rugometer in order to measure the height of the crests (h) and the roughness average parameter (Ra). Afterwards, experimental values are compared to theoretical values.

Experimentation was carried out in a Deckel-Maho 105Vlinear 3 axes vertical high speed machine centre with a Heidenhain iTNC 530 Control. Four cutting tool radius were used. Cutting tools were Mitsubishi VC-2PSB ball end mill 3, 4, 5 and 6 mm of radius and 2 cutting edges with regular pitch and helix angleTools were clamped in HSK-63-A toolholder with a mechanical chuck and each tool was used to perform one set of 10 experiments. Tool wear is not considered because each tool is new. Machined material was Hardened AISI H13 Steel with 52-54HRC hardness commonly used in dies and moulds industry.

Experiments consisted on a simple raster metal removal operation along the machine tool Y axis. Surface was flattened once clamped in the vice so it can be considered as totally flat (α=0). A total of 40 experiments were planned divided in four set of 10 experiments, one set for each cutting tool diameter. Spindle speed (S) had 10 levels, from 6,000 rpm to 24,000rpm in increases of 2,000 rpm. Radial depth of cut was constant in all experiments Ae=0.4mm. Relation Ae/R is Ae/R=0.133 when R=3mm; Ae/R=0.100 when R=4mm; Ae/R=0.080 when R=5mm; Ae/R=0.067 when R=6mm. Each experiment carried out 20 passes so it took 8mm of width which is the space required by the rugometer to measure the surface profile.

Axial depth of cut was chosen following the parameters suggested by tool provider to ensure a stable cut without chatter presence (Ap=0.24mm). Feed rate (f) was also calculated in order to keep the feed per tooth (fz) recommended cutting tool provider (f=fz·S·z).

Table 1 shows the parameters and levels used to perform the experimental work. Expected surface parameters crest height (h_{exp}) and roughness average (Ra_{exp}) have been calculated applying Equations 4 and 13 respectively. Transversal cutting section (Cs) and material removal rate (MRR) have also been calculated with Equation 16. Figure 12 shows geometrical performance of the material removal operations and results expected by each parameters combination.

Exp.	S (rpm)	f (mm/min)	fz (mm/z)	R (mm)	Ap (mm)	Ae (mm)	Vc (m/min)	$h_{exp.}$ (µm)	$Ra_{exp.}$ (µm)	Cs (mm^2)	MRR (mm^3/min)
1	6000	1273					226.19				121.64
2	8000	1697					301.59				162.16
3	10000	2121					376.99				202.67
4	12000	2545					452.39				243.19
5	14000	2970	0.1061	6			527.79	3.3343	0.8555	0.0956	283.80
6	16000	3394					603.19				324.32
7	18000	3818					678.58				364.83
8	20000	4242					753.98				405.35
9	22000	4667					829.38				445.96
10	24000	5091					904.78				486.47
11	6000	1125					188.50				107.40
12	8000	1500					251.33				143.20
13	10000	1875					314.16				179.00
14	12000	2250					376.99				214.80
15	14000	2625		5			439.82	4.0016	1.0267	0.0955	250.60
16	16000	3000	0.0938				502.65				286.40
17	18000	3375					565.49				322.20
18	20000	3750			0.24	0.40	628.32				358.00
19	22000	4125					691.15				393.80
20	24000	4500					753.98				429.60
21	6000	900					150.80				85.80
22	8000	1200					201.06				114.40
23	10000	1500					251.33				143.00
24	12000	1800					301.59				171.60
25	14000	2100	0.0750	4			351.86	5.0031	1.2836	0.0953	200.20
26	16000	2400					402.12				228.80
27	18000	2700					452.39				257.40
28	20000	3000					502.65				286.00
29	22000	3300					552.92				314.60
30	24000	3600					603.19				343.20
31	6000	692					113.10				65.82
32	8000	923					150.80				87.79
33	10000	1154					188.50	6.6741	1.7122	0.0951	109.76
34	12000	1385	0.0577	3			226.19				131.73
35	14000	1615					263.89				153.60
36	16000	1846					301.59				175.57

37	18000	2077					339.29				197.55
38	20000	2308					376.99				219.52
39	22000	2538					414.69				241.39
40	24000	2769					452.39				263.36

Table 1. Parameters and levels used in the 40 experiments.

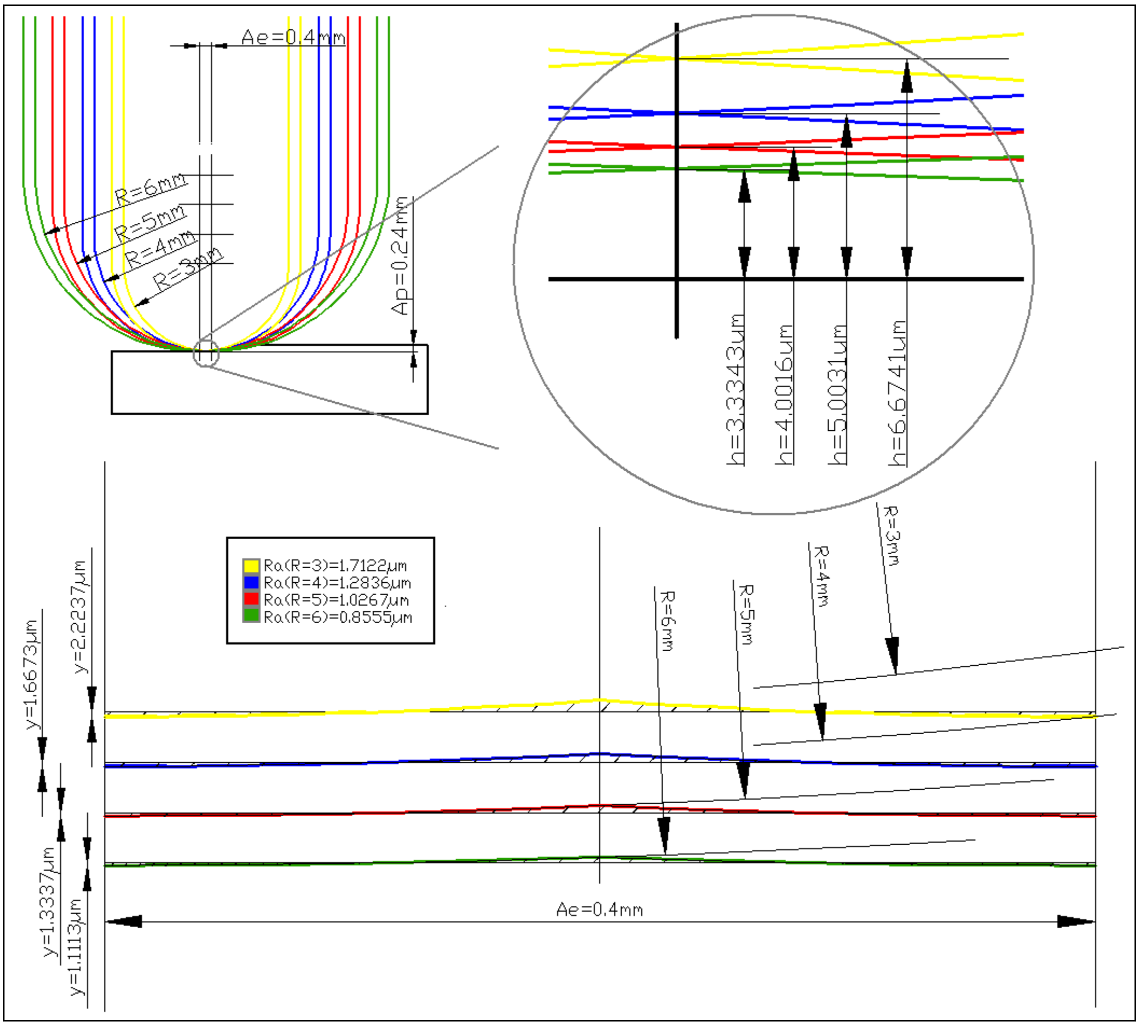

Figure 12: Surface expected given the geometrical cut parameters

Experiments were carried in dry machining. PowerMill software was used to generate the g-codes. A warm-up cycle with progressive increase of the revolution spindle speed from 4,000 rpm to 14,000 rpm increasing it 2,000 rpm every 60s were used as experimental protocol.

4. Results and discussion

Surface roughness was measured with a Mitutoyo SV-2000N2 roughness tester. Evaluation length was 7.002mm and nominally 2µm stylus tip was used at a speed of 2m/s and with0.75mN static stylus force to obtain 2334 surface points. Surface profile measured for experiments 1, 11, 21 and 31 are shown in Figure 13. Figure 14 presents results obtained in the 40 experiments carried out by tool radius and spindle speed. The first 4mm of the measured profile is displayed in columns depending on the tool radius and in rows depending on the spindle speed. It is possible to observe relevant differences depending on tool radius.

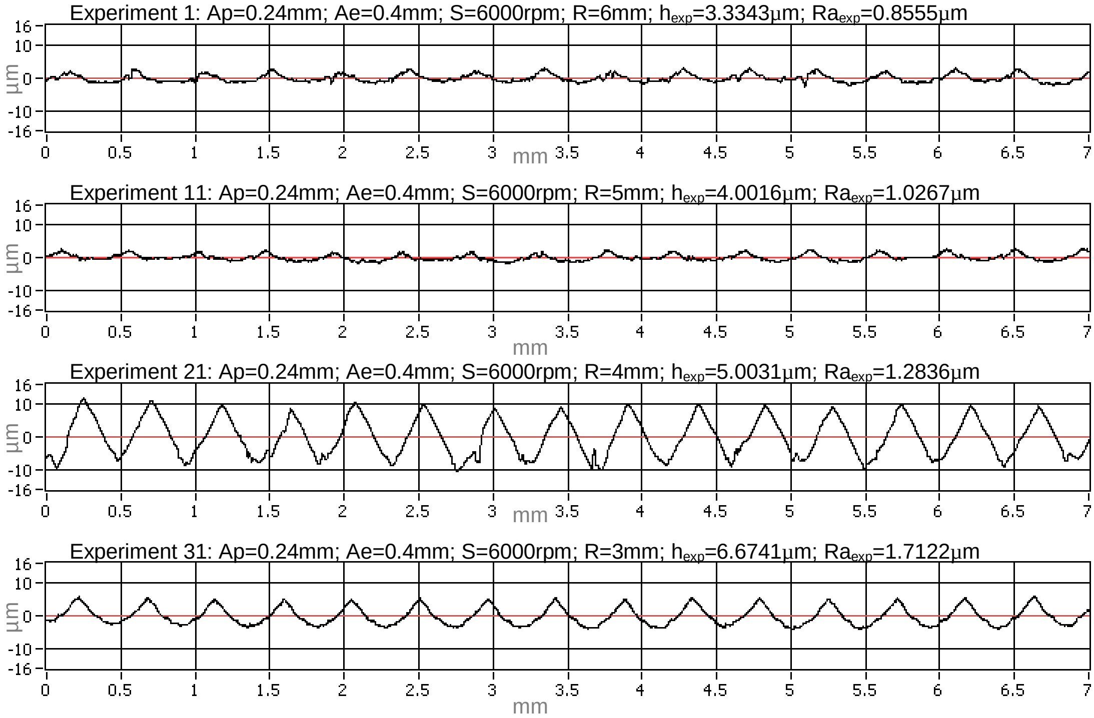

Figure 13. Surface profiles of experiments 1, 11, 21 and 31.

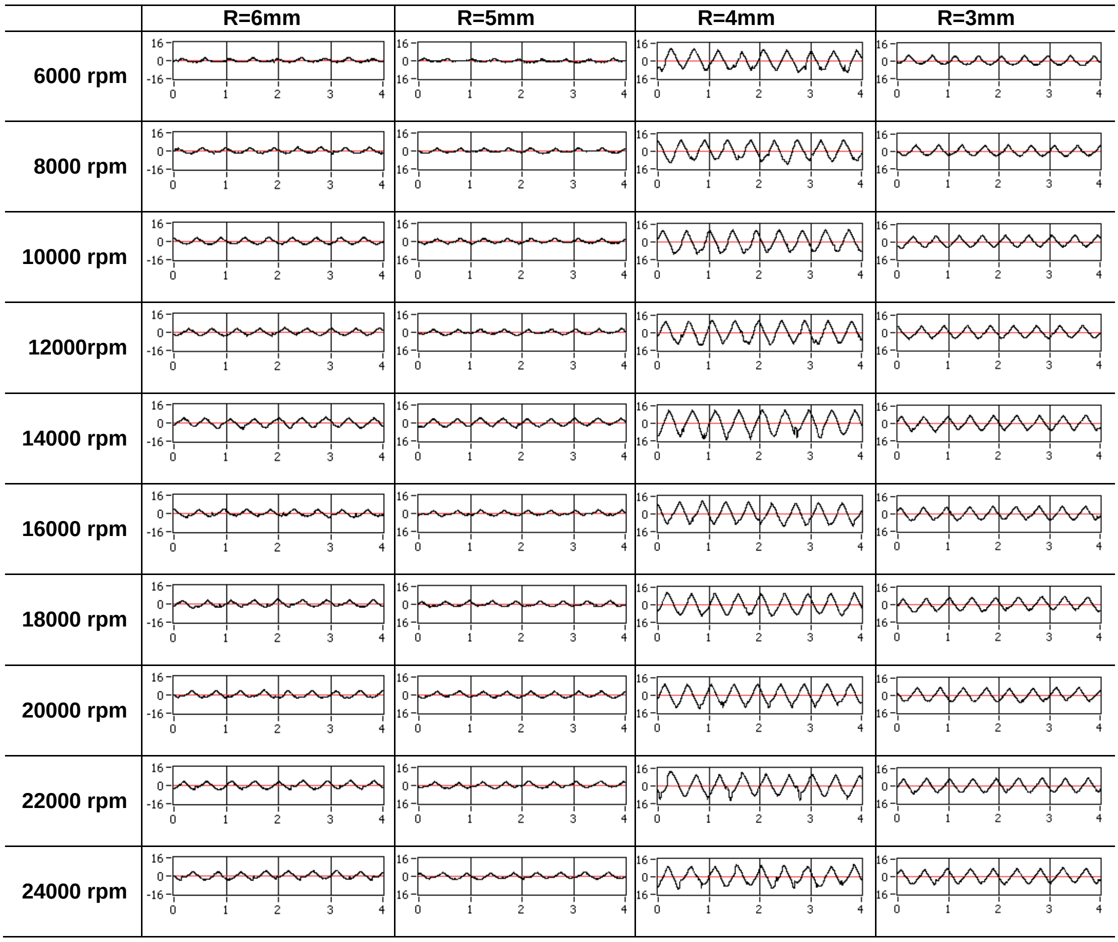

Figure 14. Surface profiles of the 40 experiments.

Figure 15 compares expected and experimental results for the 40 experiments carried out. Profile characteristics taken into consideration have been the surface crest height (h) and the roughness average (Ra). Figure 15 shows the theoretical and measured surface crest height and also the roughness average theoretical and measured. Absolute (ε) and relative (e) errors have been calculated in order to quantify the deviations occurred due to several factors that the metal removal process entails different to the geometric characteristics of the cut.

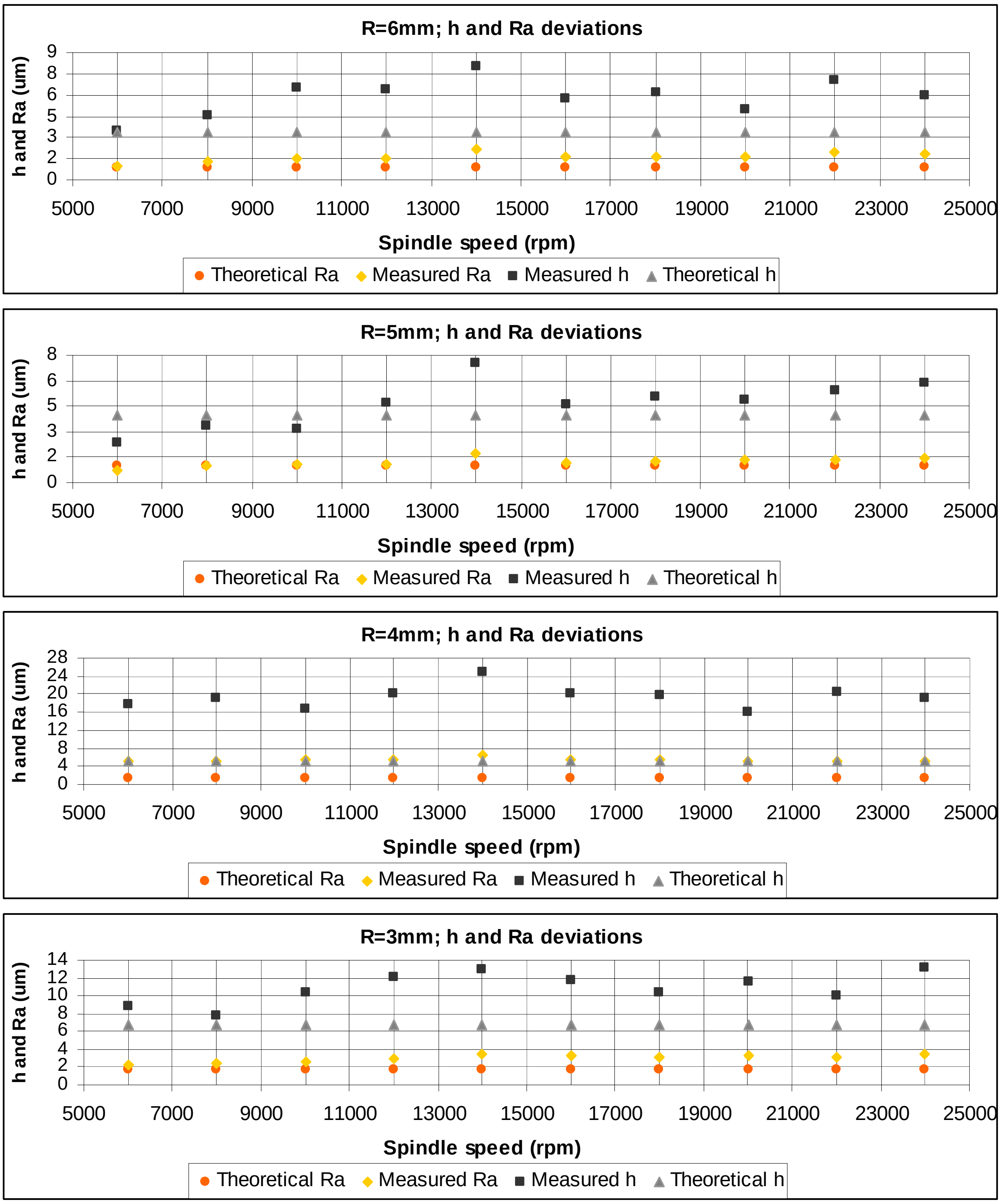

Figure 15. Expected and experimental results for the 40 experiments

As it is possible to observe in Figure 15, comparison between expected and measured values is not very accurate. Mean absolute and relative error values committed for surface crest height parameter are ε_h =5.63 µm and e_h=44.94%. Maximum error values are obtained when 4 mm diameter tool is used. Otherwise, mean absolute and relative error values committed for surface roughness are ε_{Ra} =1.59 µm and e_{Ra}=45.94%. Concerning the tool radius it is possible to observe considerable differences depending on the cutter radius. Table 3 presents the absolute and relative errors for *h* and R_a. The most accurate approximation occurs when tool radius is 5mm and the worst values are obtained when tool radius is 4mm.

	ε_h (μm)	e_h (%)	ε_{Ra} (μm)	e_{Ra} (%)
R=6mm	2.57	40.55	0.75	44.38
R=5mm	1.27	28.11	0.27	21.90
R=4mm	14.44	73.90	4.05	75.85
R=3mm	4.23	37.19	1.28	41.63

Table 3. Absolute and relative errors concerning tool radius.

Another interesting point is that expected *h* and *Ra* are in most of cases lower than experimental *h* and *Ra*. Considering that *h* and *Ra* only depend on radial depth of cut (Ae) and tool radius (R), this error can not be originated due to an error in the g-code generation. As it is possible to observe in Figure 14 the radial depth of cut is 0.4mm and tool radius has to be considered also a very exact value. As axial depth of cut *Ap*, does not influence from the theoretical point of view, the height of the crests (h) or the roughness average (Ra) there is not the possibility of considering a possible difference between the planned and the real value due to the operator when introducing the zeros in the machine as surface was flattened before starting with the experiments. Different temperatures between the machine tool enclosure, when machining and, the metrology chamber, when measuring, can also have influence in deviations observed.

With these analyses, it its demonstrated that surface roughness prediction is not an easy task. Surface generation is influenced by a lot of factors and their interrelations but it is not possible to accurately predict surface characteristics only with mechanic approximations. Other factors should be considered to obtain a more realistic model considering other influencing factors such as material behaviour, hardness, fluency and inhomogeneities, process kinematics and dynamics, vibrations, runout, tool wear, the use of lubricants, etc. but as interactions among these factors are complex and it is not easy to find cause-effect relations it seems that artificial intelligence approaches through, for example, artificial neural networks, genetic algorithms, fuzzy logic, expert systems etc. suit, with these requirements. However, the theoretical approach presented in this research offers a useful background that should also be considered and integrated in further more complex and realistic computer approaches.

5. Conclusions and further work

Surface characteristics influence the final part performance and are used as quality indicators. In metal removal operations surface generation is affected by an enormous number of complexly interrelated factors; it is difficult to predict the surface characteristics knowing only cut characteristics and usually surface roughness is post-process evaluated with the help of a profilometer making quality assurance in advance, not an easy task.

Surface generation in ball end milling operations has been studied considering the geometrical cut characteristics. Equations to calculate surface crests height (h) and surface roughness average parameter (Ra) have been developed as function of tool radius (R) and radial depth of cut (Ae) considering surface angularity. Charts for the graphical calculation of the theoretical surface crest height and surface roughness have been constructed. Material removal rate (MRR) is a productivity indicator. Equations for MRR calculation have also been developed and plotted for easily MRR calculations.

Experimentation has permitted to quantify deviations and differences between theoretical approach and machined surface. These analyses demonstrate that the surface roughness prediction is not an easy task due the complexity of its generation.

In future works, to have accurate surface characteristics calculations more realistic process modelling would be required taking into account the mentioned influencing factors. Approaches a kind of artificial intelligence seem to suit, with these requirements. Nevertheless, the theoretical approach exposed in this research provides a useful background that should also be considered and integrated in further more complex and realistic computer approaches.

Moreover, recent years trends seem to be focused on the on-line monitoring, measuring and controlling machining incidences thanks to the improvements and advances in the fields of computers and sensors. Surface roughness monitoring and controlling is the next step of this investigation taking into account the characteristics of the cut, on-line measured factors and the theoretical knowledge generated in this research.

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Chapter 6. Surface roughness monitoring in ball end milling operations

Chapter 6 presents the development of a reliable surface roughness monitoring application based on artificial neural networks for ball end milling operations. Five full factorial series of experiments were carried out in order to obtain data that was used to train the artificial neural network. In the design of experiments were considered geometrical cutting factors, dynamic factors, part geometries, lubricants, materials and machine tool. Vibration was captured on-line with two piezoelectric accelerometers placed following the X and Y axes of the machine-tool.

This study was presented in an article entitled *"Surface Roughness Monitoring Application Based on Artificial Neural Networks"*, published in the Proceedings of the 12th CIRP Conference on Modelling of Machining Operations, held in Donostia-San Sebastián in May 2009 (Quintana et al., 2009).

Surface Roughness Monitoring Application Based on Artificial Neural Networks

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Abstract
Surface roughness plays an important role in the performance of a finished part. Surface roughness is usually measured off-line when the part is already machined. The recent years trends seem to be focused on the on-line monitoring, measuring and controlling the machining process and this is possible thanks to the improvements and advances in the fields of computers and sensors.

The aim of this work is to develop a reliable surface roughness monitoring application based on artificial neural networks approach for vertical high speed milling operations. Experimentation has been carried out in order to obtain data that was used to train the artificial neural network. Geometrical cutting factors, dynamic factors, part geometries, lubricants, materials and machine tool have been considered. Vibration was captured on-line with two piezoelectric accelerometers placed following the X and Y axes of the machine-tool.

1. INTRODUCTION

Machining is applied to a wide range of materials to create a great variety of geometries and shapes, practically without complexity restrictions. Typical workpiece materials are: aluminium alloys, cast iron, titanium, austenitic stainless or hardened steels, copper, carbon graphite and also plastics, woods and plastic composites. Machined components can be either simple forms with planes and round shapes or complex shapes. In the latter case, two types of surfaces are usually defined: ruled surfaces, (e.g. for blades) and sculptured surfaces or free-form surfaces (e.g. for moulds and dies). This enormous number of combinations is able to meet the specific manufacturing requirements of a wide range of manufacturing industries, such as automotive, aerospace or dies and moulds [1].

There has been a constant innovation and technical advances in all manufacturing systems fields during last years. New technologies have been introduced in the market and new concepts in metal cutting such as high speed machining (HSM) have been developed.

The term 'High Speed Machining' has been used for many years to describe end milling with small diameter tools at high rotational speeds. The process was first applied in the aerospace industry for the machining of light alloys. However, mould and die industry began to use the technology for the production of components, including those manufactured from hardened tool steels. This has only been made possible by advances in machine tools, cutting tools and CAD/CAM systems [2].

Surface properties play an important role in the performance of a finished part. They have an enormous influence on several features such as dimensional accuracy, friction coefficient and wear, thermal and electric resistance, fatigue limit, corrosion, post-processing requirements, appearance and cost. Surface roughness is usually measured off-line when the part is already machined [3] and it is a widely used index of product quality and a technical requirement for mechanical products [4].

A lot of research has been focused on surface generation in order to understand the process and provide the knowledge necessary to be capable to ensure the surface quality before starting the metal removal operation [4-15].

In 1931 Martellotti [5,6] studied mathematical point of view process to show that cutting tool path is an arc of trochoid for peripheral milling operations. Later on, Thomas et al. [7] analyzed tool vibrations effect on surface roughness for lathe dry turning processes. Abouelatta and Mádl [8] studied the relationship between tool life, surface roughness and vibration considering cutting speed, feed rate, depth of cut, tool nose radius, tool overhang and the accelerations amongst others parameters in radial and feed directions. Ghani et al. [9] followed an analogous approach using vibration signals and verified surface finish due to tool wear evolution. Risbood et al. [10] used neural networks to predict surface finish in turning processes considering tool holder vibration level. The usefulness of artificial neural networks approach has been demonstrated in several fields [16-19]. Correa et al. [11,12] show the efficacy of Bayesian Netwoks and Artificial Neural Networks for predicting surface roughness in high-speed machining. Others propose in-process methods [13-15].

In 2003 Bernardos and Vosniakos [4] published a review of the state of the art on the surface roughness prediction in machining operations. They provide a extensive study about the main research lines and classify the different approaches considering those based on machining theory, experimental investigation, design of experiments and artificial intelligence.

Beside the several methodologies and strategies adopted by researchers in order to study the surface roughness generation and the finishing techniques applied in industry, several standards have been developed [20,21]. ISO-4287 and ISO-4288 are both about dimensional and geometrical product specifications and verification and are focused mainly on surface texture.

Actually, systems seem to be focused on monitoring processes by measuring and controlling the surface roughness. This on-line monitoring is possible due to the improvements and advances in computers and sensors fields.

The purpose of this research is to develop a reliable surface roughness monitoring application based on artificial neural networks models for ball end mill finishing operations. As nowadays surface roughness can only be evaluated out-of-process it seems necessary to introduce in-process solutions to control the surface generation process and avoid dropping away unacceptable parts once the part is finished and time and energy have been spent on it. A monitoring approach can permit to detect lacks of quality as soon as occur and modify the cutting parameters or interrupt the process to reconsider or redefine the operation.

The paper is structured as follows. Section 2 explains experimental procedure followed to obtain data used to feed the neural network for surface roughness prediction. Section 3 introduces the neural network developed. Section 4 shows the surface roughness monitoring platform implemented and finally conclusions are summarized in Section 5.

Nomenclature	
Ae	Radial depth of cut (mm)
Ap	Axial depth of cut (mm)
C.L.A.	Center line average
F	Feed rate (mm/min)
Fz	Feed per tooth (mm/z)
Lm	Length of measurement
R	Cutter radius (mm)
Ra	Roughness average (μm)
S	Spindle speed (rpm)
Y	Vertical deviations from the nominal surface
Z	Number of teeth

2. EXPERIMENTAL PROCEDURE AND DATA COLLECTION

Surface roughness is a parameter which refers to the small, finely spaced deviations from the nominal surface determined by the material characteristics and the process that formed the surface. Surface roughness can be defined as the average of the vertical deviations from the nominal surface over a specified surface length. According to the standard ISO 4287:1999, an arithmetic average is generally used, based on the absolute values of the deviations, as shown in Equation 1, and the roughness value is referred to by the name of average roughness [3].

$$Ra = \int_0^{Lm} \frac{|y|}{Lm} dx \tag{1}$$

Where Ra is the arithmetic mean value of roughness also known as C.L.A. Centre Line Average; y is the vertical deviation from the nominal surface converted to absolute value and Lm is the specified distance over which the surface deviations are measured.

The determination of the process parameters that permit to yield the required product quality by defining surface roughness, while maximizing the manufacturing process performance is not an easy task. Usually conservative combinations of cutting parameters are selected by the operators. The set of parameters that influence the surface roughness and have motivated researchers is compiled by Benardos and Vosniakos [4] in a fishbone diagram that considers: machining parameters such as process kinematics, cooling fluid, stepover, depth of cut, tool angle, feed rate and cutting speed; the cutting tool properties such as the tool material, runout errors, tool shape and nose radius; the workpiece properties such as the length, diameter and hardness; and the cutting phenomena such as the cutting force variation, friction in the cutting zone, chip formation, vibrations and accelerations. Interactions among these factors are complex and make difficult understanding of cause-effect relationships necessary to implement surface roughness models.

Design of experiments was carried out considering the majority of parameters that affect surface roughness presented in [4]. This would permit to capture and evaluate the effects of the main factors and implement a reliable artificial neural network able to calculate the surface roughness generated given a certain combination of cutting characteristics among all the possibilities available.

Experiments consisted on a simple raster metal removal operation along machine tool Y axis. Spindle speed (S), feed rate (f), feed per tooth (fz), axial and radial depths of cut (Ar and Ae) and type of lubricant used (dry machining or minimum quantity of lubricant, MQL) were considered. A total of 250 experiments were designed and performed were divided in 5 full factorial series of 50 experiments. Cutting parameters and levels are summarized in Table 1.

Due to the influence of geometrical aspects, such as radial depth of cut (Ae) and cutter radius (R), on the surface roughness generation (see Figure 2) two series of 50 experiments were designed. First, one series of 50 experiments was performed maintaining a constant feed per tooth of 0.075 mm/z and axial depth of cut of 0.24mm. Influence of spindle speed (S) and radial depth of cut (Ae) was analyzed. Then, one series of 50 experiments was carried out with a constant radial depth of cut of 0.4mm and an axial depth of cut of 0.24mm as suggest the cutter provider tables. In this set of experiments was varied the spindle speed (S) and the cutter radius (R). In all series spindle speed (S) had 10 levels from 6,000rpm to 24,000rpm with an increase of 2,000rpm in each level.

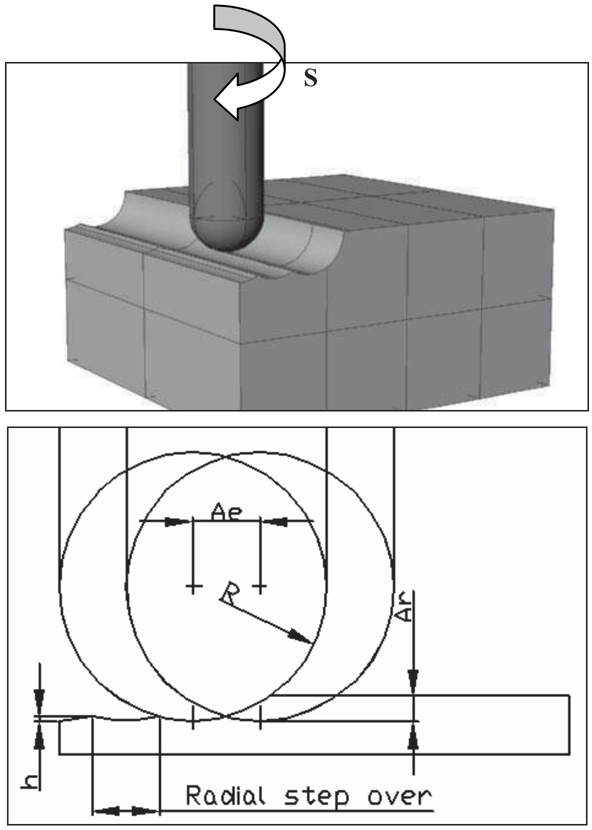

Figure 1. Surface roughness generation in a vertical ball end milling operation.

Two series of 50 experiments were carried out, first in dry machining then applying MQL, with a constant feed per tooth of 0.075mm/tooth and a radial depth of cut of 0.4mm (as suggested by the cutting tool provider in the cutter tables) and varying spindle speed (S) and axial depth of cut (Ar) following a full factorial design with the levels showed in Table 1. As the frontier between stable and unstable cut is shown as combinations of spindle speed and the axial depth of cut in stability lobe diagrams, the influence of these two cutting parameters has been considered.

Other factors analyzed were the feed rate (f) and the feed per tooth (fz) which both affect the chip generation and the cutting forces. Both parameters are related among each other in the expression:

$$f = fz \times z \times S \qquad (2)$$

One series of 50 experiments was carried out with a constant radial depth of cut of 0.4mm and an axial depth of cut of 0.24mm as is suggested in the cutting tool provider tables. The influence of spindle speed, the feed per tooth was considered and the feed rate was calculated with expression 2.

Parameters	Units	Levels									
		1	2	3	4	5	6	7	8	9	10
Spindle speed	rpm	6000	8000	10000	12000	14000	16000	18000	20000	22000	24000
Radial depth of cut	mm	1.0	0.8	0.6	0.4	0.2					
Tool radius	mm	2	3	4	5	6					
Axial depth of cut	mm	0.10	0.14	0.19	0.24	0.29					
Feed per tooth	mm/z	0.150	0.125	0.100	0.075	0.050					

Table 1. Experimentation parameters.

A Mitsubishi VC-2PSB ball end mill cutting tool of 4mm 6mm, 8mm, 10mm and 12mm diameters were tested. This solid cutter has 2 cutting edges and a regular pitch and helix angle. In Figure 2 and Table 2 are showed the geometric characteristics of the radius 4mm cutter.

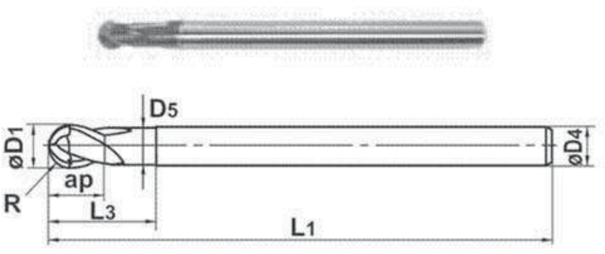

Figure 2. Mitsubishi VC-2PSB cutter schematically represented.

L_1	Overall Length (mm)	90
L_3	Neck Length (mm)	16
ap	Length of Cut (mm)	12
R	Radius of ball nose (mm)	4
D_1	Diameter (mm)	8
D_3	Neck diameter (mm)	7.85
D_4	Shank diameter (mm)	8
Z	Number of teeth	2

Table 2. Geometric characteristics of the Mitsubishi VC-2PSB cutter.

The milling centre used to perform the experimentation was a Deckel-Maho 105Vlinear three axes vertical high speed machine centre with a Heidenhain iTNC 530 Control. Material used was quenched steel 1.2344, analogue of AISI H13 with a hardness of 52-54 HRC, very common in dies and moulds industry. PowerMill software was used to generate the CAM G-code.

Labview^{TM} was used to develop a data acquisition platform to acquire and analyze the vibrations occurred in X and Y axes. Current vibration was obtained with two unidirectional piezoelectric accelerometers placed, one in the spindle, (see Figure 3) and other in the table following the corresponding axes. In Figure 4 is showed vibrations captured example with both accelerometers. It is possible to observe the rapid traverses of the table between the effective metal removal passes where the machined surface is generated.

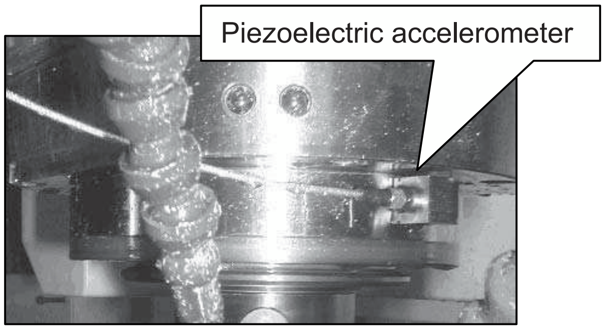

Figure 3. Piezoelectric accelerometer allocated in the machine-tool spindle.

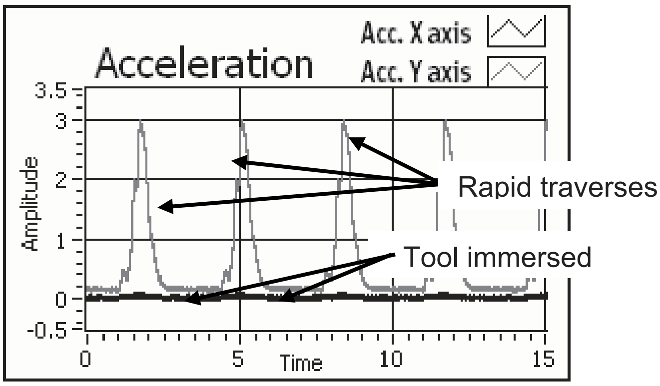

Figure 4. Accelerations captured by the accelerometers.

Once experiments were performed, surface roughness was measured with a Mitutoyo SV-2000N2 roughness tester. Evaluation length was 7.002mm and a nominally 2μm stylus tip was used at a speed of 2m/s and a 0.75mN static stylus force to obtain 2334 surface points. Figure 5 shows one of the profiles obtained with the roughness tester.

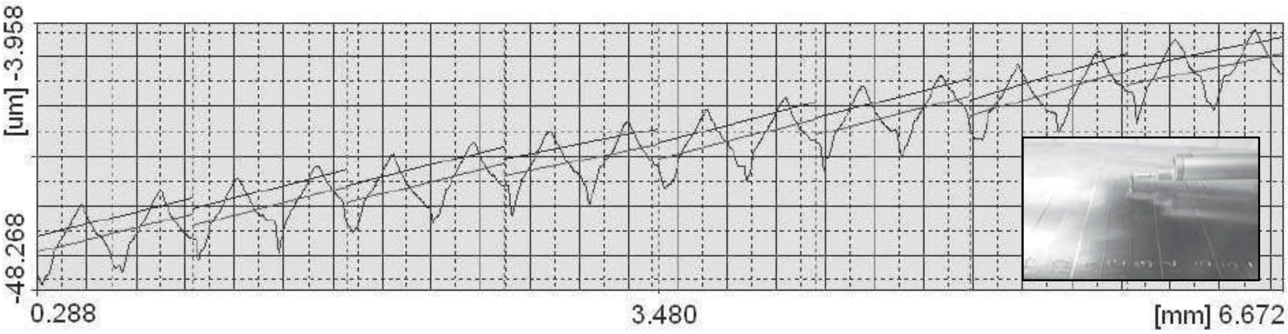

Figure 5. One of the surface profiles measured with the rugometer.

3. ARTIFICIAL NEURAL NETWORK MODEL

All data collected in experimental stage of this work was used to feed and train the artificial neural network for surface roughness predictions. A neural network is an interconnected group of artificial neurons arranged in several layers and linked through variable weights that uses a mathematical or computational model for information processing. Weights are calculated by an iterative method in the training process when the network is fed with training data. They can be used to model complex relationships between inputs and outputs or to find patterns in data. Inputs are represented by the cutting parameters and accelerations collected. The output or target is surface roughness (Ra).

Network accuracy and efficiency depend on various parameters such as hidden nodes, activation functions, training algorithm parameters and characteristics such as normalization and generalization. There is no well established procedure for finding them, and most researchers employ a trial and error procedure to determine some of them. This research work tests and trains several networks. The neural network structure was build with MATLAB™ Neural Network Toolbox.

Three kinds of samples were used to train, validate and test the neural networks. The 250 samples were randomly divided in 70% of training samples, which is a total of 175 samples introduced during the training and the networks was adjusted according to the error. 15% of validation samples, which are 38 samples, were used to measure the network generalization and stop the training when the generalization stops improving. 15% of testing samples, which means 37 samples, have no effect on training and so provide independent measure of the networks performance.

After a trial an error procedure for several network configurations attempts, the network that obtained the best correlation values was saved. Regression (R) values measure the correlation between outputs and targets.

Figure 6 shows the correlation value for the training sample (R=0.99355). Figure 7 shows the correlation value obtained in the validating sample (R=0.96399). Figure 8 presents the correlation value for the testing sample (R=0.96296) and finally in Figure et is shown the fitting correlation of the whole surface roughness prediction model (R=0.98053).

The network was trained following a Levenberg-Marqurdt backpropagation algorithm. This training automatically stops when generalization stops improving, as indicate by an increase in the mean square error of the validation samples. One hidden layer was used and the number of neurons in the hidden layer is 20. Inputs are composed by process parameters, geometric parameters, cutting tool characteristics, fluids, material properties and the vibrations measured by accelerometers in X and Y axes.

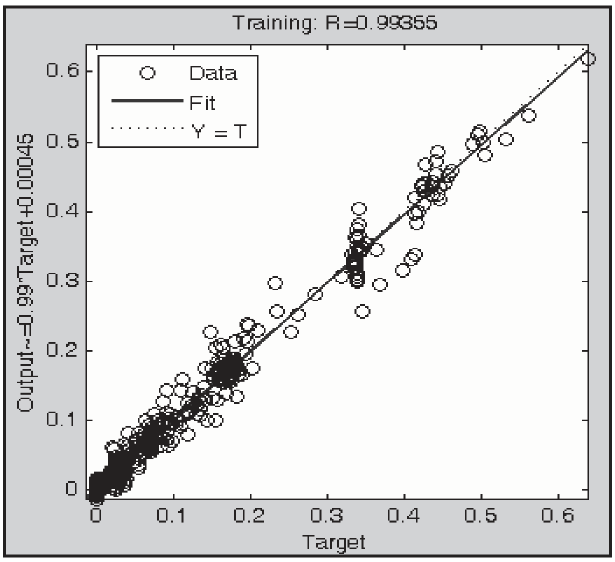

Figure 6. Regression plot and correlation value (R) for the training samples.

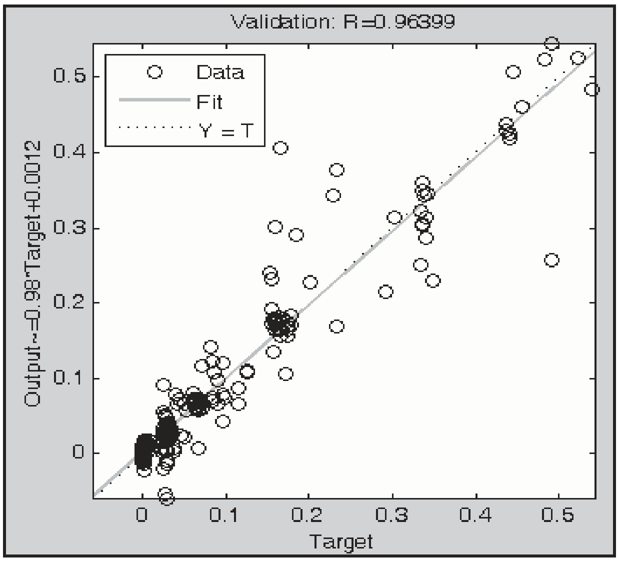

Figure 7. Regression plot and correlation value (R) for the validation samples.

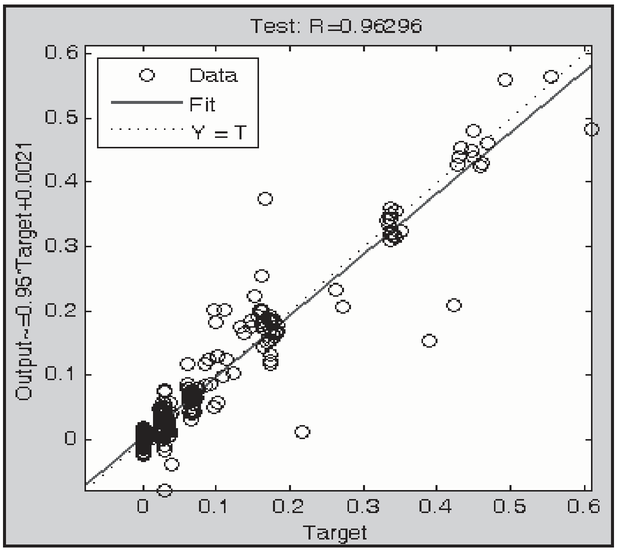

Figure 8. Regression plot and correlation value (R) for the testing samples.

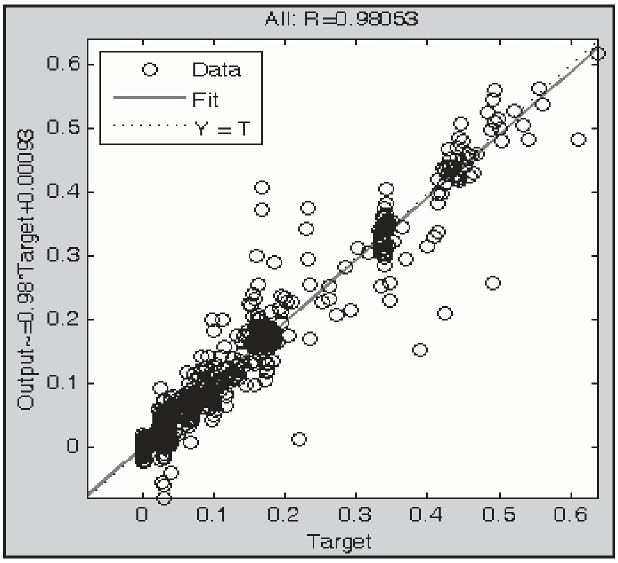

Figure 9. Regression plot and correlation value (R) of the neural network model.

Results provided by the ANN developed are clearly accurate as is possible to see in Figures 6, 7, 8 and 9 observing the high correlation values (R).

4. MONITORING MODEL IMPLEMENTATION

Surface roughness monitoring application was implemented as an interface combining LABVIEW™ and MATLAB™. LABVIEW™ was used to build a platform to capture the vibration and read the cutting parameters introduced by the user. MATLAB™ was used to calculate surface roughness applying the neural network developed once all the data was introduced by the user and while vibrations where captured on-line. The software is also capable to give the surface roughness following the ISO 1302:1996 ranges that establish 12 levels from 0.006μm to 50 μm as shown in Table 3. In finishing milling operations typical surface roughness levels use to vary from N6 to N9.

ISO 1302:1996			
N12	50 μm	N6	0.80 μm
N11	25 μm	N5	0.40 μm
N10	12.5 μm	N4	0.20 μm
N9	6.30 μm	N3	0.10 μm
N8	3.20 μm	N2	0.050 μm
N7	1.60 μm	N1	0.025 μm

Table 3. Surface roughness levels.

The main screen of the implemented software is shown in Figure 10. Operator introduces the parameters required (left side of the screen) and the model calculates several process parameters and provides, in the screen right side, with on-line surface roughness calculations which, as already mentioned, are also classified into the ISO levels.

To perform the roughness calculations it is necessary to cut the vibration signals to extract only the vibration occurred when the cutter is effectively immersed in the part generating surface. Rapid traverses are on-line removed with a trigger block.

5. CONCLUSIONS

Surface roughness has a considerable influence on the performance of a finished part and is a characteristic that is usually evaluated out-of-process when the part is already machined and it is not possible to remove defective parts from the production chain. Roughness average (Ra) is a surface parameter that is often associated with quality.

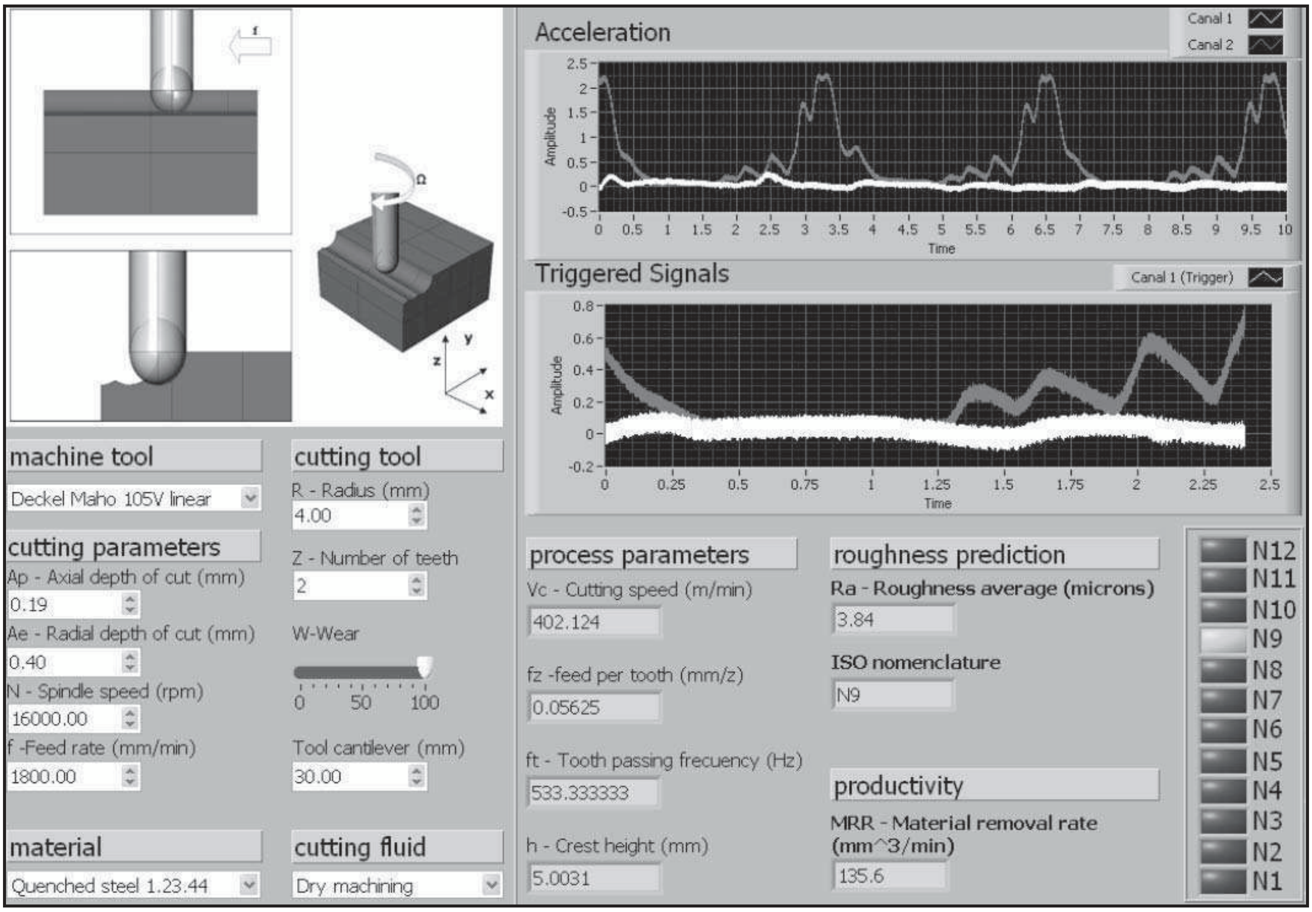

Figure 10. Surface monitoring application main screen.

Recent innovations and improvements in computers and sensors permit to obtain on-line process information that can be used to monitoring. In this paper, a reliable surface roughness monitoring application based on artificial neural networks approach for vertical high speed milling operations has been presented. The model has been characterized for ball end mill finishing operations.

Experimentation has been performed in order to obtain data enough to feed and train the artificial neural network for surface roughness prediction.

Next step in this research should be to develop an adaptive control to modulate on-line the surface roughness of the part in process ensuring a desired level of quality while increasing the productivity in terms of material removal rate.

In order to implement the ANN to other vertical milling centres it would be necessary to study how what would be the model performance. At first, it seems that would be necessary to repeat experimentation in order to capture the machine tool behaviour.

It would be possible to extend this methodology to study other types of machine tools, processes or technologies. Also, the use of other sensors or other monitoring technologies could be analyzed.

6. ACKNOWLEDGEMENTS

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Chapter 7. Conclusions and outlook

Chapter 7 presents the conclusion of the Thesis, summarizes the main contributions presented and points out possible further works arising from the research exposed.

7.1 Conclusions

Machine tool operators often select conservative cutting parameters for several reasons, such as, avoiding chatter occurrence, ensuring quality requirements and avoiding to dump non-valid final parts having to restart the manufacturing process with the looses in time, energy and money that entails.

The methodologies employed nowadays for SLD identification require the use of additional equipment such as impact hammers, piezoelectric transducers, software, sensors, and qualified staff is necessary to perform tests, validate data and interpret frequency response functions. In most of cases workshops are not capable to acquire this additional equipment and, if they could, operators are not able use these complex SLD generation systems.

Surface roughness has a considerable influence on the performance of a finished part and is a characteristic that is usually evaluated out-of-process with the help of a profilometer when the part is already machined and it is not possible to remove defective parts from the production chain. Roughness average (Ra) is a surface parameter that is often associated with quality.

The objectives of this Thesis were established considering the limitations and trends of the nowadays metal removal sector, and according with the research fields and interests of the Product, Process and Production Engineering Research Group, GREP and ASCAMM Technology Centre.

Regarding the chatter problem, the experimental methodologies for stability lobe diagrams identification presented in Chapter 3 and Chapter 4 can be easily applied in small and medium-sized workshops overcoming the mentioned restrictions of the already existing methods. Advantages and drawbacks of the inclined plane methodology and the sound mapping procedure are presented in the corresponding chapter.

Concerning the monitoring and diagnosis trends of the workpiece surface condition, the theoretical analyzes presented in Chapter 5 and the development of a surface roughness monitoring application for ball end milling processes exposed in Chapter 6, provide a reliable solution that permits to carry out simultaneously the manufacturing process and the quality control.

Applying the methodologies for stability lobe diagrams identification presented, the theoretical studies on surface roughness generation and the surface roughness monitoring application developed will permit machine tools operators to optimize the parameters selection, maximizing productivity while ensuring quality requirements.

7.2 Main contributions

The main contributions of the work presented in this Thesis are summarized below:

- A novel experimental methodology for Stability Lobe Diagram identification in milling operations based on empirical tests where, thanks to workpiece surface inclination it is possible to gradually increase the axial depth of cut in the feed direction permitting to obtain a *metallic SLD* physically machined onto the workpiece.

- A novel experimental methodology for Stability Lobe Diagram identification in milling operations based on the sound mapping methodology. Considering the SLD chart as a region and dividing this region with a mesh, a diagram can be constructed by applying the sound mapping technique.

- A new theoretical approach for the calculation of quality and productivity indicator factors in ball end milling operations. Surface crest height (h), surface roughness average parameter (Ra) and material removal rate (MRR) are calculated as function of cutting tool radius (R) and radial depth of cut (Ae) considering surface angularity.

- An original computer application for surface roughness monitoring in ball end milling operations based on artificial neural networks. Surface roughness average parameter (Ra) can be accurately evaluated in-process.

7.3 Further work

Further work in stability lobes diagram identification could include a comparison of the performance provided by different types of cutting sensors such as, table or rotating dynamometers, accelerometers, acoustic emission sensors, or electrical power sensors, when it comes to chatter onset detection. Then, the best sensor or multisensor system for chatter identification should be decided following scientist and economical criteria. This new sensor platform could be used to improve both experimental methodologies presented for stability lobe diagrams identification. Another interesting focus of research is the idea of automating the procedures presented in order to avoid as much as possible the operator intervention with the loose of accuracy that entails.

Next step in the surface roughness monitoring research should be to develop an adaptive control to modulate on-line the surface roughness of the part in process ensuring a desired level of quality while increasing material removal rates. The CNC should be able to evaluate surface quality in-process, decide optimal process parameters and modify them on-line to improve performance. In this case, it would be necessary to create a human machine interface (HMI) that would permit to give to industry a final exploitable compact solution to the problem of surface roughness assurance. The use of other computing techniques such as genetic programming (GP), fuzzy-logic techniques, Bayesian networks, should be also analyzed. In order to implement the model to other vertical milling centres it would be necessary to repeat experimentation in order to capture the machine tool behaviour. The methodology followed to develop the surface roughness monitoring system explained in this work could be also extended to any manufacturing process involving other materials, cutting tool shapes, metal removal operations or different kinds of machine tool, or manufacturing process.

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