Universitat de Girona

CONTRIBUTION TO MICRO-MILLING PROCESS PARAMETERS SELECTION FOR PROCESS PLANNING OPERATIONS

Elisa Virginia Vázquez Lepe

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DOCTORAL THESIS

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2014

Supervisor: Joaquim de Ciurana Gay

Thesis submitted in partial fulfillment of the requirements for the degree of Doctor from the University of Girona (Doctoral Programme in Technology)

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El Dr. Joaquim de Ciurana, catedràtic del Departament d'Enginyeria Mecànica i de la Construcció Industrial de la Universitat de Girona,

CERTIFICO:

Que aquest treball, titulat “Contribution to micro-milling process parameters selection for process planning operations”, que presenta Elisa Virginia Vázquez Lepe per a l’obtenció del títol de doctora, ha estat realitzat sota la meva direcció i que compleix els requeriments per poder optar a Menció Internacional.

Signatura

Girona, 27 de gener de 2014

To my parents Víctor and Virginia.

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List of publications

This doctoral thesis is presented as a compendium of publications. The following list contains the publications presented as chapters of this PhD thesis.

CHAPTER 3: Vázquez, E., Rodríguez, C. A., Elías-Zúñiga, A., & Ciurana, J. (2010). An experimental analysis of process parameters to manufacture metallic micro-channels by micro-milling. The International Journal of Advanced Manufacturing Technology, 51(9-12), 945-955.

For 2012, the journal INTERNATIONAL JOURNAL OF ADVANCED MANUFACTURING TECHNOLOGY has an Impact Factor of 1.205.

This table shows the ranking of this journal in its subject categories based on Impact Factor.

Category Name	Total Journals in Category	Journal Rank in Category	Quartile in Category
ENGINEERING, MANUFACTURING	39	18	Q2

CHAPTER 4: Vázquez, E., Gómez, X., & Ciurana, J. (2012). An experimental analysis of process parameters for the milling of micro–channels in biomaterials. International Journal of Mechatronics and Manufacturing Systems, 5(1), 46-65.

CHAPTER 5: Amaro, A., Gomar, J., Vázquez, E., Ciurana, J., & Rodríguez, C. (2012). Experimental Analysis of Process Parameters to Manufacture Micro-Cavities by Micro-Milling. Advanced Materials Research, 498, 91-96.

CHAPTER 6: Vázquez, E., Gomar, J., Ciurana, J., & Rodríguez, C. (2014). Evaluation of the machine-tool motion accuracy using a CNC machining centre in micro milling processes. Accepted in International Journal of Advanced Manufacturing Technology. DOI: 10.1007/s00170-014-5787-6.

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ENGINEERING, MANUFACTURING	39	18	Q2

CHAPTER 7: Vázquez, E., Gomar, J., Ciurana, J., & Rodríguez, C. (2013). Analyzing effects of cooling and lubrication conditions on micro-milling of Ti6Al4V. Submitted in Materials and Manufacturing Processes Journal/ LMMP-2013-08216.

For 2012, the journal MATERIALS AND MANUFACTURING PROCESSES has an Impact Factor of 1.297.

This table shows the ranking of this journal in its subject categories based on Impact Factor.

Category Name	Total Journals in Category	Journal Rank in Category	Quartile in Category
ENGINEERING, MANUFACTURING	39	14	Q2

CHAPTER 8: Vázquez, E., Kemmoku, D. T., Noritomi, P. Y, Silva, J. V. L., & Ciurana, J (2014). Computer Fluid Dynamics analysis for efficient cooling and lubrication conditions in micro-milling of Ti6Al4V. Submitted in in Materials and Manufacturing Processes Journal/LMMP-2014-0155.

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Category Name	Total Journals in Category	Journal Rank in Category	Quartile in Category
ENGINEERING, MANUFACTURING	39	14	Q2

CHAPTER 9: Vázquez, E., Amaro, A., Ciurana, J., & Rodríguez, C. (2013) Process planning considerations for micro-milling of mould cavities used in ultrasonic moulding technology. Submitted in Precision Engineering/ PRE-S-13-00310

For 2012, the journal PRECISION ENGINEERING-JOURNAL OF THE INTERNATIONAL has an Impact Factor of 1.393.

This table shows the ranking of this journal in its subject categories based on Impact Factor.

Category Name	Total Journals in Category	Journal Rank in Category	Quartile in Category
ENGINEERING, MANUFACTURING	39	12	Q2

CHAPTER 10: Vázquez, E., Ciurana, J., Rodriguez, C. A., Thepsonthi, T., & Özel, T. (2011). Swarm intelligent selection and optimization of machining system parameters for microchannel fabrication in medical devices. Materials and Manufacturing Processes, 26(3), 403-414.

For 2012, the journal MATERIALS AND MANUFACTURING PROCESSES has an Impact Factor of 1.297.

This table shows the ranking of this journal in its subject categories based on Impact Factor.

Category Name	Total Journals in Category	Journal Rank in Category	Quartile in Category
ENGINEERING, MANUFACTURING	39	14	Q2

List of symbols

μ	Viscosity [Ns/m^2]
a_e	Radial depth of cut [%*D*]
Al2O3	Aluminium Oxide
AlCrN	Aluminium Chromium Nitride
AlTiN	Aluminium Titanium Nitride
a_p	Depth of cut per pass [μm]
CaF2	Calcium fluoride
CD	Cut direction
CP	Cut pattern
d	Channel depth [μm]
D	Tool diameter [min^{-1}]
d_a	Actual depth [μm]
E	Geometric error
ε_H	Dimensional error [%]
f_z	Feed per tooth [μm/tooth]
h	Undeformed chip thickness [mm]
H	Final depth [μm]
H_a	Actual depth [mm]
HfN	Hafnium nitride
h_m	Minimum chip thickness [mm]
INT	Interpolation
M	Major axis [μm]
m	Minor axis [μm]
N	Spindle speed [min^{-1}]
NbC	Niobium carbide

NiTi	Nickel Titanium Alloy (Nitinol)
O	Order
OFHC	Oxygen-free copper
Ra	Surface roughness [µs]
Si3N4	Silicon Nitride Ceramic
SiC	Silicon Carbide
Ta(Nb)C	Tantalcarbide
TaC	Tantalum Carbide
Ti	In tolerance [mm]
Ti6Al4V	Titanium alloy
TiAlN	Titanium aluminide nitride.
To	Out tolerance [mm]
V	Cutting speed [m/min]
V_f**/F**	Feed rate [mm/min]
w_a	Actual width [µm]
WC-Co	Tungsten Carbide
ZrO2	Zirconium Dioxide
εØX	Major axis error [±%]
εØY	Minor axis error [±%]
P	Density [Kg/m^3]

List of acronyms

AFM	Atomic Force Microscopy
AI	Artificial Intelligence
AISI	American Iron and Steel Institute-Society of Automotive
AMMS	Advanced Modular Micro-Production System
ANNOVA	Analysis of Variance
ASCAMM	Associació Catalana d'Empreses de Motlles i Matrius
CFD	Computational Fluid Dynamics
CMM	Coordinate Measuring Machine
CNC	Computer Numerical Control
DLC	Diamond-like Carbon
DNA	Deoxyribonucleic Acid
DOC	Depths-of Cut
EDM	Electrical Discharge Machining
GREP	Grup de Recerca en Enginyeria de Producte, Procés i Producció
HRB/HRC	Rockwell Hardness-B Rockwell Hardness-C
HSM	High Speed Machining, High Speed Milling
IREBID	International Research Exchange for Biomedical Devices Design
LBM	Laser Beam Machining
MEMS	Micro-electro-Mechanical Systems
mMT	Meso-scale Machine Tool
MQL	Minimum Quantity Lubrication
OPF	Optical Profile Followers
PC	Personal Computer
PDMS	Polydimethylsiloxane

PMMA	Polymethylmethacrylate
PSO	Particle Swarm Optimization
SAE	Society of Automotive Engineers
SEM	Scanning Electron Microscope
SP	Single Profile
STM	Scanning Tunneling Microscopy
TECNIPLAD	Caracterització de tecnologies innovadores per a la planificació detallada dels procesos
UdG	University of Girona
USM	Ultrasonic Machining

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Summary *Resum* Resumen

El desenvolupament de nous productes amb característiques micro-mètriques i geometries complexes ha estat una tendència de producció en diferents sectors industrials, en particular per a les indústries electròniques, biomédica, militars i aeroespacials. Les tecnologies de producció com l'electroerosió (EDM), mecanitzat làser (LBM), mecanitzat per litografia (LM) i mecanitzat per ultrasons (USM) són processos comunament usats per a produir peces petites. No obstant això, hi ha barreres econòmiques i tecnològiques que redueixen la seva viabilitat per a aplicacions específiques.

Ja que les màquines i eines de tall CNC poden aconseguir alts nivells de precisió, el micro-fresat (procés de reducció d'escala) representa un procés tecnològic adequat per a la fabricació de micro-productes. Aquesta tesi es centra en augmentar el coneixement sobre el micro-fresat, establir relacions entre els paràmetres del procés, així com les condicions de mecanitzat i els aspectes clau de la peça final com són la precisió, acabat superficial de qualitat i qualitat geomètrica.

El desarrollo de nuevos productos con características micro-métricas y geometrías complejas ha sido una tendencia en la manufactura en diferentes sectores industriales, particularmente para la industria electrónica, militar, biomédica y aeroespacial. Las tecnologías de producción como la electroerosión (EDM), mecanizado láser (LBM), mecanizado por litografía (LM) y mecanizado por ultrasonido (USM) son procesos comúnmente usados para producir piezas pequeñas. No obstante, existen barreras económicas y tecnológicas que reducen su factibilidad para aplicaciones específicas.

Puesto que las máquinas-herramientas de corte CNC pueden lograr altos niveles de precisión; el micro-fresado (proceso escalado del fresado convencional) representa un proceso tecnológico adecuado para la fabricación de micro-productos. Esta tesis se centra en aumentar el conocimiento sobre el micro-fresado, estableciendo relaciones entre los parámetros del proceso, así como las condiciones de mecanizado y los aspectos clave de la

pieza final pieza final como por ejemplo, la precisión, el acabado superficial de calidad y la calidad geométrica.

The development of new products with micro-metric characteristics and complex geometries has been a manufacturing trend in different industrial sectors, particularly for electronic, military, biomedical and aerospace industries. Manufacturing technologies such as electro discharge machining (EDM), laser beam machining (LBM), lithography machining (LM), and ultrasonic machining (USM) are commonly processes used to produce small pieces. Nonetheless, there are economical and technological barriers that reduce their feasibility for specific applications.

Since CNC cutting machines and tools can achieve high levels of accuracy, micro-milling (milling downscaled process) represents a suitable technological process to manufacture micro-products. This thesis focuses on increasing knowledge about the micro-milling, establishing relationships between the process parameters as well as machining conditions and the key aspects of the final piece such as accuracy, quality surface finishing and geometrical quality.

Introduction

Chapter 1 presents a general introduction of the micro-milling technology and gives the justification and the motivation for this thesis.

1.1 Micro-milling technology

The micro-manufacturing processes have become a growing area and have found widespread use in a variety of applications, such as biomedical devices, representing a niche market, creating the need to find alternative process to manufacture these components with low-cost, high-accuracy and high-quality surface finishing. Despite there are many differences between manufacturing in macro and meso scale, manufacturing processes can be applied in both scales. However, important factors, which differ from the macro-point of view to the micro-point of view, need to be addressed. In order to keep focused in micro-manufacturing processes, this work is aimed to present information related with the micro-scale

Manufacturing processes can be grouping according to the type of energy used in the process itself, such as mechanical, chemical, electrochemical, electrical and laser processes. The classification is appropriate to micro-manufacturing (Razali and Qin, 2013).

Micro-machining is defined as mechanical cutting of features with tool engagement less than 1 mm with geometrically defined cutting edges. This technology includes numerous characteristics of traditional machining; however, increases a great number of issues mainly due to size or scale (Dornfeld *et al.*, 2006). This has generated a constant search of knowledge to improve the technological capacity of the current manufacturing processes. Likewise on the research field there is an experimental and scientific lack of knowledge related to process parameters in micro-manufacturing technologies.

In this way micro-milling has demonstrated to be a suitable process to develop micro-parts with complex shapes, with great surface integrity and high accuracy. The advantages of micro-milling in contrast with other processes such as silicon etching processes, energy beam and chemical used to manufacture the micro-devices systems are fewer material restrictions and the capacity to manufacture true three-dimensional features in comparison with other methods such as lithography, electro discharge machining and laser beam machining.

1.2 Interest

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.

Since the beginning of the research group in 1998 one of the main GREP research interest focuses along the machining topic and currently has a great expertise in this subject having developed several experimental works and a review of the state of research on chatter (Quintana *et al.*, 2008; Quintana *et al.*, 2009; Quintana and Ciurana, 2011). In addition, ASCAMM Technology Centre interested for micro-manufacturing suitable process to provide solutions for their innovative products such as the first high precision moulding machine based on ultrasounds and exclusively designed for the reproduction of mini and micro-scale pieces. This is how this thesis arises, using the joint-venture in the knowledge already had in the research group and the need to increase it to try to answer the growing demand for micro-products.

As demonstration of the miniaturisation of products is a current megatrend (Frazier *et al.*, 1995), nowadays, as part of the evolution and progress of the technology, human being needs become more exigent in terms of complexity and functionality of the products used daily. For instance, smaller cell phones, smaller laptops, smaller tablets are some examples of the necessity of micro-components for these final consumer products.

Specifically for biomedical industry, according to Yole Développement (BIOMEMS 2010 Report), in the technologies & markets report carried out in October 2010, micro-system technologies market for healthcare applications will grow from $1.2 billions in 2009 to $4.5 billions in 2015, representing over 1 billion units per year in 2015 (Figure 1.1). The market growth shows a great opportunity primarily for micro-devices applied to In-vitro diagnostics, as well as pharmaceutical and biological research, home care, and for medical devices.

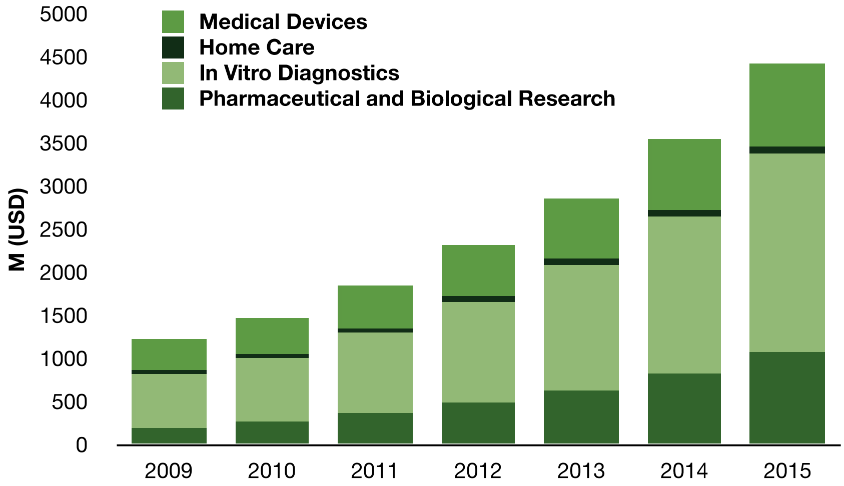


Figure1.1: MEMS for healthcare applications market (2009-2015) (BIOMEMS 2010 Report)

Although there are many processes to fabricate micro-components, most of them present economical and technical limitations that reduce their feasibility. Hence, scientific knowledge is required in order to achieve major technological advances in the conventional manufacturing processes. In response, adoption of current process technologies and machine tools to the requirements of micro-production is an option frequently selected. Thus, it is necessary to explore the capacities of current technology to perform micro-processes, and generate knowledge of high added value.

1.3 Motivation

The use of conventional machining processes has been subject to important decline probably due to the increment in the use of emerging technologies. Therefore, the main applications of these traditional processes, such as automotive industry, are in crisis (Shih 2008). In order to have a chance to compete successfully in the new trends, the machining industry must meet the needs of alternative sectors. Therefore, micro-milling due to its technologic capabilities, flexible applications and economical benefits, represents a suitable machining process to manufacture micro-products with complex 3D geometry. Therefore, to fabricate micro-components using conventional machines, initially designated for different purposes, represents an enriching activity. Especially since many conventional milling machines can be found in university floor-shops as well as inside of small and medium enterprises (SME´s). In this way it is possible to use these machines for advanced applications and reduce costs of new machinery. Currently, many of micro-manufacturing processes are focused in 2D geometries fabrication. Due to the difficulty to manufacture 3D complex geometries, there is a lack of experimental and scientific knowledge in this field.

The following lists of benefits and drawbacks can serve as a summary of the different aspects related to micro-milling (Table 1.1).

Table 1.1: Benefits and drawbacks.

☺	☹
• Extensive knowledge of macro-milling. • Micro-milling as situable technology to produce micro parts. • Micro-milling research has been studied for some topics as: micro-structure, micro-tools, forces, etc. • Interest of emerging market. • Micro-milling research focused to 2D geometries.	• Experimental and scientific lack of knowledge related to process parameters in micro-manufacturing technologies. • Current micro-milling process is limited to some materials. • There is limited knowledge about micro-milling of complex 3D geometries.

Gaining ground the micro-milling process and overcoming the limitations listed above, we can make the following initial hypothesis:

Integrating the current knowledge of macro-milling and micro-milling will improve the performance of the micro-milling process and produce micro-products using a conventional CNC machine.

To achieve it, it is necessary to work on the following issues:

- Improve the knowledge related to the influence of micro-milling process parameters and machining conditions on accuracy, quality surface finishing and geometrical feature in an extensive range of materials.

- Improve the knowledge related to the tool motion of the conventional CNC machine applied to micro-milling case.

- Improve the milling as a micro-manufacturing process suitable to produce complex geometries. Staring with simple geometries until to arrive at complex geometries.

- Once understanding the relations between process parameters and quality of the final micro-feature develop a predictive system to identify the optimum set of process parameters.

1.4 Objectives

The main objective of this thesis is to increase the existing knowledge in the micro milling process, evaluating and defining the parameters involved to improve the process based on the analysis of qualitative and geometrical properties of the final product. This should help to design process methodology in the micro manufacturing as a process suitable for the manufacture of complex micro-parts.

This thesis aims to develop studies and experiments needed to reach a level of knowledge of the process and to develop tools for planning and selection of the micro-milling process conditions as well.

More specifically, the objectives of the thesis are:

- Analyze the influence of key process parameters and machining conditions on desired dimensions, geometrical feature and quality surface finishing on different process configurations (2.5D and 3D micro-milling).
- Study of the effect of the process on different materials. The micro-milling technology is able to manufacture a wide range of materials including biocompatible materials. However, the materials have different response to the same process parameters.
- Study of the theoretical principles of kinematics and develop experimental work to evaluate the tool motion in micro-milling using a conventional CNC machine.
- Development of intelligent selection of parameters for process planning. The development of AI models and genetic algorithms should allow the selection of the optimum process parameters for the micro-milling of a feature with its specific quality and dimensional requirements.
- Development of process planning for micro-milling of mould cavities.
- Focus and test the process for biomedical applications. For this reason, several experiments carried out in this thesis will end on.

Achieving the objectives established will permit to improve the knowledge about micro-milling process in order to ensure quality requirements for micro-products with complex geometries.

1.5 Thesis structure

The Thesis is organized as follows:

Chapter 1 presents the general domain of the Thesis, brief introduction of the micro-milling technology and exposes the interest, motivation and objectives persecuted in this work.

Chapter 2 reviews the state of the art of micro-milling. First, presents the context of the machining process studying briefly the High Speed Machining (HSM) and presenting a classification of machine-tools. Afterwards, presents an extensive research about micro-machining.

Chapter 3 presents an experimental study of the process parameters on surface finishing, shape and dimensional features of micro-channels with standard milling machine, for aluminium and copper workpieces.

Chapter 4 presents experimental work to study the relation between process parameters and quality characteristics of micro-channels performed in stainless steel (316L) and titanium (Ti6Al4V).

Chapter 5 presents investigations on the effect of process parameters on accuracy and geometrical feature of micro-cavities carried out in aluminium.

Chapter 6 performs an evaluation of the machine-tool motion accuracy using a CNC machining centre in micro milling processes performing elliptical cavities.

Chapter 7 presents a study related to the influence of cooling and lubrication conditions on micro-milling of Ti6Al4V.

Chapter 8 exposes a comparison between Computational Fluid Dynamic analysis and experimental work evaluating the cooling and lubrication conditions on micro-milling of Ti6Al4V.

Chapter 9 presents the proposed process planning for micro-milling of mould cavities using a complex geometry.

Chapter 10 presents a multicriteria decision making for material and process parameters selection for response variables by using particle swarm optimization (PSO) method. The dimensional accuracy and the surface roughness are the main responses studied.

Finally, Chapter 11 presents conclusions and outlook. The list of publications is presented at the end of this chapter.

Figure 1.2 presents the relationships between the different chapters of the thesis.

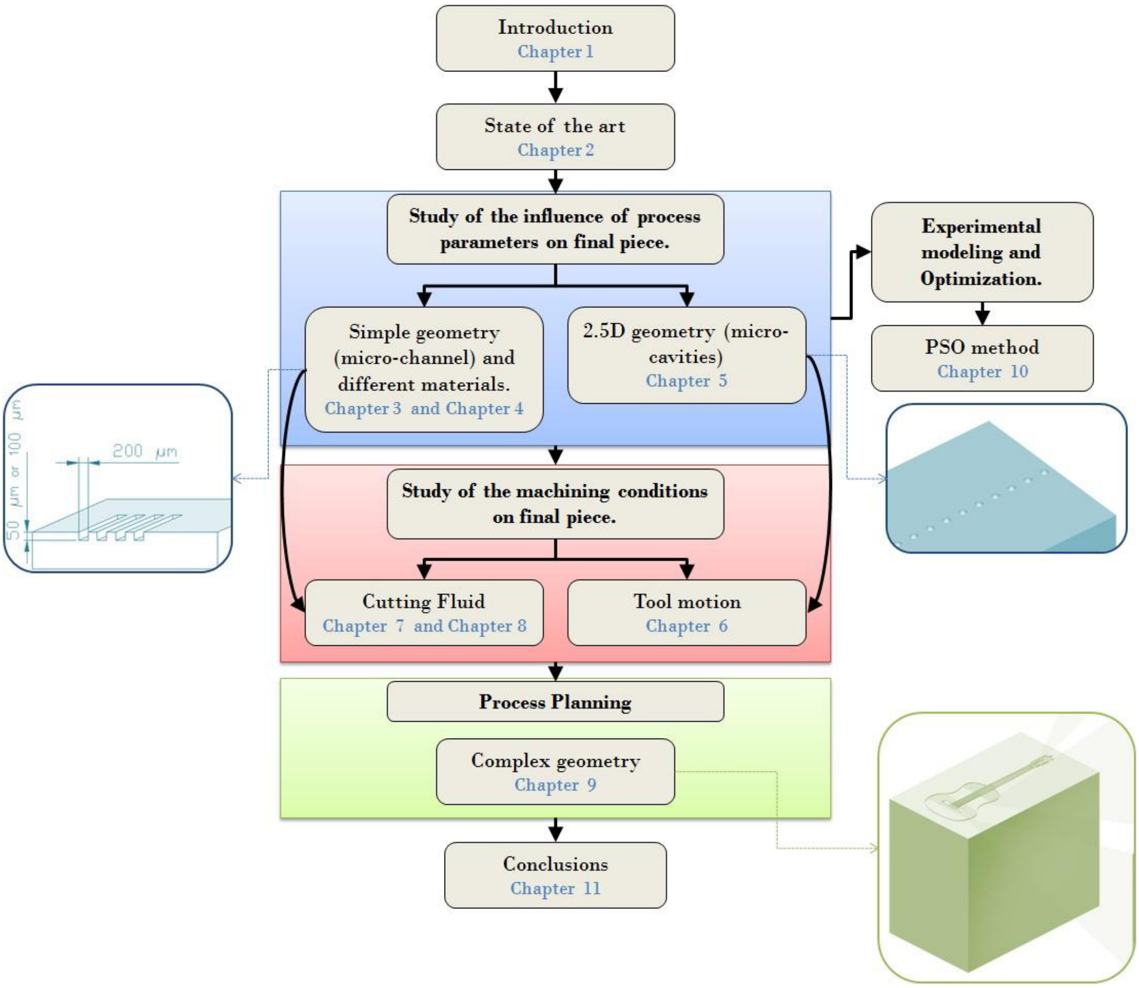


Figure 1.2: Thesis Road Map

Chapter 2. State of the art

Chapter 2 reviews the state of the art of micro-milling. First, presents the context of the machining process studying briefly the High Speed Machining (HSM) and presenting a classification of machine-tools. Afterwards, presents an extensive research about micro-machining, including topics such as: micro-milling tools, microstructure effect, minimum chip formation, ductile mode machining, burr formation, tool wear, tool deflection, chatter, run-out, cutting fluid, forces and metrology in micro-machining.

2.1 Introduction

Current manufacturing processes require changes and adaptation in order to face new challenges because traditional sectors such as automotive and mechanical machinery are decreasing its activity. In contrast to, medical field with the intention of improvement quality of life is an emerging opportunity for manufacturing processes to take advantage of actual capabilities and transform them, contributing in the healthcare sector (Shih 2008). For example, biomedical devices (useful for dosifying drugs to the human body, analyze DNA or for cultivating cells), representing a niche market, require to finding alternative process to manufacture these demanding components with low cost, high accuracy and high quality surface finishing.

While the late 20th century has seen a silicon-based microelectronics revolution, the 21st century looks forward to the adoption of micro- and nano-manufacturing technologies making use of a variety of materials, components and knowledge-based technologies that provide functionality and intelligence to highly miniaturized systems (Dimov *et al.*, 2006). To meet the large scale production needs of mechanical components and micro products, many existing technologies are being downscaled and many new processes have been and are being developed. Besides conventional processes (such as micro turning and micro milling), non-conventional processes (such as electrical discharge machining and laser machining) are also being studied. Even though these processes are able to create micro-parts, there are some economical and technical constraints that reduce their feasibility.

2.2 High Speed Machining

High-speed machining (HSM) may be defined in various ways. A common definition is based on spindle speeds between 30,000 and 100,000 revolutions per minute (rpm) (Robinson *et al.*, 2007). Furthermore, with regard to attainable cutting speeds, it is suggested that operating at cutting speeds significantly higher than those typically utilized for a particular material may be termed HSM (Figure 2.1 and Table 2.1).

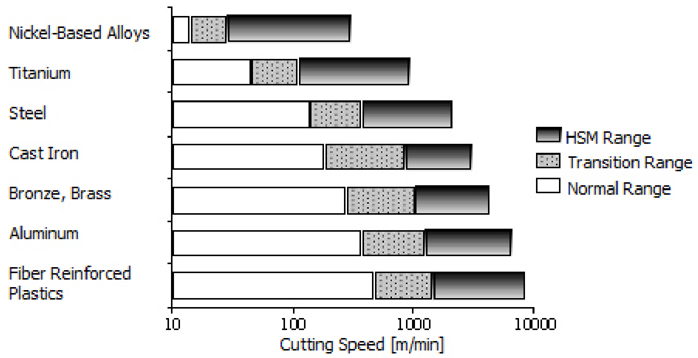


Figure 2.1: Attainable speed in the machining of various materials (Schulz 1997).

Table 2.1: Summary of the advantages of HSM discussed by Schulz.

Benefit	Application field	Application examples
Large cutting volume per machining time	Light metal alloys, steel and cast iron	Aircraft and aerospace production, die and mould manufacturing
High surface quality	Precision machining, special workpieces	Optical industry, fine mechanical parts
Low cutting forces	Processing thin walled workpieces	Aircraft and aerospace industry, automotive industry
High frequencies of excitation	No machining in critical frequencies	Precision mechanisms and optical industry
Heat transported by the chips	Machining of workpieces with critical heat influence	Precision mechanism magnesium alloys

2.2.1 Milling machines-tools

One of the concerns about this topic is the differentiation between ultraprecision milling machines and micro machines. According to Uriarte *et al.* (Uriarte *et al.*, 2009), ultraprecision processes - including micro-milling, and processes based on silicon machining techniques- based on conventional machining processes, but the most important characteristic of these is the critical dimensions require submicrometric geometrical precision. In contrast, micro machining in semi-conductors that offers relatively a) high capacity in terms of resolution and precision b) limited to 2½ D geometries c) relatively small range of materials, and high production volumes are required to make them profitable. They conclude that the most typical meaning of a micro-milling machine is referred to ultraprecision milling machines. Machine tools capable of such extreme accuracy may be applied to microscopic workpieces (micro-machining).

Ultraprecision milling machine

According to Dornfeld, recent research highlights the significant challenges in order to improve the actual designs of the ultraprecision machine (Dornfeld *et al.*, 2006):

- Thermal stability: compact size, enclosure for temperature controlled air circulation.

- Precise spindle bearings and linear guides: hydrostatic air bearing/guide or hydrostatic oil bearing/guide: air flow from turbulent to lamellar so that forced vibration of the machine parts induced by the turbulent air flow is eliminated.

- High resolution of linear and rotary motions: special motors and encoders, typically 64 M pulses/revolution for encoder, 1nm for linear motion, 1/100,000 deg for rotary motion.

Recently, multi-axis control ultraprecision machining centers with different degrees of freedom are commercially accessible. The availability of multi-axis controlled ultraprecision machining centers due to continues development based on of traditional machine tools. These are used to manufacture small workpieces with complex geometries as well as micro-scale patterns and texture, such as those used in molds and dies for the lenses industry per example (Tönshoff *et al.*, 1997).

Dornfeld suggest that the classification of these ultraprecision machine tools can be into several types, based on positioning mechanism used. Mechanisms include a screw-based system driven by a rotary motor, line motor drives, and a ball screw or aero-/hydrostatic screw-based system. With respect to the table slide mechanism, two common configurations include the roller slide system or aero-/hydrostatic slides in order to feed the table with low friction and high straightness. Bearings for rotational elements are similar to those found in the table slide mechanism.

Original machines have been proposed by some investigations. Furukawa *et al.* (Furukawa and Moronuki 1988) built a machine based on alumina-based ceramics for the structural elements by virtue of their high rigidity and thermal reliability and surface-restricted type aerostatic slideways to prevent friction. Also, Takeuchi *et al.* (Takeuchi *et al.*, 2000) constructed a five-axis ultraprecision milling machine employing non-friction servomechanisms for the creation of 3D micro-parts with translational resolution of 1nm, rotational resolution of 0.00001 degree, and slideway straightness of about 10 nm/200mm. A similar work was developed by Sriyotha *et al.* (Sriyotha *et al.*, 2006) creating 5-axis ultraprecision machining center using aerostatic guideways and coreless linear motors to provide noncontact, high resolution drive mechanisms achieving 1nm motion accuracy. To guarantee thermal stability, alumina ceramics were used for structural components (Figure 2.2).

An elliptical vibration milling machine was developed by Moriwaki *et al.* (Moriwaki *et al.*, 2004) used a double spindle mechanism to generate circular vibratory motion of the cutting tool, due to improved surface finish, even with a diamond tool on ferrous materials. Experiments with this machine confirm that the cutting performance, in terms of the cutting force (about 1/8 of that obtained by traditional milling) and the chip thickness, is improved significantly by applying the elliptical vibration to the cutting tool. The experimental results prove that the method can be applied to practical ultraprecision cutting of metals.

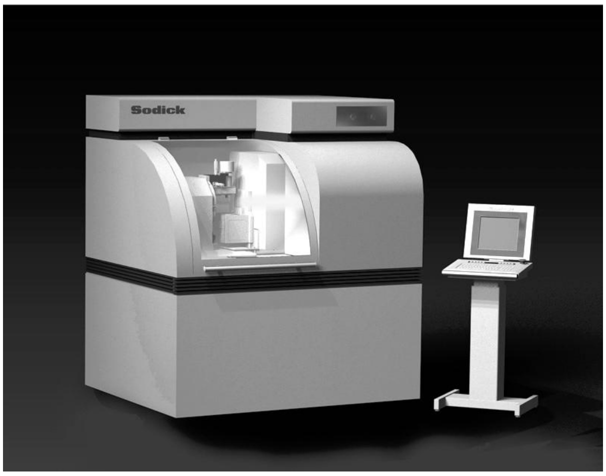


Figure 2.2: Commercial 5-axis control ultraprecision machining centre (Sriyotha *et al.* 2006).

Subrahmanian and Ehmann (Subrahmanian and Ehmann 2002) developed a multi-axis meso-scale machine (mMT) prototype (Figure 2.3). The machine tool used a spindle system -derived from a high-speed dental air-turbine capable of achieving speeds up to 320,000 rpm-, a piezoelectric actuator positioning system, and a two-axis micro-pulse system controller.

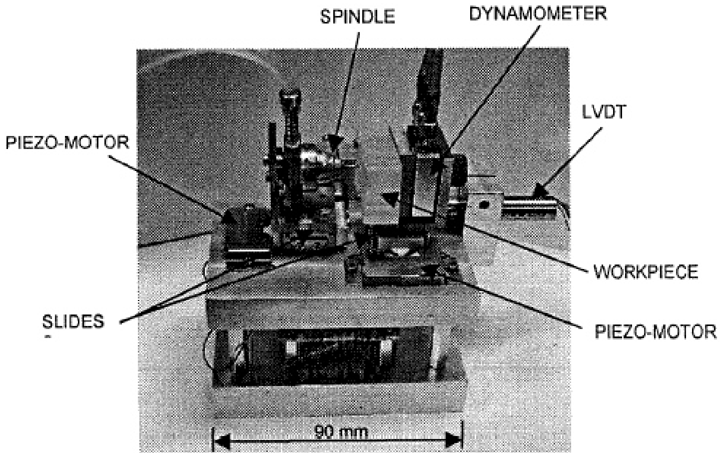


Figure 2.3: The first-generation prototype (Subrahmanian and Ehmann 2002).

Bang *et al.* (Bang *et al.*, 2005) developed a 5-axis micro milling machine for micro 3D parts machining (Figure 2.4). The precision machine was constructed at a low cost with commercially available parts such as a micro stage, air spindle, and PC-based control board. A simple method to coincide the tool axis with A-axis was proposed; this includes cylindrical surface cutting and diameter measuring. Test machining of micro walls, micro columns, and micro blades showed that the constructed micro-milling machine is capable of producing practical micro parts.

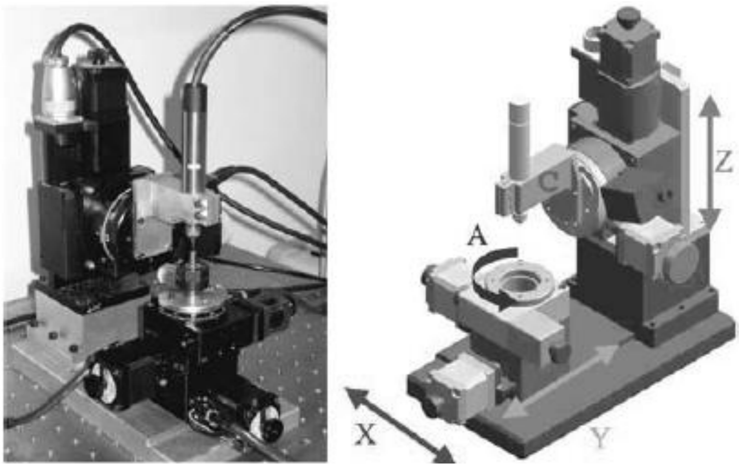


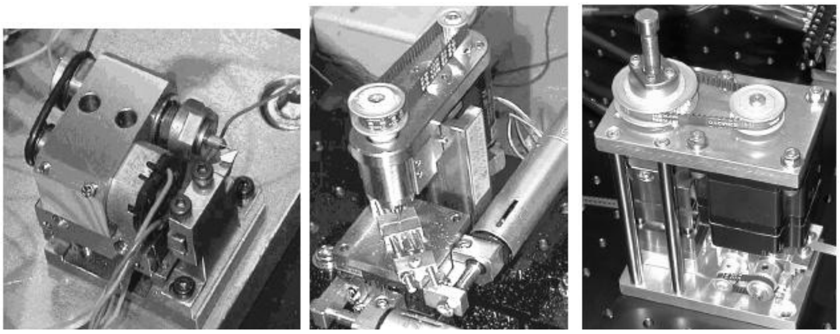
Figure 2.4: Constructed 5-axis milling machine (Bang *et al.* 2005).

Micro-factories

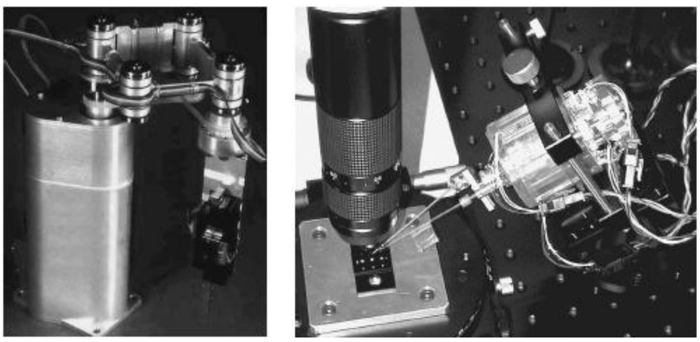
According to Razali and Qin (Razali and Qin, 2013), a micro-factory can be defined as a small manufacturing system created in order to achieve higher throughput with reduced space and less consumption of resources and energy via downsizing of manufacturing processes.

Typically, according to Dornfeld, micro-machining is performed on precision machine tools with conventional dimensions. However, the work size and the required power for processing are relatively much smaller for micro-machining. Downsizing the machine tool itself has been attempted by several machine tool builders and researchers in order to obtain economic benefits such as structural cost savings, shop floor space savings, energy reduction and performance the advantages including reduction of thermal deformation, enhancement of static rigidity and dynamic stability as well (Kussul *et al.*, 1996) The antecedents of machines for micro-machining date from 80's.

Japanese researchers started fabricating micro-factory prototypes, and the first realization of the concept was a micro-lathe smaller than a human palm with 1.5W spindle motor, followed by more powerful and precise desktop and portable machines (Dornfeld *et al.*, 2006). On other hand, Kussul *et al.* (Kussul *et al.*, 2002) developed a micro-machining centre having an overall size of 130 × 160 × 85 mm3. They achieved manufacture of micromechanical details having sizes from 50 μm to 5 mm in different materials, such as bras, steel, various plastics etc. These details have complex three-dimensional shapes (for example, screw, gear, graduated shaft, conic details, etc). In the same way, Okazaki *et al.* (Okazaki *et al.*, 2004) studied the concept of micro-factory, in addition with some prototypes of miniaturized machine tools (Figure 2.5). Potentials of those machines to save space and power consumption have been evaluated, as well as their machining performances.



a) Micro-lathe b) Micro milling machine c) Micro press machine



d) Micro transfer arm e) Micro manipulator

Figure 2.5: Components of the machining micro-factory (Okazaki *et al.*, 2004).

Advanced Modular Micro-Production System (AMMS) is the title of a new concept developed by Gaugel *et al.* (Gaugel *et al.*, 2004) refers to flexible micro-machines using a modular concept due to is ideal for the integration and interconnection of processes required for micro-parts production, which have yet to be separated.

2.3 Micro-machining

According to Robinson *et al.* (Robinson and Jackson 2005), micro machining has the potential to become a successful small scale manufacturing process. Micro-machining is defined as mechanical cutting of features with tool engagement less than 1 mm with geometrically defined cutting edges. This technology includes numerous characteristics of traditional machining, simultaneously micro-machining increase a great number of issues mainly due to size or scale (Dornfeld *et al.*, 2006). According with Mian *et al.* the main difference with macro-scale, relates to the size effect which is generally identified as (Mian *et al.*, 2009):

- Tool-edge radius effect
- Material microstructure effect
- Material strengthening effect due to strain, strain rate, strain gradient etc
- Subsurface plastic deformation
- Material separation effect

This work focuses particularly in micro-milling technology.

2.3.1 Micro-milling tools

Recently, the demand of the industry of micro components changes the traditional tool market. The tools used in micro-milling applications are comparatively miniaturized. The suppliers of the cutting tool manufacturers industry provide cutting tools in diameters as small as 0.1 mm and unique as small as 0.01 mm. According to Uriarte *et al.*, (Uriarte *et al.*, 2009), two different cutting tool materials are generally used: diamond and tungsten carbide. The first ones with approximately atomic cutting edge sharpness which prevent the "cutting edge radius effect". However, these are limited to non-ferrous materials due to the high chemical affinity between diamond and ferrous materials causing severe wear (Kalpakjian and Schmid 2002). The second ones, sintered tungsten carbide tools, include spherical and straight two flutes mills made with different coatings: TiAl, TiAlN, DLC, etc. They conclude about the offer that is limited explaining that are not different geometries and is not available the option to choose face angle, helix angle, rake angle or other geometrical parameters.

According to Dornfeld (Dornfeld *et al.*, 2006) fabrication of micro-tools is another challenge in general in micro-machining. The micro tools for micro-milling actually are characterized by imprecision in the geometry and irregularities. Figure 2.6 and Figure 2.7 shows the tool geometry deviation with respect to the size of the tool; as the tool size decreases from 2 mm to 0.2 mm, the deviation of the given tool geometry from the tool design increases. Also, scaling effects can play a significant role in process physics, which are closely related to the cutting mechanism, caused by a change in tool geometry during cutting.

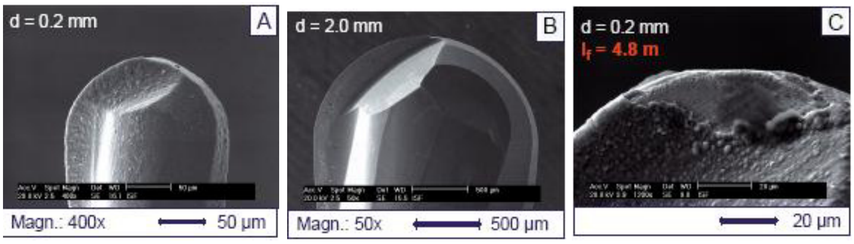


Figure 2.6: Scaling effect on tool geometry and wear (work material: 40CrMnMo7, 50 HRC, V_c =200/100 m/min, $a_p = a_e = 0.04$ x d, $f_z = 0.01$ x d, z= 2, down milling, tool material: cemented carbide with TiAlN coating (Dornfeld *et al.*, 2006).

Nowadays the researchers attempt to find alternative process to fabricate micro-tools in order to improve their characteristics. Vasile *et al.* (Vasile *et al.*, 1996) used the focused ion beam process in order to fabricate 25µm diameter steel milling tools. Also, Adam *et al.* (Adams *et al.* 2000) use the same technology to fabricate micro tools designed for micro-grooving and micro-threading with 13 µm of diameter using high speed steel and tungsten carbide. In addition, Adam *et al* (Adams *et al.*, 2001) and Sandia Labs developed a 25µm diameter carbide end mill tool with five cutting edges, also using focused ion beam machining, as shown in Figure 2.8. The technology used was gallium ion beam to generate a number of cutting edges and tool end clearance and machined trenches with widths nearly the same as the diameter of the tool.

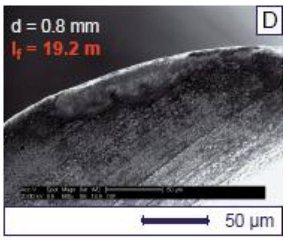


Figure 2.7: Demonstrates tool wear occurring during the micro-milling of hardened steel as a function of the engagement length and tool diameter (Dornfeld *et al.*, 2006).

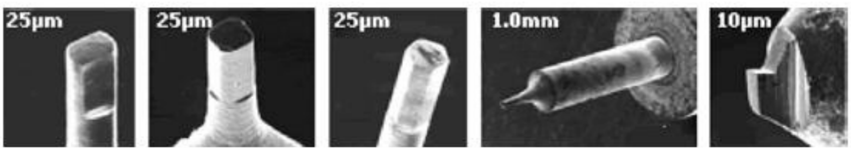


Figure 2.8: Scanning electron micrograph (SEM) of micro-cutting tools (Adams *et al.*, 2001).

Egashira and Mizutani (Egashira and Mizutani 2003) used electrical discharge machining (EDM) in order to fabricate end mills with a radius of 10 µm. They also used a wire electro discharge machining to manufacture a micro-drill with a D-shaped cross section and cutting edge radius of 0.5 μm.

Schaller *et al.* (Schaller *et al.*, 1999) manufactured micro-carbide tools using diamond-grinding disks. These tools are classified as single-edge end mills and their diameters range from 35 μm to 120 μm. Similarly, Onikura *et al.* (Onikura *et al.*, 2000) proposed ultrasonic vibration grinding to fabricate an 11μm diameter micro-carbide tool and 17μm diameter flat micro-drill. The concept of this grinding is to reduce the grinding forces such that they will not cause any breakage to the micro tools.

2.3.2 Material microstructure effect

Workpiece material microstructure effects play a critical role in micro-machining. In macro-scale the workpiece material is treated as isotropic and homogeneous, however, in micro-scale the tool dimension or a feature to be generated is of the same order as the grain size and cannot be assumed that the microstructure of the workpiece material is homogeneous. Typically chip formation takes place inside the each grain as a result of the cutting depth is a few micrometers. The surface roughness differs between the grains of material due to their crystallographic orientation and material phase elastic recovery. They suggest to set the depth of cut at about ten times the grain size of the specific material in order to avoid crystallographic influence of grains and obtain a good quality finish (Furukawa and Moronuki 1988). Likewise, Shimada *et al.* (Shimada *et al.*, 1995) works the interaction between tool edge and workpiece material. Using molecular dynamics they found that the kinetic energy imparted to the workpiece is far greater than the cohesive energy of the workpiece, the simulations running cutting speeds at 2000 m/s.

Vogler *et al.* (Vogler *et al.*, 2002) also recognize the tool edge and workpiece material grains become comparable in size. Additionally Vogler *et al.* (Vogler *et al.*, 2004a; Vogler *et al.*, 2004b) study the microstructure effects of single and multi-phase materials on surface generation and cutting force in a micro-end milling process. They confirmed that the edge radius effect contributes significantly to surface generation due to a minimum chip thickness, particularly for single phase materials. Moreover, for multi-phase materials, the surface roughness was revealed to be a combination of three separate effects: a geometric effect, a minimum chip thickness effect, and a burr formation at the grain boundaries effect.

Komanduri *et al.* (Komanduri *et al.*, 2001) conducted simulations. In this case study, the volume change occurred when silicon is machined. They explain that the pressure induced phase change, changing the microstructure from cubic to body centered tetragonal. On the other hand, Lee *et al.* (Lee *et al.*, 2002) conducted a study to examine the vibrations caused by non homogeneous material. They found that crystallography and grain orientation affects shear angle and strength.

Grum *et al.* (Grum and Kisin 2003) study the cutting force in turning as related to workpiece material and hardness. They conclude that when the cutting tool moves from one material phase to another, the cutting conditions change, resulting in machining errors, vibration, or accelerated tool wear. The material used, in this investigation were aluminum and silicon alloys.

According to Dornfeld (Dornfeld *et al.*, 2006), the contribution by Furukawa and Moronuki´s is an experimental investigation related with micro-machining on various materials in order to prove that the cutting mechanism are very different for single crystal, polycrystalline or amorphous materials and for brittle or ductile materials. They found that the specific cutting force depends highly on the aspect ratio of the undeformed chip thickness (feed per tooth) to tool engagement length and increases exponentially as depth of cut decreases below 3 μm for all materials tested (pure copper, aluminum alloy, PMMA, CaF2, and germanium). Cutting force varied as the tool passed grain boundaries, Figure 2.9. Cutting of single crystal fluorite and amorphous acrylic resin gave more consistent cutting forces with rather regular and homogeneous surface properties. They suggested the use of about ten times larger depth of cut than the grain size for a specific material to avoid the crystallographic effects of grains.

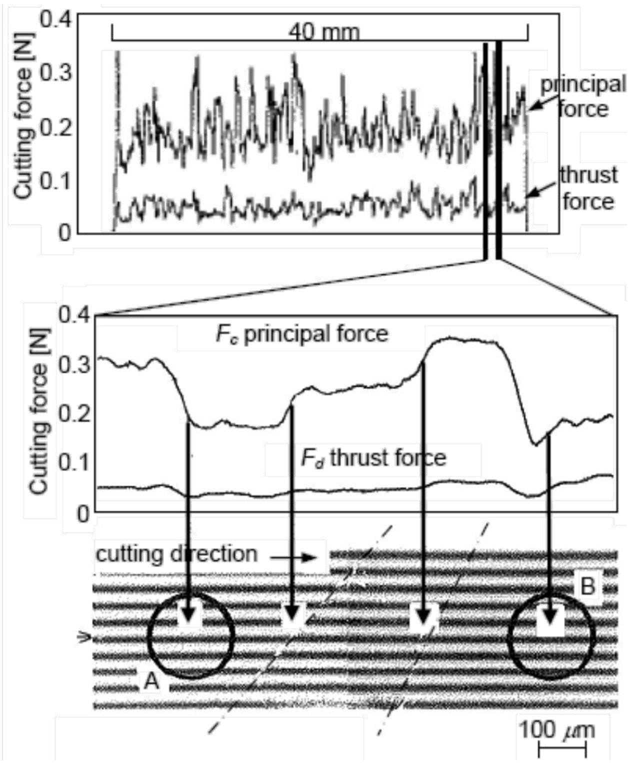


Figure 2.9: Cutting force variation corresponding with the grain boundary of Al alloy (grain boundaries can be seen in magnified image in A and B) (Dornfeld *et al.*, 2006).

Weule *et al.* (Weule *et al.*, 2001) conducted a series of experiments in SAE 1045 steel. They quenched and tempered the workpiece material in order to obtain a homogenized workpiece. Additionally they found that an increase in the feed rate would improve the surface finish. In order to see the effect of the crystallographic orientation on surface and subsurface crack generation.

Sumomogi *et al.* (Sumomogi *et al.*, 2002) conducted a series of micro-turning experiments on single crystal silicon. They used a micro-Vickers hardness indenter as a tool for turning with decreasing depth of cut. Machining was designed to be ductile mode when surface cracks disappeared. The depths of cut where no subsurface cracks was detected were smaller than ductile depths of cut and be conditioned on the crystallographic orientation of silicon. Furthermore, Yuan *et al.* (Yuan *et al.*, 1996) proved the crystallographic orientation effect on surface roughness and cutting force for single crystal, aluminum and copper in ultra precision diamond cutting were used in the experimentation. In order to explain the variations in cutting force and surface roughness as a result of crystallographic orientation, they used a micro-plasticity model. This model allows calculate the shear strength of a particular crystal orientation using and effective Taylor M factor and compared this with experimental data. Fluctuation in shear strength generate cutting force variation over different cutting directions and the resulting material induced vibration, in addition to machine induced vibration, degraded surface quality. They proposed the use of fine grain material or cutting isotropically to avoid such problems.

Popov *et al.* (Popov *et al.*, 2006) investigates the effects of material microstructure on part quality in micro-milling. They modified Al Alloy mechanically and metallurgically in order to observe the response of machining in micro-scale with these conditions. The investigation has shown that through refinement of material microstructure it is possible to improve considerably the surface integrity of the machined micro-features. Respect to roughness of micro-features is highly dependent on the material grain size. Similar research was developed by Attanasio *et al.* (Attanasio *et al.*, 2013) they investigated the influence of microstructure on cutting force, cutting tool wear and micro-channel quality performing micro-milling in Ti6Al4V alloy. They suggested to use material with lamellae thus obtaining lower cutting forces and lower built up edge together with high part quality.

2.3.3 Minimum chip formation

Both isotropic and anisotropic cutting are greatly influenced by the ratio of the depth of cut to the effective cutting edge radius of the tool. In micro-machining, the edge radius of the tool tends to be the same order-of-magnitude as the chip thickness. Thus, a small change in the depth of cut significantly influences the cutting process. This ratio predominantly defines the active material removal mechanism such as cutting, plowing, or slipping and thus the resulting quality, surface roughness for example (Dornfeld *et al.*, 2006).

Robison *et al.* (Robinson and Jackson 2005) explain that during macro machining, the feed per tooth is larger than the cutting edge radius; but, during micro machining the phenomenon is different the feed per tooth is equal to or less than the cutting edge radius for this reason the chip may not be formed and finally the tool may bend or fracture.

Chae *et al.* (Chae *et al.*, 2006) proposed basic mechanism of micro-machining as shown in Figure 23. Firstly when the undeformed chip thickness (h) is less than the minimum chip thickness (hm) as shown in Figure 2.10(a), elastic deformation occurs and the cutter does not remove any workpiece material. Therefore, there is no material actually removed as a chip. Secondly, when undeformed chip thickness is equal to the minimum chip thickness, Figure

2.10(b), the chip starts to form through the shearing of the workpiece coupled with a portion of elastic deformation and recovery. Thus, the removed material is less than the desired value (undeformed chip thickness). Finally, when the chip thickness is larger than the minimum chip thickness as shown in Figure 2.10(c), material is removed and formed as a chip (Robinson *et al.* 2007).

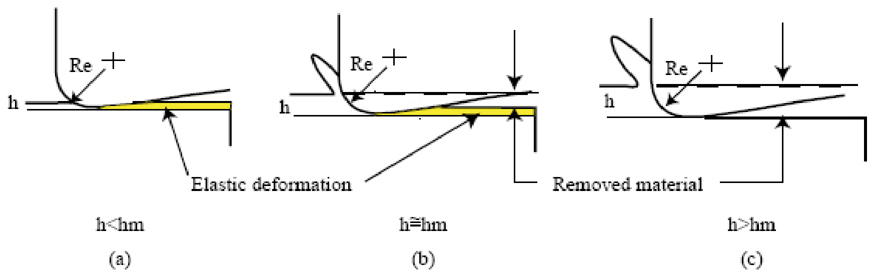


Figure 2.10: Schematic of the effect of the minimum chip thickness (Chae *et al.*, 2006).

Respect to the concept of minimum chip thickness effect, Ikawa *et al.* (Ikawa *et al.*, 1992) suggested there is critical minimum depth of cut, below which chips do not form. This value was found to be predominantly driven by workpiece material/tool combination rather than tool–work interaction. In addition, the analysis of Yuan *et al* (Yuan *et al.*, 1996) indicates chip formation is not possible if the depth of cut is less than 20-40% of the cutting edge radius.

Son *et al.* (Son *et al.*, 2005) propose a cutting model in which the tool edge radius and the friction coefficient are the principal factors determining the minimum cutting thickness with a continuous chip. According to the model, a smaller edge radius and a higher friction coefficient make the cutting depth thinner. The study by Weule *et al.* (*Weule et al.*, 2001) found that minimum chip thickness (or minimum cutting depth) depends of two variables primarily on sharpness of the tool and secondarily on material properties.

Kim *et al.* (Kim *et al.*, 2002) observes that if the feed rate is too low a chip is not necessarily formed by each revolution of the tool. Additionally conclude that a tool rotation without the formation of a chip is due to the combined effects between the ratio of cutting edge radius to feed per tooth and the lack of rigidity tool of the tool. In this way the less rigid the tool, the higher is the ratio of cutting edge radius to feed per tooth and the more is the accumulation of workpiece material as the tool advances. In other investigation by Shimada *et al.* (Shimada *et al.*, 1995) using molecular dynamics simulations found that the minimum chip thickness is around 5% of the cutting edge radius for copper and aluminum.

According to Komanduri (Komanduri and Raff 2001), Mizumoto shows that the depth of cut and cutting edge radius are critical parameters that determine chip formation. This can be predicted with simulations, diving the process into small intervals it is possible to compute the position of each atom.

According to Vogler *et al.* (Vogler *et al.* 2004a) the minimum chip thickness depends of the phase material for this motive found two ranges: for when machining perlite is about 14 to

25 per cent, and in the case of ferrite is about 29 to 43 per cent (these conclusions using finite element simulations).

2.3.4 Ductile mode machining

According to Dornfeld (Dornfeld *et al.*, 2006), the fabrication of micro-scale structures in brittle materials represents a potential area for micro-machining, providing increased flexibility in geometries produced, and higher material removal rate, converting to higher production throughput. However, machining brittle material at the high depths-of cut (DOC) found in conventional machining contributes with excessive surface and subsurface cracking. In order to overcome this condition, machining in a ductile mode at a low enough DOC has been proposed by many researchers.

Fang and Chen (Fang and Chen 2000) developed a research studying brittle-ductile transition of glass materials. They conclude that in contrast to metals, glass viscously deforms exclusive in a very small region under hydrostatic compressive stresses at temperatures inferior the softening point. Furthermore, they carried out ultra-precision turning operations on glass materials and deduce that a negative rake face angle create the necessary hydrostatic compressive stress and allow ductile regime cutting, although resulted rapid tool wear like a disadvantage.

As reported by Dornfeld (Dornfeld *et al.*, 2006), Bifano found the way to obtain good surface finish and no surface pitting or cracking this when cutting below a critical DOC due to brittle materials can be machined in a ductile configuration. In comparison with polishing or other techniques, the chip thickness in micro-machining can be on the order of the critical DOC. This micro-machining approach can serve as a new method of manufacturing unique features in brittle materials not feasible by polishing or other techniques. Also, Blake and Scattergood explored ductile regime diamond tuning of brittle optical components as silicon and germanium. They propose optimal cutting parameters such as critical depth of cut, tool geometry, and cutting speed based on an analytical model and experiments (Figure 2.11).

Similar work was developed by Egashira and Mizutani (Egashira and Mizutani 2002) investigated critical depth of cut for ductile mode micro-drilling f single crystal silicon. Also, Nakasuij *et al.* (Dornfeld *et al.*, 2006) focused on critical depth of cut for ductile mode cutting and surface finish in machining of germanium (Ge) and silicon (Si) considering the crystallographic orientation as stated in research of Dornfeld.

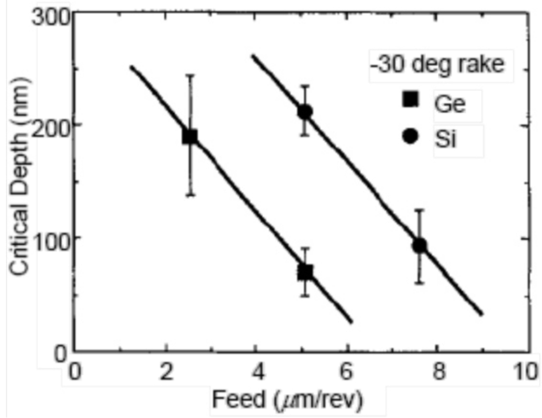


Figure 2.11: Apparent critical depth of cut versus feed: (100) germanium and silicon with -30° rake and 6° clearance angles (Dornfeld *et al.*, 2006).

According to investigation developed by Dornfeld (Dornfeld *et al.*, 2006), Ueda *et al.* studied the same phenomenon in ceramics, they found that part of ceramic materials can be machined in a ductile mode by reducing the DOC and/or augmenting cutting speed. ZrO2 and WC-Co were easily machined in a ductile mode by cause of their high fracture toughness. However, Al2O3 and SiC presented only brittle mode cutting with the smallest possible depth of cut at that time, 2 μm. The machining mode of Si3N4 modified from brittle to ductile as cutting speed increased.

2.3.5 Burr formation

In micro-machining, burr formation is another critical factor on surface finish. Burrs can be described as undesirable projections of material beyond the edge of the workpiece owing to plastic deformation, i.e. bending of chips rather than shearing at the end of a cut.

According with Mian *et al.* (Mian *et al.*, 2009) the defect depends principally on the workpiece material in terms of ductility, cutter geometry, cutting parameters, tool wear and shape of workpiece. Burrs frequently occur when micro-machining hard materials due to of increased tool wear (Weule *et al.*, 2001).

Gillespie attempted remove burr formation at micro-scale with techniques traditionally used in macro-scale but the results were not positive. Accuracy and repeatability of macro burr removal techniques are lost at the micro-scale. Additionally affirm that minimize or eliminate the imperfections such as burr formation can contribute to 30 per cent of cots to produce part. There are three generally accepted burr formation mechanisms: lateral deformation, chip bending, and chip tearing furthermore four basic types of burrs as Poisson, tear, rollover, and cut-off burrs. Burr formation progress is described a three-stage: initiation, development, and formation (Lee and Dornfeld 2005).

Lee and Dornfeld (Lee and Dornfeld 2002) found that up-milling commonly creates smaller burrs than down milling and this investigation led to the categorization of different burr types (Figure 2.12). The undeformed chip thickness will determine burr height, that once the work material and other process parameter are specified.

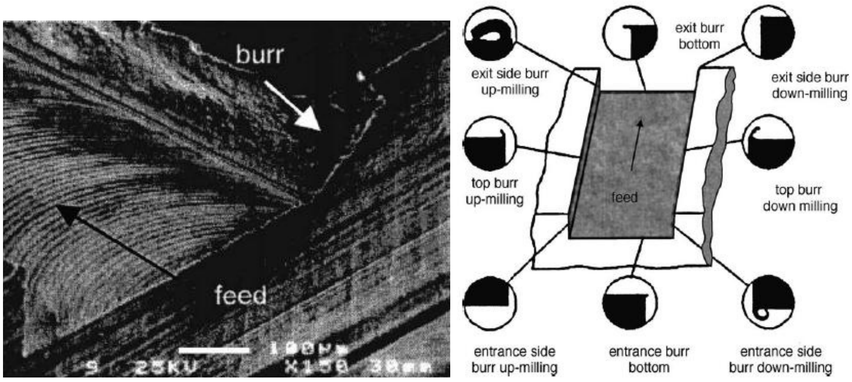


Figure 2.12. a) An exit burr b) Categorization of burr types (Lee and Dornfeld 2002).

In medical field, NiTi is a common used work material and the technology used to manufacture micro components is micro-milling. The material characteristics are very ductile and easily work hardens over machining resulting adhesion and high burr formation. Others effects caused by high ductility are adverse chip formation, long and continuously snarled chips. The final result is a finished part with poor surface quality conforming to Dornfeld by Zhang (Dornfeld *et al.*, 2006).

Ahn and Lim (Ahn and Lim 2000) developed a burr formation model in a micro-grooving operation established on a side shear plane and an extended deformation area which as a result of the tool edge radius effect. The result of hydrostatic pressure in the material near the cutting edge is a side shear deformation. Moreover aluminum and OFHC produce larger burrs than brass; they conclude that the thickness of the burr is proportional to the ductility of the material. In the same aspect Schaller *et al.* (Schaller *et al.*, 1999) conducted experimentation and showed that when manufacturing micro-grooves in brass, burr formation can be extremely reduced.

Min *et al.* (Min *et al.*, 2006) used experimental investigation in micro-fly cutting and microdrilling on single crystal and polycrystalline OFHC copper for understand the effects of cutting speed, chip formation, crystal orientation, grain boundaries on surface roughness, and burr formation. The investigation demonstrates that crystallographic orientations affect in surface finish, in addition to significant burrs and breakout at the tool exit edge. The evidence in <100> and <110> direction (Figure 2.13) of machining exhibited the greatest amount of variation in formation of burrs and breakout at the exit edge and in chip topology as caused by the angular orientation of the workpiece.

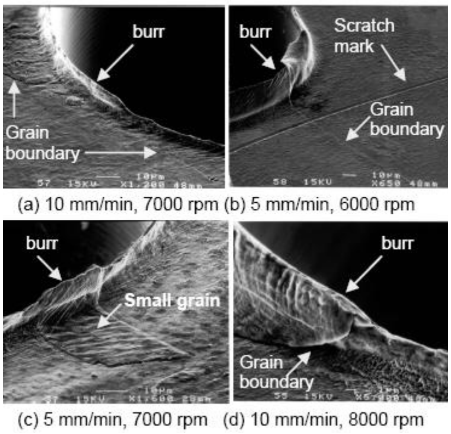
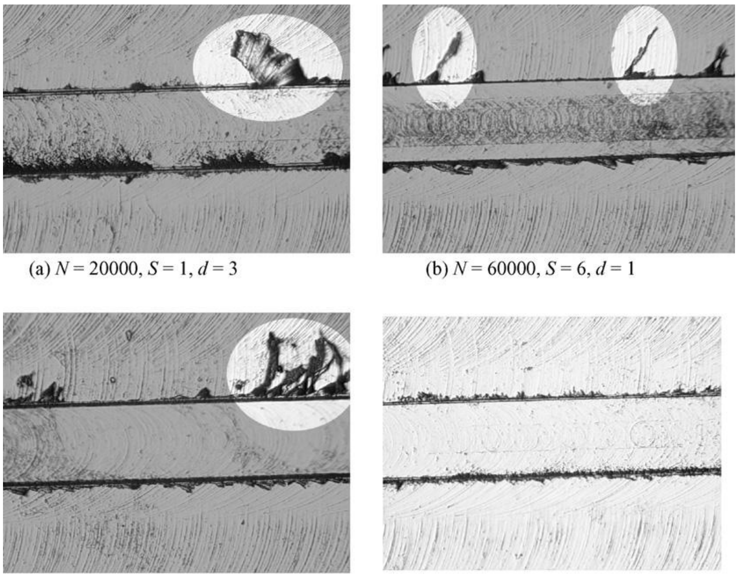


Figure 2.13: a) Microdrilling burr formation (250 μm) (Min *et al.*, 2006).

Lee and Dornfeld also conducted slot milling experiments on the same material and found a strong relation of top burr formation on slip systems of each crystal orientation excluding (100) workpiece (Min *et al.*, 2006). Top burrs are relatively large in micro-milling considering the size effect (Bissacco *et al.*, 2005). Bissacco *et al.*, (Bissacco *et al.*, 2005) explain that when the ratio of the depth of cut to the cutting edge radius is small, high biaxial compressive stress pushes material close to free surface and generates large top burrs.

As reported by Dornfeld (Dornfeld *et al.*, 2006), Sugawara *et al.*, conducted experimental investigation related with the effect of drill diameter and crystal structure on burr formation in microdrilling. The experiments were performed in single crystal and polycrystalline iron with a thickness between 0.06 mm and 2.5 mm. They conclude that burr size is reduced and cutting ability increased as drill size decreases.

Chern *et al.* (Chern *et al.*, 2007) studied burr formation in micro-machining using micro-tools fabricated by micro-EDM. In this research aluminum alloy was used as workpiece material. In previous investigations by Chern observed five types of burrs in his face-milling experiments on aluminum alloys: knife type burr, wave-type burr, curl-type burr, edge breakout, secondary burr. In this research there are four types of burrs: primary burr, needle-like burr, feathery burr, minor burr (Figure 2.14). In order to avoid severe burr formation they suggested keeping both the axial engagement and the feed to a minimum.



(a) $N = 20000$, $S = 1$, $d = 3$ (b) $N = 60000$, $S = 6$, $d = 1$

(c) $N = 40000$, $S = 4$, $d = 3$ (d) $N = 20000$, $S = 1$, $d = 1$

Figure 2.14: Photos of burrs (100×) in micro-machining: (a) primary burr; (b) needle-like burr; (c) feathery burr; (d) minor burr. N is in rpm, S in mm/min and d in μm (Chern *et al.*, 2007).

Schaller *et al.* (Schaller *et al.*, 1999) found ways to minimize burring. They coated brass with a cyanacylate polymeric material, this material filled voids in the vicinity of the edges of the workpiece, where burrs form, letting the cutting tool always to be engaged with the workpiece or the cyanaclylate layer. In order to eliminate cynacylate is used an ultrasonic bath with acetone. Electro-chemical polishing techniques were used to remove burrs in stainless steel. This post-processing to minimize burrs can be expensive but necessary.

Filiz *et al.* (Filiz *et al.*, 2008) conducted a research in the medical field with a fabrication of micro-barbs for medical implants using micro-milling, respect to burr formation they conclude in specific case of V-shape tool the burr formation increases with increasing feed for both axial depth-of-cut levels. Although the effect of axial depth of cut was small, the lower depth of cut of 10μm produce more burrs. The most extensive burr formation was seen for the condition with the higher depth of cut (20μm), the higher speed (100krpm), and the highest feed (5μm/flute). The least amount of burr formation was seen for the conditions with the higher depth of cut (20μm), the lower speed (50krpm), and the highest feed (5μm/flute). In the case of T-shape tool the lowest burr formation was observed for the lowest feed rate of 1μm/flute and the lower speed of 50 krpm.

Aramcharoen and Mativenga (Aramcharoen and Mativenga 2009) investigated the influence of the size effect on product quality in micro-milling of H13 hardened tool steel. They conclude that the burr size decrease with an increase of the ratio of undeformed chip thickness to the cutting edge radius. Also, the lowest size for the burr was found to occur at undeformed chip thickness larger than the edge radius. Thus the selection of optimum micro-milling variables involves a compromise between best surface finish and burr size. Since burr formation appears inevitable in micro-machining then micro-milling with undeformed chip thickness equal to the edge radius will give best surface finish and reasonably low burr size. In addition, geometry of the cutting edges considerately affects the surface finish and burr size in micro-milling, they suggested that rounded cutting edges or chamfered geometries were found to be more favorable in terms of generating better surface finish.

Piquard *et al.* (Piquard *et al.*, 2013) studied the cutting parameters effect on burr formation in NiTi alloys by micro-milling. They found that an increase of feed per tooth implies a decrease of top burr height and width. In addition, an increase of width cut implies an increase of top burr height and width.

2.3.6 Tool wear

The small depth of cut in micro-machining significantly increases friction between the tool and the workpiece, resulting in thermal growth and wear (Xiao *et al.*, 2003). This phenomenon has been studied with neural networks. Tansel *et al.* (Tansel *et al.*, 2000) trained neural networks in order to predict tool wear using cutting force and wear data. The aim of the neuronal networks is estimate tool condition in the micro-machining of steel and aluminum. The limitations of this work are that requires ample experimental data and is generally inconsistent for different material and cutting conditions. Weule *et al.* (Weule *et al.*, 2001) confirmed the results about tool wear in the soft/hard workpiece cutting.

Rahman *et al.* (Rahman *et al.*, 2001) studied micro-milling of copper. They demonstrated the wear of a 1 mm diameter tool depend on the tool helix angle and the depth of cut. Experimental result observed is a small depth of cut (0.15 mm) has a higher tool wear rate than a larger depth of cut (0.25 mm). This as a result of continuous chip being removed-up the helix of the micro-tool, increasing the force on its rake face. Furthermore, Filiz *et al.* (Filiz *et al.*, 2007) works micro-milling experiments in OFHC copper demonstrating that greater tool wear at low undeformed chip thickness.

Uriarte *et al.* (Uriarte *et al.*, 2008) conducted investigation related with tool wear evolution. They used 300μm diameter tool with TiAIN coating, and the workpiece material was a steel AISI H13 of 54 HRC. The cutting conditions were rotational speed of 60 000 r/min, a depth of cut 10μm, and a feed pert tooth of 0.4μm. The Figure 2.15 a) to b) shown the changes after removing a volume of 0.2mm^3, then from b to c removing a volume of 1mm^3. They concluded wear tool appears in the cutting edge area, however, in some cases wearing appears in the opposite zone, a cause of high tool deflection.

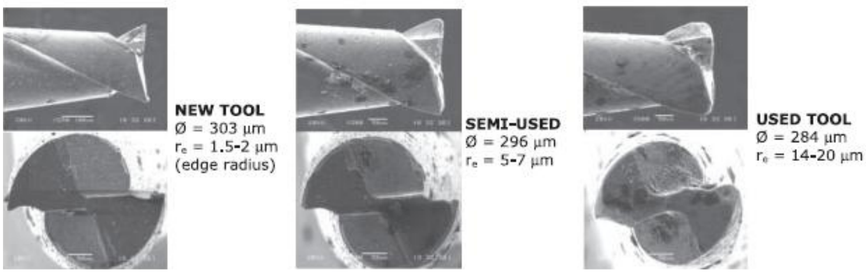


Figure 2.15: SEM image of a) a new tool, b) a semi-used tool and c) a used tool (Uriarte *et al*, 2008).

Rahman *et al.* (Rahman *et al.*, 2001) experimentally predict tool life. They conclude that feed rate and cutting speed have a more critical influence over the micro-cutting tool than the axial depth of cut ant the flank wear at the end of cutting edge is highest.

Dow *et al.* (Dow *et al.*, 2004) worked with a scanning electron microscope (SEM) in order to monitor the tool wear. They observed that as cutting tools wear, the edge of the cutting tool becomes flat. The limitation respect to use SEM is the long time and difficult set-up. Also Weinert and Perzoldt (Weinert and Petzoldt 2004) used an SEM to measure the influence of the tool size on tool wear.

Based on the work of Bhattacharyya and Ham, Ramanujachar and Subramanian (Ramanujachar and Subramanian 1996) investigating crater wear, related with chemical and mechanical components (Figure 2.16). They used calcium treated AISI 1045 grade steel with a cemented carbide tool, their components were 97% tungsten carbide, 0.4% Ta(Nb)C and 2.6% cobalt. The results prove that when a tungsten carbide tool was used to machine steel, a TiN coating decreased the thermodynamics potential for dissolution by six orders of magnitude compared to uncoated case. Additionally, they found that cutting speed affected the cutting temperature. A similar work was conducted by Ramanujachar and Subramanian (Ramanujachar and Subramanian 1996) using AISI 1040 grade steels with a tungsten carbide tool at speeds of 175m/min and higher. They observed diffusion to be the main source of crater wear. Furthermore, experiments were conducted with coated and uncoated tools made from K1 cemented tungsten carbide containing 85% WC, 11% Co and 4% (TaC/NbC). They found two types of wear, firstly mechanical wear characterized by loss of tungsten carbide particles from the workpiece and secondly chemical wear characterized by dissolution of tungsten carbide. The solution proposed in order to prevent dissolution of tungsten from the workpiece, when is used high cutting, is a thin HfN coating. Without coating the tool can lose a large amount of tungsten by dissolution to the chips.

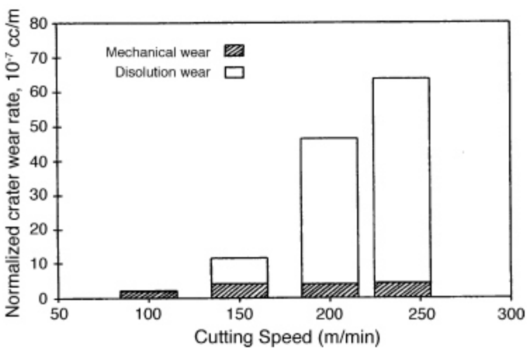


Figure 2.16: The contribution made to overall wear by chemical and mechanical sources (Ramanujachar and Subramanian 1996).

Mian *et al.* (Mian *et al.*, 2009) explored the effects in micro-milling, one of these was tool wear for a coarse grained AISI 1045 steel. They used SEM images in order to investigate the progression of tool wear. Figure 2.17-a) shows a new tool while Figure 2.17-b) shows the tool after machining with an undeformed chip thickness of 0.02 μm for 300 mm length of cut.

They found tool wear at the cutting edges; moreover some fragments of workpiece material adhere to surface of the cutting edges. The ploughing effect is critical to accelerate tool wear (Figure 2.18). Flank wear increased with reduced undeformed chip thickness (Figure 2.19). They suggested that the lowest chip load should be avoided in order to obtain maximum tool life.

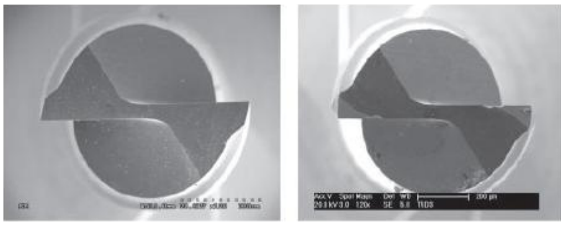


Figure 2.17: Microend mill: a) new; b) worn tool (Mian *et al.*, 2009).

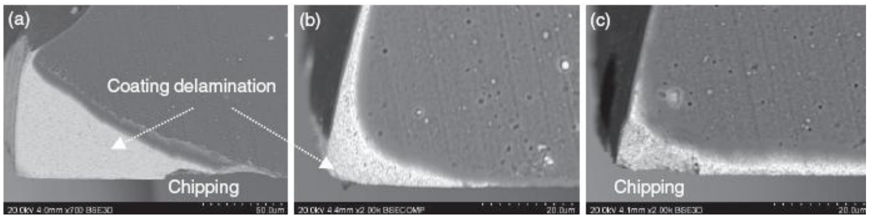


Figure 2.18: Microend mill cutting edges at different chip load: a) 0.02 μm/tooth; b)2 μm/tooth; c) 152 μm/tooth (Mian *et al.*, 2009).

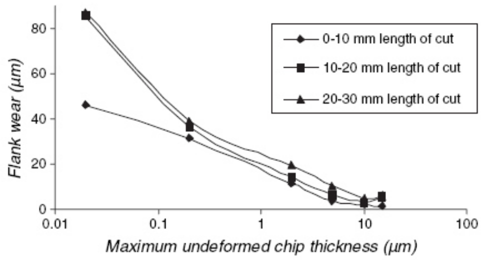


Figure 2.19: Tool flank wear (Mian *et al.*, 2009).

According to Chae *et al* (Chae *et al.*, 2006), the investigation by Mitsubishi demonstrates there is no relationship between the amount of wear and the coolant pressure. In addition, Malekian *et al.* (Malekian *et al.*, 2009) conducted an experimental investigation to monitor micro-milling operations using neuro-fuzzy algorithm. In this study, various sensors and a vision system were utilized. After performed each experiment the edge corner radius of the tool was observed with a vision system in order to measure the amount of wear and the sensor works off-line to capture the cutting signals and the edge radius then were applied to a neuro-fuzzy method to train and determine the relations and rules. Once a neuro-fuzzy algorithm was trained, the cutting signals could be interpreted to determine the tool wear through on-line analysis. The performance of the neuro-fuzzy method is acceptable; the actual wear was compared with simulated results and observed good agreement.

Zhu *et al.* (Zhu *et al.*, 2009) studied the selection of hidden Markov models (HMM) structures for tool state estimation in the micro-milling of pure copper and steel. The model was able to use different conditions, such as working or machining conditions, workpiece materials, and variations of observation sequence length. They conclude that the approach based on continuous HMM proposed is highly effective for micro-milling tool wear monitoring. In addition, providing the prediction of the tool life (Figure 2.20).

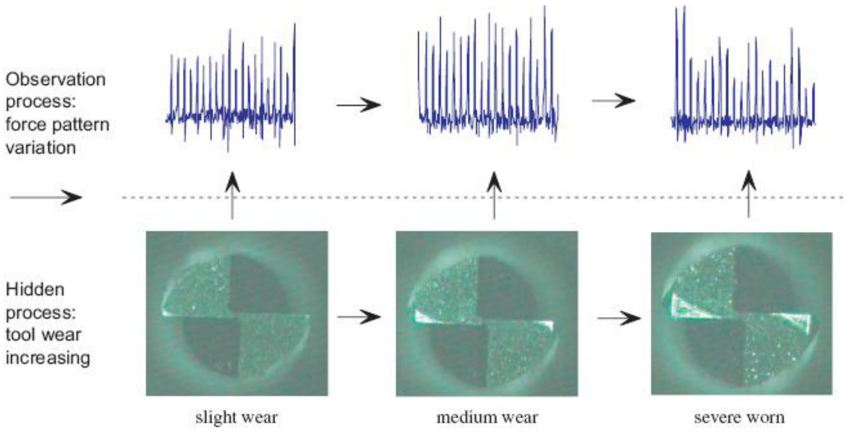


Figure 2.20: Stochastic modelling of tool wear processes (Zhu *et al.*, 2009).

According to Dornfeld (Dornfeld *et al.*, 2006), the investigation by Sugano *et al.* related with the study of the relation between wear of single crystal diamond tools and their effects on the surface roughness and the residual stress of surface layers using different machining conditions. They demonstrated that wear of the diamond tool has less influence on micro-roughness.

Miyaguchi *et al.* (Miyaguchi *et al.* 2001) found that tool wear in a micro-milling process is partly responsible of the stiffness of a micro-end-mill tool. They concluded that, tool life can be prolonged by reducing tool stiffness, because the cutting forces are balanced, resulting in even tool wear on both cutting edges as tool stiffness is lowered to almost the breakage limit of the end mill. In addition the effect of tool run-out is reduced and the abrasion of each tool edge tends to be uniformity.

Regarding to the effect of coating material on tool wear in micro-milling Ucun *et al.*(Ucun *et al.*, 2013) performed an experimental work using Inconel 718 super alloy. The results obtained showed that the cutting tools coated with AlTiN, TiAlN+AlCrN, and AlCrN displayed better performances compared to those coated with TiAlN+WC/C and DLC.

2.3.7 Tool deflection

Dow *et al.* (Dow *et al.*, 2004) studied the tool deflection and bending stress. They conclude that the forces generated during milling with a miniature ball end tool are relatively small (less than 10N) due to the limited size and strength of the tool edge. However, tool deflections can be a significant source of profile error because of low radial stiffness. Predicting tool deflection using real-time cutting force measurements can be used to compensate for errors arising from tool deflections and workpiece misalignment. The force model was then combined with tool stiffness to calculate the deflection of the tool as a function of the depth of cut, the up-feed per revolution and the geometry of the part. Two experiments were used to demonstrate the effectiveness of this error compensation technique. Each experiment reduced the error due to tool deflection by an order of magnitude from 20–50 μm to 2–5 μm.

Dugas *et al.* (Dugas *et al.*, 2002) developed a machining simulator for an NC machining applications. Simulator is able to analyze error caused by tool deflections. The values generated by the similar can be introduced as input data in developing optimization algorithms in order to remove or reduce errors.

2.3.8 Chatter

One of the challenges in micro-machining is the phenomenon of chatter, which is an unstable vibration that can cause critical tool wear and breakage, especially in the micro-scale. Rahnama *et al.* (Rahnama *et al.*, 2009) investigated chatter stability in micro-end milling related with the use of process damping in order to suppress this issue. Firstly they required the tool tip dynamics and cutting coefficients in order to predict chatter stability. However, in micro milling, the elasto-plastic nature of micro machining operations results in considerable process damping in the machining process, which affects the chatter. They used the equivalent volume interface between the tool and the workpiece to determine the process damping parameter. The dynamics at the tool tip was indirectly obtained from experimental cutting tests. Chatter stability experiments have been performed to examine the proposed chatter stability. In contrast, Shi *et al.* (Shi *et al.*, 2012) proposed a new measuring method for online chatter detection via piezoactuators in order to detect the chatter frequency in the transition field from the stable state to the unstable state, i.e., with the axial depth of cut lower than the actual stability boundary.

Also Park *et al.* (Park *et al.*, 2003) investigated in order to improve the representation of the dynamics at the tool tip. They developed the receptance coupling and joint dynamics identification method. In addition, they analyzed the relation between tool and spindle dynamics. FE analysis was used to obtain the complete dynamics of the micro-end mill, in contrast to dynamics of the spindle-tool which was measured through the experimental hammer test. The joint dynamics was then indirectly acquired based on two translational measurements using a blank tool. Similar research was developed by Filiz and Ozdoganlar (Filiz and Ozdoganlar 2011). They proposed a three-dimensional model for the dynamics of micro-end mills including bending, torsional and axial vibrations. The experimental validation study showed that the natural frequencies can be obtained with better than 2% accuracy for two-and-four fluted micro-end mill, and for all the modes up to 90 kHz.

In other hand, Afazov *et al.* (Afazov *et al.*, 2012) developed a new micro-milling chatter model. The model considers the nonlinearities of the cutting forces caused mainly by the run-out phenomenon, cutting tool edge radius and cutting velocity. In order to validate the micro-milling chatter model, an experimental work was developed to inspect the surface finish for chatter marks in micro-milling at different spindle speeds and depths of cut using an inclined surface where the depth of cut gradually increases.

Robust prediction of chatter stability in micro-milling comparing edge theorem and Linear Matrix Inequality (LMI) was developed by Graham *et al.* (Graham *et al.*, 2013).

2.3.9 Run-out

The issue of the tool run-out highlights the importance of aligning the cutting tool with spindle. In micro-machining the diameter of the tool decreases and spindle speed increases considerably. Therefore, the tool run-out represents a challenge for the researchers.

Related with this research field, many authors studied the tool run-out by investigating cutting forces during cutting and non-cutting. Bao and Tansel (Bao and Tansel 2000b) investigated the cutting force characteristics of micro-end milling operations with tool run-out. They developed an analytical cutting force model in order to estimate the cutting force characteristics. In comparison with numerical approaches the advantage of their model is fast cutting force computation. The validation of the model with experimental data demonstrates good agreement with the model.

According to Dornfeld (Dornfeld *et al.*, 2006) the contribution related with run-out by Liu et al. is the use of the capacitance sensor to examine tool run-out. Although, Vogler *et al.*, demonstrates that capacitance sensors was inaccurate on round surfaces with the displacement measurement becoming non-linear. Similarly, Lee and Cheung (Lee and Cheung 2001) investigated the phenomenon of run-out. They observed large marks from the cutting tooth due to tool run-out. In addition to producing features with inaccurate dimension, run-out also unfavourable impacts surface roughness. They found that the tool is not perfectly orthogonal to the surface being cut. In order to reduce the deflection, they propose minimize the length of the tool and toolholder, the use of a stiffer toolholder and clamping unit for the cutter, however they suggests deserves more study. In the same way, Rivin *et al.* (Rivin *et al.*, 2000) developed advanced state of the art about tool holders. They conclude that active or passive control of tool holders using actuators may be required to compensate for nay unbalance and minimize tool run-out.

2.3.10 Cutting fluid

Regarding to the use of cutting fluids in micro-milling is a topic relatively unexplored. Prakash *et al.* (Prakash *et al.*, 2001) used the MQL technique with a flow rate of 1mlh-1 and evaluated the results in terms of tool wear, chip shape, cutting speed and feed rate. The diameter of the tool used in this investigation was 1 mm and they worked with copper as workpiece. They found that the chips produced during MQL are smaller in comparison with dry cutting. Additionally, the tool life increases with the increase of federate and of depth of cut.

Weinert and Petzoldt (Weinert and Petzoldt 2004) studied the machinability of NiTi by micro-milling. They found that the best results could be obtained with Minimum Quantity Lubrication (MQL) leading to a significant increase of efficiency and quality in comparison to a dry machining process. They tried with unconventional cooling conditions. Dry ice (CO_2) demonstrates some promise on micro-machining of NiTi materials. Figure 2.21 shows surface and edge quality under two different lubrication conditions: (a) minimum quantity lubrication (MQL) and (b) dry. Burrs form only at the end of the trench under MQL while a burr is present along the entire trench length under dry conditions (Figure 2.22). The proper combination of nozzle distance, supply pressure and supply method (continuous and intermittent) is under investigation for optimal process results.

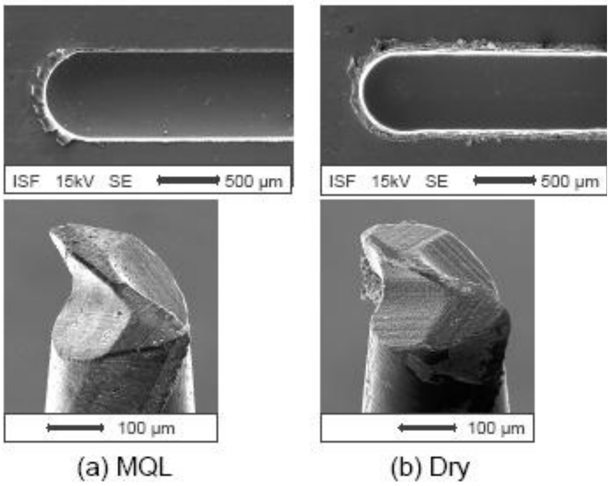


Figure 2.21: Micro-end milling under MQL and dry (Weinert and Petzoldt 2004).

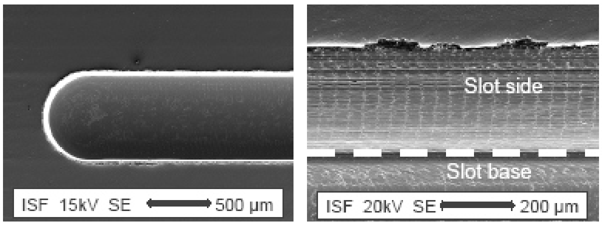


Figure 2.22: Micro-end milling under dry ice supply (Weinert and Petzoldt 2004).

A similar research was performed by Li and Chou (Li and Chou 2010) they studied the performance of the minimum quantity lubrication (MQL) technique in near micro-milling compared to dry condition evaluating the tool wear, surface roughness and burr formation. Additionally, they considered the effect of the tool material, oil flow rate and air flow rate on tool performance in MQL cutting. The tests were performed using a meso-scale milling, 0.600 mm diameter end mill and hot work die steel (SKD61) as workpiece. They concluded that the application of MQL will significantly improve the tool life, surface roughness and burr formation compared to those in dry cutting. They recommended the following conditions: oil flow rate of 1.88 ml/h and air flow rate of 40 l/min. It is also found that the air flow rate has a more significant influence on tool life than the oil flow rate under MQL conditions in this study.

Other approach of cooling is the cryogenic technique, when materials such as soft polymers (used in microfluidic applications) are machined it is difficult due to these materials presents low toughness. Study research confirms that with cryogenic cooling, Polydimethylsiloxane

(PDMS) can be machined and a micro groove can be obtained. This is achieved working at temperatures below the glass transition temperature (Kakinuma *et al.*, 2008).

Marcon *et al.* (Marcon *et al.*, 2010) investigated the effect of a graphite nanoplatelet based lubricant in micro-milling of hardened steel. Using this lubricant they found lower tangential force, however, this lubricant has negative effect on the slot depth and causes burnishing of the machined surface.

2.3.11 Forces

Such as other consequences due to change between macro and micro-scale, forces produced under micro-milling are also an important factor to consider. Compared with conventional tool, micro-tools are more likely to experience relatively large vibrations and forces, due to size, reduced stiffness, and the size effect. Vibrations and forces normally increase significantly the stresses on micro-cutters and thus the tool life is reduced drastically (Popov *et al.*, 2006).

Vogler *et al.* (Vogler *et al.*, 2003) achieved predict the cutting force for the primary metallurgical phases, ferrite and pearlite, of multi-phase ductile iron workpieces and was validated with experimental values obtaining good agreement. Bao and Tansel (Bao and Tansel 2000a; Bao and Tansel 2000b; Bao Tansel 2000c) propose analytical cutting force model for micro-end milling operations with tool run-out and then this model was modified to represent tool wear, using estimations by genetic algorithms. They worked with steel and aluminum alloy and end mills of 0.800 mm of diameter. Using the same materials for experimental data Bissacco *et al.* (Bissacco *et al.*, 2008) presents a theoretical model for cutting force prediction in micro milling, considering the cutting edge radius effect, the tool run out and the deviation of the chip flow angle from the inclination angle. They verified the model using tools of 0.600mm diameter. The results demonstrated good agreement between predicted and measured forces. Zaman *et al.* (Zaman *et al.*, 2006) developed a three-dimensional analytical cutting force model for micro-end milling process, while machining pre-hardened steel with two fluted, coated (AlTiN) micro grained carbide tool with flat end and 30° helix angle and 1 mm in diameter. The developed model can be used to simulate the cutting forces accurately to 90% average accuracy.

At the same topic of research Friedrich and Kulkarni (Friedrich and Kulkarni 2004) developed a model of the micro-milling process based on the elastic contact between the tool and the workpiece along the side and bottom cutting edges of the tool. In order to compare the results obtained with the model were conducted experiments in 6061-T6 aluminum using end mills of 0.05-0.100mm diameter. They found that this model is acceptable for predicting micro-milling forces, furthermore, to reduce tool breakage and tool deflection.

An analytical micro-scale milling force model is developed by Lai *et al.* (Lai *et al.*, 2008) using FE (Finite Element) considering size effect, micro cutter edge radius and minimum chip thickness. The model is well validated through the micro-scale milling experiments in OFHC copper using 0.100mm diameter micro tool.

Similarity Filiz *et al.* (Filiz *et al.*, 2007) developed an experimental investigation of micro-machinability of copper 101 using tungsten carbide micro-end mills of 0.254mm diameter and taking into account tool wear, cutting forces, surface roughness, and burr formation. Newby *et al.* (Newby *et al.*, 2007) presents an analysis of cutting forces in micro-end milling operations where the feed per tooth per radius is higher than conventional milling operations. They conducted an experimental machining in aluminum 7075-T6 and forces were recorded. The model developed for cutting force constants will aid in better understanding of friction and forces in the micro-end milling process.

Other research works on mechanistic models. Park and Malekian (Park and Malekian 2009) developed a mechanistic model in order to predict micro-end milling forces for both the searing and ploughing dominant cutting regimes. They assumed that there was a critical chip thickness that determined whether the cutting is predominantly shearing or ploughing. In order to proved the validity were performed experiments in aluminum 7075 (Al7075) with micro-end mills with 500 mm diameter flat micro-end mills. The proposed mechanistic model was able to predict micro-end milling forces at high rotational speeds with good agreement. Besides, Lee *et al.* (Lee e*t al.*, 2008) propose a mechanistic cutting force model for the precise prediction of the cutting force in micro-end milling with specific cutting conditions. Also Kang *et al.* (Kang *et al.*, 2007) investigated a mechanistic model of cutting forces taking into account the cutting edge radius. In addition, this study performed aluminum cutting with a micro-end mill with a diameter of 0.200mm in order to verify the prediction results and clearly demonstrates that the predicted cutting forces were consistent with the experimental cutting forces.

In other hand, Jin and Altintas (Jin and Altintas 2012) developed a cutting forces model using cutting force coefficients obtained from the finite element (FE) simulations. Previously they performed a FE model of orthogonal micro-cutting with round cutting edge using Brass 260 as workpiece (Altintas and Jin 2011).

2.3.12 Metrology in micro-machining

The challenge of the manufacturing is the new requirements in machining, positioning control, and metrology down to nanometer tolerances. According to Dornfeld (Dornfeld *et al.*, 2006), a variety of sensors are available, each having a degree of applicability according with the level of precision appropriate or type of characteristic or control parameter that needs to be measured. These are used to acquire information related with manufacturing process. Figure 2.23, illustrates numerous different kind of sensors and their applicability to both level of precision and type of control parameter.

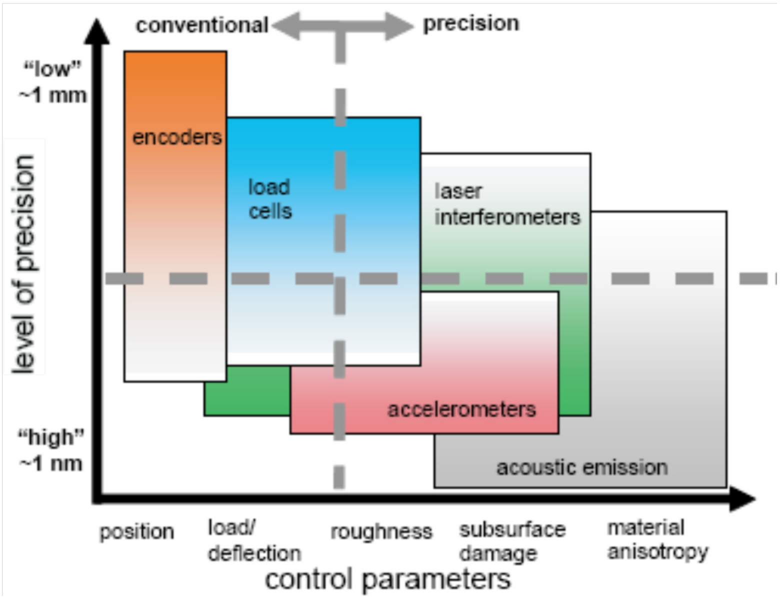


Figure 2.23: Sensor application vs. level of precision and control parameters (Dornfeld *et al.*, 2006).

Measurement devices can be divided in two general categories: the first includes those that measure the distance between edges of a feature, (for example, electron microscopes and optical profilometer) also includes a sensor (mechanical, magnetic, optical or capacitive), a workpieces holding table, and a transducer to displace the workpiece. In order to measure height, profile, or surface topography another category is used. This can be classified into two types, whole field contouring and single profile (SP) methods. Whole field contouring involves interferometric and holographic techniques. Single profile methods include mechanical stylus instruments, optical profile followers (OPF), scanning tunneling microscopy (STM), scanning electron microscopy (SEM) and atomic force microscopy (AFM) (McGeough 2002).

Efforts are directed to seek new devices by modifying or combining existing mechanism. Howard and Smith (Dornfeld *et al.*, 2006) used conventional atomic force microscopy (AFM) technology to cover long areas of surface metrology. This was achieved using a precision carriage and slideway mechanism to cover 20 mm of travel and the AFM.

In order to measure the inside dimensions of micro-holes, Masuzawa *et al.*, (Dornfeld *et al.*, 2006) investigated the use of vibroscanning techniques. Although, this method can only be used to conductive materials due to it uses a sensitive electrical switch by contacting a vibrating micro-probe onto the workpiece.

Other topic of research in measurement devices is a precision coordinate measuring machine (CMM) characterized by micron or submicron level resolution. Vermeulen *et al.* (Vermeulen *et al.*, 1998) improve the precision of CMMs, they designed an alternative high precision 3D-CMM with measuring uncertainty below of 0.1 µm in a measuring volume of 1 dm3. According with Dornfeld, the germane Jäger *et al.* (2000) (Dornfeld *et al.*, 2006) developed a

3DCMM with a resolution of 1.3 nm using a probe and laser interferometers with angle sensor for guiding deviation.

Chapter 3. An experimental analysis of process parameters to manufacture metallic micro-channels by micro-milling.

Chapter 3 presents an experimental study of the influence of the process parameters (spindle speed, depth of cut per pass, depth and feed per tooth) on the dimensional accuracy, surface roughness and shape. This study is based on micro-channel manufacturing using aluminium and copper as workpiece.

This study was presented in an article entitled "*An experimental analysis of process parameters to manufacture metallic micro-channels by micro-milling*", published by International Journal of Advanced Manufacturing Technology in May 2010 (Vázquez *et al.*, 2010).

Vázquez, E., Rodríguez, C. A., Elías-Zúñiga, A., & Ciurana, J. (2010). "An experimental analysis of process parameters to manufacture metallic microchannels by micro-milling". *International Journal of Advanced Manufacturing Technology*, 51(9-12), 945-955

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Abstract

Miniaturisation of products is a current megatrend, and it presents a wider range of opportunities to expand manufacturing markets. Micro-device design and manufacturing is a growing area of scientific interest for large number of industrial fields. This paper reports the characterisation of micro-milling process to manufacture micro-channels in order to understand the behaviour of process parameters when a standard milling machine is used. This study is based on micro-channel manufacturing through a set of experiments varying parameters such as spindle speed (N), depth of cut per pass (a_p), depth (d), feed per tooth (fz) and coolant application. Materials used were aluminium and copper with a hardness of 21 HRB and 72 HRB copper, respectively. Results are obtained by evaluating dimensions, shape and surface finish of the micro-channel. The use of coolant in micro-milling is found to be a relevant factor to improve micro-channel-achieved dimensions and surface finish. In general, micro-channels in aluminium were found to achieve better quality than those in copper.

Keywords

Micro-milling; Micro-channels

Chapter 4. An experimental analysis of process parameters for the milling of micro-channels in biomaterials.

Chapter 4 presents a characterisation of micro-milling process to manufacture micro-channels in order to understand the behaviour of process parameters when a standard milling machine is used. An experimental analysis was carried out using stainless steel (316L) and titanium (Ti6Al4V) evaluating dimensions, shape and surface finish of the micro-channel.

This study was presented in an article entitled "*An experimental analysis of process parameters for the milling of micro-channels in biomaterials*", published by International Journal Mechatronics and Manufacturing Systems in April of 2012 (Vázquez *et al.*, 2012).

Vázquez, E., Gómez, X., & Ciurana, J. (2012). "An experimental analysis of process parameters for the milling of micro–channels in biomaterials". *International Journal of Mechatronics and Manufacturing Systems*, 5(1), 46-65

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Abstract

The increase in the demand for micro-parts, in combination with an ample range of shapes and materials, has created strong interest in micro-mechanical machining. The field of medicine provides an opportunity to use micro-production to manufacture micro-devices for tissue engineering surgery, surgical instruments and minimally invasive devices (catheters, stents, aneurysm clips, etc.). In an effort to understand the relationship between process parameters and the quality of the geometrical features of the final micro-part an experimental analysis was carried out using stainless steel (316L) and titanium (Ti6Al4V) with hardnesses of 88 HRB and 107 HRB respectively. The experiments were performed with varying parameters such as spindle speed (N), depth of cut per pass (ap), channel depth (d), feed per tooth (fz) and coolant application. This study finds better results when micro-channels were made in wet conditions. When coolant was used, the shape profiles of micro-channels created in titanium were of better quality than those made in stainless steel.

Keywords

micro-end milling; micromachining; microchannels; end milling; process parameters; biomaterials; geometrical features; stainless steel; titanium; spindle speed; depth of cut; channel depth; feed per tooth; coolant

Chapter 5. Experimental analysis of process parameters to manufacture micro-cavities by micro-milling.

Chapter 5 presents investigations with the aim of to prove the capacity of micro-milling, by machining complex micro-cavities on aluminum workpiece using a conventional milling machine. Results are obtained by evaluating accuracy and geometric features.

This study was presented in an article entitled "*Experimental analysis of process parameters to manufacture micro-cavities by micro-milling*", published by Advanced Materials Research in April of 2012 (Vázquez *et al.*, 2012).

Amaro, A., Gomar, J., Vázquez, E., Ciurana, J., & Rodríguez, C. (2012). "Experimental Analysis of Process Parameters to Manufacture Micro-Cavities by Micro-Milling". *Advanced Materials Research*, 498, 91-96

http://dx.doi.org/10.4028/www.scientific.net/AMR.498.91

http://www.scientific.net/AMR.498.91

Abstract

The use of conventional machining processes has been subject to important decline probably due to the increment in the use of emerging technologies. Therefore, the main applications of these traditional processes, such as automotive industry, are in crisis. In order to have a chance to compete successfully in the new trends, the machining industry must meet the needs of alternative sectors such as biomedical field. The aim of this study is to prove the capacity of micro-milling, by machining complex micro-cavities on aluminum workpiece using a conventional milling machine. Results are obtained by evaluating accuracy and geometric features. This study finds that the feed per tooth is a significant factor in order to obtain better results. The use of coolant increases the tool wear and therefore dimensional errors. This scope is a potential opportunity to reutilize the conventional machines from a new approach.

Keywords

micro-machining; micro-tool; medical devices;, micro-cavities

Chapter 6. Evaluation of machine-tool motion accuracy using a CNC machining centre in micro-milling processes.

Chapter 6 presents a study related to evaluate through theoretical principles and experimental work, the machine-tool motion accuracy of a medium machining centre specializing in the micro milling of elliptical cavities on aluminium workpieces.

This study was presented in an article entitled "*Evaluation of machine-tool motion accuracy using a CNC machining centre in micro-milling processes*", accepted in International Journal of Advanced Manufacturing Technology in March 2014 (JAMT-D-13-01430).

Evaluation of machine-tool motion accuracy using a CNC machining centre in micro-milling processes

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Abstract

The demand for micro holes, micro-moulds and micro forms continues to grow as high-tech industries demand miniaturized products. Sectors such as aerospace, microelectronics, medicine, and even the automotive sector, are just some examples of enterprises that are taking advantage of micro-manufacturing technologies. Within this framework, the need to adapt the knowledge of macro-scale manufacturing processes to micro-scale is evident. This paper evaluates, through theoretical principles and experimental work, the machine-tool motion accuracy of a medium machining centre specializing in the micro-milling of elliptical cavities on aluminium workpieces. Measurements were taken to evaluate: deviations and/or errors in geometric accuracy, and the geometric quality errors caused by motion control and control software. The results show that, due to the structure and inertia of the machine tool, acceleration and deceleration do indeed affect the accuracy and quality of the micro-part. Furthermore, errors from motion control and/or control software are present because differences in the moving carriages create instabilities.

Keywords: micro-machining, micro-tool, micro-cavities.

1. Introduction

As many high-tech industries are now using miniaturized parts or products the demand for micro holes, micro-moulds and micro forms continues to increase. Aerospace, microelectronics, the medical sector together with the automotive sector, are but some examples of enterprises that are making the most of the micro-manufacturing technologies. Nowadays, the key success factor of these technologies comes from the ability to be flexible and manufacture a complete part in a single machining process. To meet the large scale production needs of mechanical components and micro products, the need to adapt the manufacturing process knowledge from macro-scale to micro-scale is evident.

One of the most significant research subjects in milling processes is in evaluating machine-tool motion accuracy, as this has a noticeable influence on the quality of the final machined part.

One of the first works in this field of research was developed by Weck and Schmidt [1], where they proposed a method using a laser beam and a four quadrant photodiode to evaluate the radial error-motion of a rotating table of a gear hobbing machine. Furthermore, they quantified the parallelism between the rotating axis and a linear guide-way. With the same approach, Zhang et al. [2] developed a displacement method to measure the 21 error components in the geometric error using a laser interferometer. Similar research work found that by measuring the positioning errors along the 15 lines in the machine work zone, a total of 21 geometric error components can be determined [3]. Iwasawa et al. [4] used a laser displacement interferometer and a rotary encoder to measure a much longer range of motion than ordinal circular test methods such as the double ball bar method can. Additionally, the proposed method allows positioning accuracy and other more complex test paths to be evaluated.

Measurement and evaluation of motion errors by the Double Ball Bar (DBB) test is a commonly used method, particularly in dynamic circle path tests. Bryan [5] and Kakino et al. [6] were pioneers in the use of this technique. Lai et al. [7] proposed a mathematical model that diagnoses the nonlinear error source in a guide-way system by measuring the contouring error using a double ball bar. A more robust system was developed by Qiu et al. [8, 9], when they developed a device consisting of a double-bar linkage and two Canon K-1 laser rotary encoders. The experimental results demonstrated that the method and device developed are capable of evaluating most items of motion accuracy in NC machine tools. Similar work used three laser ball bars [10].

Die-manufacturing demands have allowed a measuring method to be developed that consists of a cross grid encoder. This method is widely used in two dimensions, i.e. in an XY, YZ or XZ-plane, because it has the ability to work with any chosen path. Rehsteiner and Weikert [11] used this method to evaluate motion accuracy in machine tools. Du et al. [12] developed a multi-step measuring method for motion accuracy in NC machine tools using a cross grid encoder and based on the kinematic error model of an NC machine tool. However, using these same macro-scale evaluation techniques to appraise machine-tool motion accuracy performance has disadvantages when applied to micro-scale. In the case of double ball bar, measuring range is greater than the scale of the interest. When this method is used, it is not possible to measure the servo induced error in machine tools in small-radius circular test paths. On the other hand, laser interferometer results are significantly dependent on environmental conditions as the laser wave length depends on temperature, humidity, air pressure and air circulation [12].

Kim et al. [13], Monreal and Rodriguez [14] and Schmitz et al. [15], conducted investigations into the contribution of acceleration and deceleration in macro-scale part dimensional errors, while Philip et al. [16], who studied a micro-scale case, proposed a new acceleration-based methodology for micro/meso-scale machine tool performance evaluation. The authors developed two micro/meso-scale machine tool (mMT) prototypes at the University of Illinois in Urbana-Champaign. These were then used as test vehicles for new performance evaluation methodology. This novel research presents a technique for measuring radial and tilt error motions of ultra-high-speed miniature spindles. The technique was based on measurements of radial motions in two mutually orthogonal directions of a precision artefact using (non-contact) laser Doppler vibrometers [17].

According to Schwenke [18], the main error sources affecting accuracy are kinematic errors, thermo-mechanical errors, loads, dynamic forces and motion control and control software. In the case of thermal-mechanical errors, these are present due to modifications of heat/cold sources in machine tools and therefore to thermal expansion coefficients. Several studies have focussed on this issue [19-21]. The finite stiffness of the structural loop can be a significant influence on the machine's accuracy; which can occur due to the weight and position of, for example, the workpiece or moving carriages of the machine. Schwenke [18] Schellekens et al. and Spaan, reported that these kinds of errors are more important in comparison with kinematic errors. In the case of dynamic forces, the machining forces, measuring forces or forces caused by accelerations or decelerations contribute to location errors relative to the workpiece. In order to measure the geometrical error caused by motion control and control software and to distinguish from errors explained by other error origins, different feed speeds are applied for the same motion path [18].

Another approach, in order to reduce errors, is to compensate the error based on a previously developed model. Eskandari et al. [22] used a tool path modification in order to compensate for the position error, geometric error and thermal error through different techniques such as regression, neural networks, and fuzzy logic. On the other hand, Fan et al. [23] investigated an error model determined by orthogonal polynomials in an attempt to obtain higher accuracy.

After reviewing the literature, there are several works pertaining to evaluating the performance of machine-tool motion accuracy on a macro-scale but there is no research at all into the characterization of the radial error using a CNC machine in micro-milling processes. This paper provides the insight needed to improve milling as a micro-manufacturing process, by considering the geometrical error caused by motion control and control software error sources when a CNC machining centre or an in-house micro machine centre is used instead of a specialized machine. It is highly useful to characterize machine-tool motion accuracy and evaluate their influence on the desired dimensions and geometrical features of the final piece. Additionally, this will help identify those process parameters — axial depth of cut per pass (ap) and feed per tooth (fz),— which have a greater effect on the ensuing feature quality and to what degree changing these process parameters will affect feature quality. Therefore, this work based on the principles of kinematics, will contribute to understanding the relationship between machine dynamics, process parameters and the quality of the geometrical features on the final micro features. This study is performed without the support of an extra controller, e.g. Aerotech, thus allowing the dynamics of the system to be able to be adjusted online in order to improve the performance of the machine tool. In contrast, an experimental methodology, as an alternative to expensive commercial solutions, is proposed to identify the motion error.

The paper is set out as follows. In Section 2, a brief study of the theoretical principles applied to the milling centre machine used in this work is presented. According to these results, an experimental work is proposed to prove that the contour error in microcavities is mainly affected by the structure and inertia of the machine tool, and that these also produce additional errors as a result of instabilities in the motion control and control software. Section 3 shows the experimental set-up carried out in this work. Furthermore, the process parameters tested allow us to analyze which of them significantly affect accuracy and final shape. The main findings, presented in Section 4, are found through practical methodology and not an expensive commercial solution. Finally, conclusions are presented in Section 5.

2. Positioning errors due to axis motion

In the following an attempt to establish the theoretical principles that characterize the CNC machining centre used in this research is made, all the time emphasizing that it is not a specialized machine for micro-milling. In the first part of this section, the structure of the machine is introduced in order to determine the possible kinematic and load errors it may cause. Then a simple model for a circular contouring system is presented with the aim of calculating the error generated by the control motion and control software.

The first consideration to take into account is the difference in the motor type on each axis. In this case, the CNC milling centre used is a Deckel Maho 64V in which the X-axis has a linear motor, whereas the Y-axis has a servomotor which, according with the machine manufacturer, has a positioning precision of 8 and 20 µm, respectively. The configuration of these actuators used on the feed axes is different and crucial to obtaining accuracy in the final pieces. A linear motor has as its base element a moving coil, with 3-phase winding, and a stationary magnet track. Mounted side by side of these is the reactive part of the motor consisting of a steel base with permanently attached magnets (Figure 1a). On the other hand, the rotary servomotor has two principal parts; the stationary stator and the inside rotor (Figure 1b).

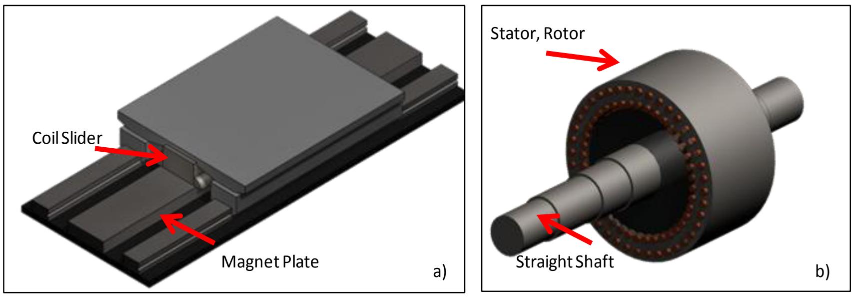

Figure 1 a) Linear Motor in X-axis. b) Servo Motor in Y-Axis.

Some advantages of the linear motor over the servomotor include the elimination of the mechanical actuation assembly. This allows the linear motor to reach higher maximum traverse speeds than the servomotor as the servomotor is limited by its components (ballscrew, leadscrews, ballnuts, gearboxes, etc). In this case, the linear motor has a maximum traverse speed of 70 m/min, while the servomotor drives up to 40 m/min. As for acceleration, significant inertia of each rotating element in the servomotor is not available in a lineal motor type. Although the linear motor can provide a linear motion system with distinct advantages, thanks to the direct coupling, it is considerably more sensitive to differences in load application. The following equations compare the total inertia of both systems:

The inertia of a rotary system is given as:

$$J_{total} = J_{motor} + J_{ball\ screw} + J_{load}\ [Kg \cdot m^2] \quad (1)$$

The ball screw inertia is calculated as a cylindrical object, according to the following equation:

$$J_{ball\ screw} = \frac{\pi \gamma_b}{32} D_b^4 L_b\ [Kg \cdot m^2] \quad (2)$$

where, γ_b is the weight of the shaft per unit volume, D_b is the shaft diameter and L_b is the shaft length.

For a load moving along a straight line the inertia is:

$$J_{load} = M_{carriage} \left(\frac{l}{2\pi}\right)^2 [Kg \cdot m^2] \quad (3)$$

where, *M carriage* includes all traversing mass and *l* is the travelling distance along a straight line per revolution of the motor.

The assumed specifications of the ball screw, mass of carriage (table and other components) and travelling distance are:

γ_b=7.8X10^3 [Kgm^3]

D_b = 40x10^{-3} [m]

L_b = 1 [m]

M carriage = 650 [Kg]

l = 0.020 [m]

According to manufacturer specifications, motor inertia is 0.0068 Kgm^2, therefore from equation.1; J_{total} is 0.01535 [kg·m^2]

In both cases, the servomotor and linear motor, *M carriage* includes all traversing mass, such as workpiece, bearings, coil slider, encoders, etc. However, according to Equation 3, the *M carriage* is reduced by the second term squared, related to the pitch of the actuator.

In comparison, the load in a linear motor system is the sum of all weights directly connected to the moving coil slider according to Equation 4:

$$M_{total} = M_{coil} + M_{carriage}\,[Kg] \qquad (4)$$

Figure 2 shows both carriages on the X and Y-axis. In order to approximate the weight of the carriage on the X-axis the following elements are taken into account: X-axis carriage structure assembly, spindle motor, heat exchanger unit, the tool's cooling system , the spindle traverse carriage (headstock and headstock support, lineal guides) and others (cable hangers, spacers, fixing attachments, etc).

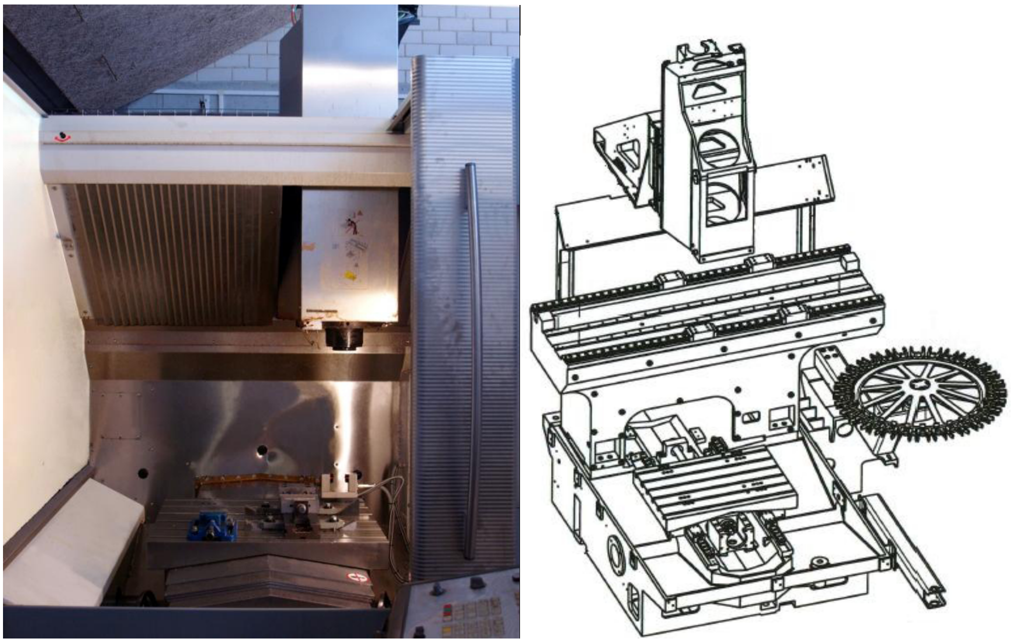

Figure 2 X and Y Axis carriage assembly.

As a result, the translating mass on the X-axis carriage is greater than that on the Y-axis carriage, and consequently, control loop sensitivity to load mass in the X-axis is also greater. This means an additional demand on the controller, in order to maintain performance and stability due to the difference of loads. The contour error for the microcavities is also affected by the servo feedback delay. According to Aun-Neow Poo et al. [24], the simple system model for circular contouring system is given by:

The closed-loop transfer function for this system is:

$$\frac{X_o(s)}{X_i(s)} = \frac{K_x}{s+K_x} \qquad (5)$$

$$\frac{Y_o(s)}{Y_i(s)} = \frac{K_y}{s+K_y} \qquad (6)$$

Where, X_i, X_0, Y_i, and Y_0 are the Laplace transform of x_i, x_0, y_i and y_0, respectively, K_x and K_y are the X-axis and Y-axis velocity gain, respectively. The system inputs for the circular contour are:

$$x_0 = \frac{K_x R}{\sqrt{K_x^2+\omega^2}} \sin(\omega t + \alpha_x) + \frac{K_x R\omega}{K_x^2+\omega^2} e^{-K_x t} \quad (7)$$

$$y_0 = \frac{K_y R}{\sqrt{K_y^2+\omega^2}} \cos(\omega t + \alpha_y) + \frac{R\omega^2}{K_y^2+\omega^2} e^{-K_y t} \quad (8)$$

Where, R is the radius of the circle and:

$$\alpha_x = \tan^{-1}\left(\frac{-\omega}{K_x}\right) \quad (9)$$

$$\alpha_y = \tan^{-1}\left(\frac{-\omega}{K_y}\right) \quad (10)$$

The radial error $e_r(t)$ is given as:

$$e_r(t) = R - \sqrt{x_0^2(t) + y_0^2(t)} \quad (11)$$

The amount of mismatching in the system velocity gains K_x and K_y is calculated by:

$$\Delta K = K_x - K_y \quad (12)$$

$$K = \frac{1}{2}(K_x - K_y) \quad (13)$$

In order to demonstrate the contour error captured when axes have different dynamic characteristics, the ideal case is shown first. When the system obtains matched gain, the dynamic contour error obtained is very small and in macro machining it is negligible.

Evaluated range for this function is 0-360 degrees but error is defined in Equation 11 as time function. Based on this analysis, it is more useful to depict results in degrees and not in time; hence the maximum value of time is calculated based on the angular velocity in order to evaluate the function from 0 to 2π radians. Figure 3 shows that when the gain mismatch increases in response the radial error also increases.

A useful accuracy indicator of a given function or process is the sum of the predictive quadratic error, which is defined as:

$$J(\theta) = \sum_{m=k}^{n} e_r(k)^2 \quad (14)$$

Figure 4 shows the sum of square errors and it is evident the growing trend means that when the speed gains are different then one of the axes is moving faster than the other.

However, Figure 5 shows the position of $x_0(t)$ and $y_0(t)$ for all cases and because errors in the cutter path of the circle are small but do exist (in the order of 10^{-3} of R) they cannot be observed by mere sight. In order to obtain a representation of the experimental results, the systems were modelled with a 20 to 1 proportion in the velocity gains (Y axis gain is 20 times greater than X axis gain, hence the X axis is slower in time response than the Y axis). Figure 6 shows that when the difference in the velocity gains is magnified, the contour error for circle generation is significant. Note that the drive element friction effects have not been considered and that the model was simplified; although these can be taken into account in future work.

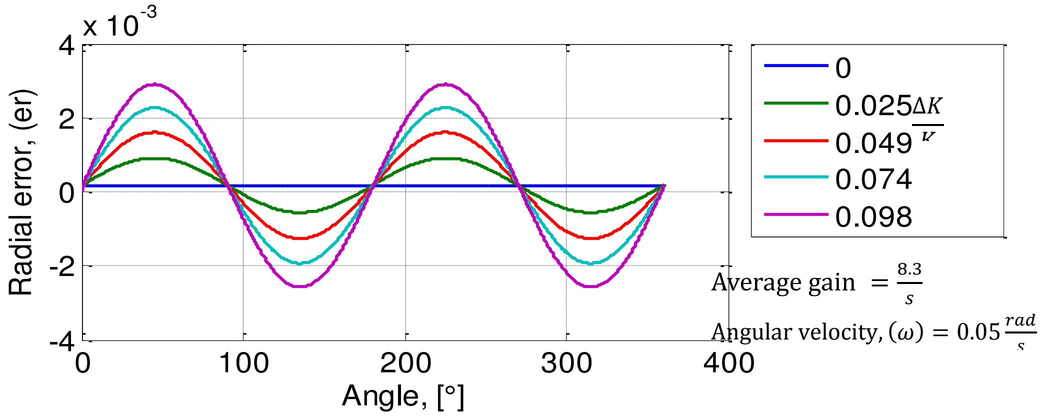

Figure 3 Radial error obtained with mismatched gains.

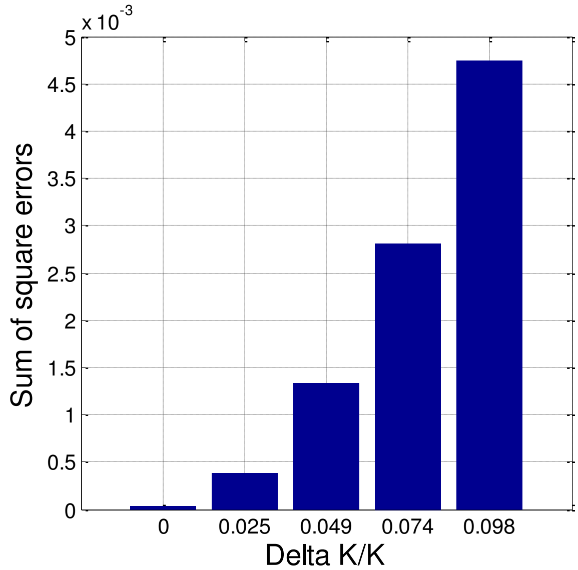

Figure 4 Sum of square errors.

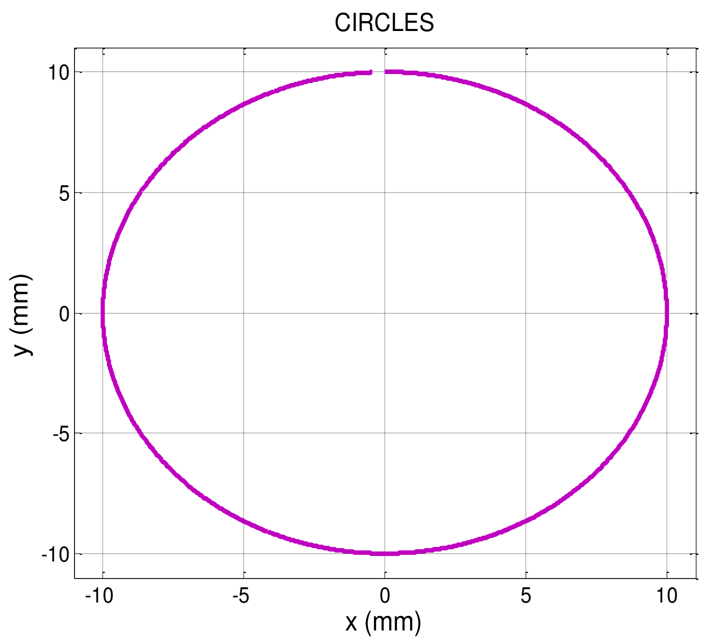

Figure 5 Circle trace for mismatched gains.

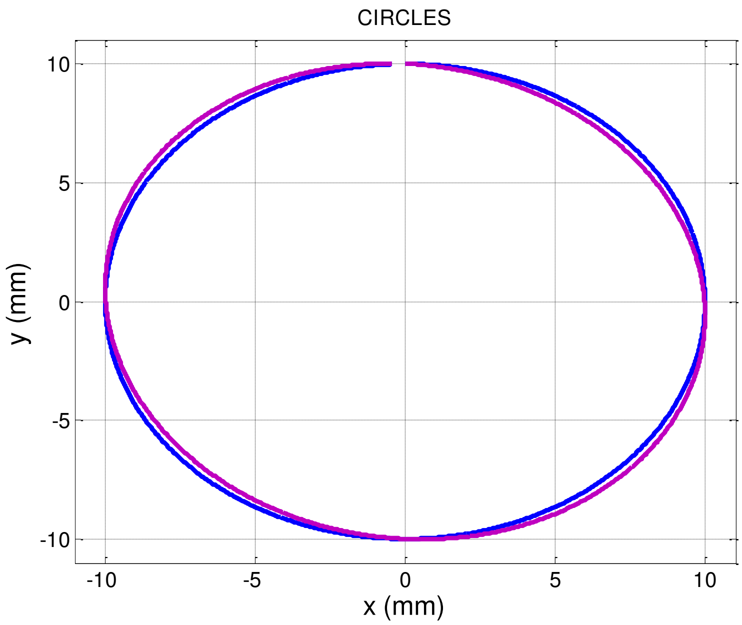

Figure 6 Circle trace for magnified mismatched gains.

3. Experimental set-up

The CNC milling machine used to perform the experiment was a Deckel-Maho© 64V Linear (3-axis, vertical spindle) with a positioning accuracy of 20 and 10 µm in Y and Z directions, respectively and 8 µm in X direction. The machine centre has a speed ranging from 1 to 12,000 rpm and is driven by a 19KW spindle drive motor. The FANUC 180i controller offers control of up to three independent part program paths with up to eight servo-controlled axes per path at increments as low as 0.1 µm. To minimize errors, heat-shrink tool holders and an EROWA©

clamping system were used in all the experiments. Figure 7 provides a close-up view of the machining set-up. Furthermore, a warm-up was performed in order to preserve the thermal conditions and avoid producing any thermo-mechanical errors.

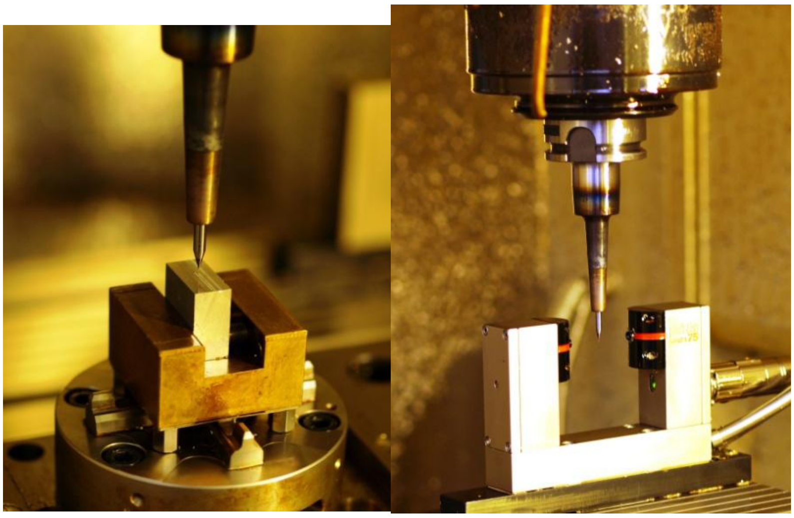

Figure 7 Left: Tool, tool holder, and EROWA© clamping system set-up. Right: Mida Laser Line©.

The workpiece material tested in this study was aluminum alloy (Al 7075-T6) with a hardness of 90 HRB due to its high machinability. Test blocks of dimensions 12x25x25 mm were prepared as a raw material. A Mitsubishi© MS2SBR0010S04 ball nose end mill tool of 200 µm in diameter was used. Figure 8 and Table 1 show the geometric characteristics of the tools. Before performing the milling operations, the micro-tool was measured with a Non-contact Laser System supplied by Mida© (repeatability of 2σ ≤ 0.2 µm) in order to compensate for tool errors (Figure 7 right). A conventional mineral-oil coolant was used (CUTTINSOL 5 by COLGESA©). Experiments were carried out by machining micro-elliptical cavities of 525 µm on the major axis, 500 diameter µm on the minor axis and 250 µm in depth, as Figure 9 shows. This geometry was selected in order to enhance the effect of the differences between the X-axis motion and Y-axis motion.

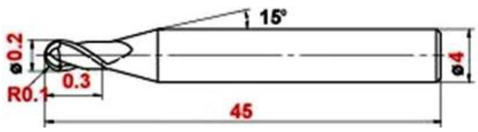

Figure 8 Mitsubishi MS2SBR0010S04 ball nose end mill schematically represented.

Table 1. Geometric characteristics of the ball nose end mill cutter.

Coating	MS: (Al, Ti)N
Tool Interference Corner (B2) [°]	15
Cutting Diameter (D1) [mm]	0.2
Shank Diameter (D4) [mm]	4

Overall Length (L1) [mm]	45
Length of Cut (ap) [mm]	0.3
Number of flutes	2

Table 2 shows the factors analyzed. Experimental design was defined by three factors: axial depth of cut per pass (ap), feed per tooth (fz), and axis machining direction. The X-Axis machining direction is defined when all micro-cavities are aligned along the X direction, as shown in Figure 9, while the Y-Axis machining direction is when cavities are aligned through the Y axis machine direction. Response variables related to accuracy were divided into two desired dimensions: (major axis (M) and minor axis (m), (see Figure 9). Micro-cavity shape was also evaluated.

Dimensional measurements on the XY plane were performed with a Microscope Discovery 12 from Zeiss© and Quartz PCI© Software was used to collect the digital images (150x magnification).

Table 2. Variable factors and factor levels performed.

Variable Factors	**Factor Levels**			
F1. Axial depth of cut per pass ap,(µm)	2.0	2.25	2.50	3.0
F2. Feed per tooth fz, (µm/tooth)	3.30		4.95	
F3. Axis machining 0=X-axis, 1=Y-axis	0		1	

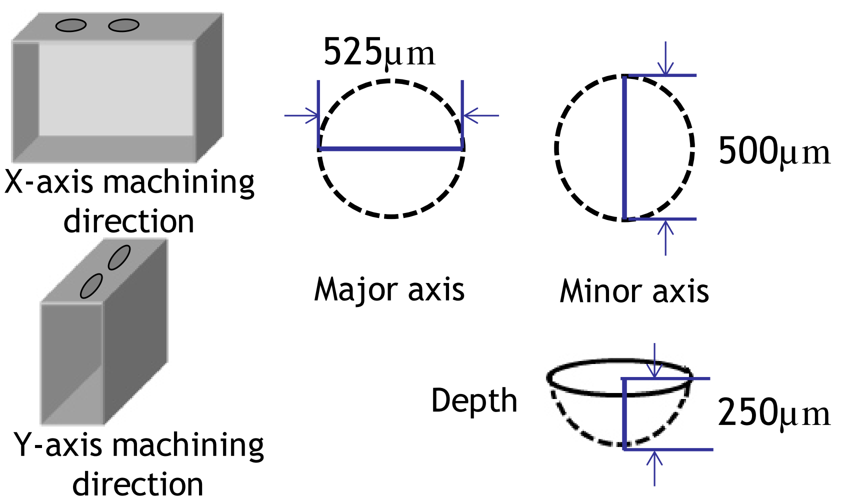

Figure 9 Sectional view and desired dimensions of micro-cavity (without scale).

4. Results and discussion

Table 3 shows three different inputs, such as axial depth of cut per pass, feed per tooth and axis machining direction for experimental sets and two measured outputs on the shape machined i.e. major axis and minor axis. In addition, relative errors were calculated using desired measures and those measures obtained. The maximum error obtained when X-axis direction machining is used is 12%, while in the Y-axis direction the maximum error is of 3.65%. Minimum error results are 1.4 and 0.6, respectively. According to these results, it may be possible to develop a compensation model in simple geometries, such as microcavities, and a practical solution could be used to compensate the desired profile in the CAD program and then generate the part machining program.

Table 3. Experimental results.

Test	Axial depth of cut per Pass a_p [µm]	Feed per Tooth f_z [µm/z]	Axis machining *0=X *1=Y	Major Axis M [µm]	Minor Axis M [µm]	Major Axis Error εØX [±%]	Minor Axis Error εØY [±%]	Test	Axial depth of cut per Pass Ap [µm]	Feed per Tooth fz [µm/z]	Axis machining *0=X *1=Y	Major Axis M [µm]	Minor Axis m [µm]	Major Axis Error εØX [±%]	Minor Axis Error εØY [±%]
1	3.00	3.30	0	550	518	4.76	3.60	25	3.00	3.30	1	539	508	2.67	1.60
2	3.00	3.30	0	548	560	4.38	12.00	26	3.00	3.30	1	540	507	2.86	1.40
3	3.00	3.30	0	550	513	4.76	2.60	27	3.00	3.30	1	543	510	3.43	2.00
4	2.50	3.30	0	548	518	4.38	3.60	28	2.50	3.30	1	538	505	2.48	1.00
5	2.50	3.30	0	541	513	3.05	2.60	29	2.50	3.30	1	540	506	2.86	1.20
6	2.50	3.30	0	550	520	4.76	4.00	30	2.50	3.30	1	537	503	2.29	0.60
7	2.25	3.30	0	553	523	5.33	4.60	31	2.25	3.30	1	544	512	3.62	2.40
8	2.25	3.30	0	543	512	3.43	2.40	32	2.25	3.30	1	537	510	2.29	2.00
9	2.25	3.30	0	540	518	2.86	3.60	33	2.25	3.30	1	543	503	3.43	0.60
10	2.00	3.30	0	553	522	5.33	4.40	34	2.00	3.30	1	541	505	3.05	1.00
11	2.00	3.30	0	543	532	3.43	6.40	35	2.00	3.30	1	542	536	3.24	7.20
12	2.00	3.30	0	542	518	3.24	3.60	36	2.00	3.30	1	537	512	2.29	2.40
13	3.00	4.95	0	544	519	3.62	3.80	37	3.00	4.95	1	546	511	4.00	2.20
14	3.00	4.95	0	552	514	5.14	2.80	38	3.00	4.95	1	557	509	6.10	1.80
15	3.00	4.95	0	549	507	4.57	1.40	39	3.00	4.95	1	552	516	5.14	3.20

16	2.50	4.95	0	558	521	6.29	4.20	40	2.50	4.95	1	545	511	3.81	2.20
17	2.50	4.95	0	553	515	5.33	3.00	41	2.50	4.95	1	554	513	5.52	2.60
18	2.50	4.95	0	550	508	4.76	1.60	42	2.50	4.95	1	545	507	3.81	1.40
19	2.25	4.95	0	549	522	4.57	4.40	43	2.25	4.95	1	544	519	3.62	3.80
20	2.25	4.95	0	551	513	4.95	2.60	44	2.25	4.95	1	520	549	0.95	9.80
21	2.25	4.95	0	548	507	4.38	1.40	45	2.25	4.95	1	548	515	4.38	3.00
22	2.00	4.95	0	551	520	4.95	4.00	46	2.00	4.95	1	557	517	6.10	3.40
23	2.00	4.95	0	551	527	4.95	5.40	47	2.00	4.95	1	552	534	5.14	6.80
24	2.00	4.95	0	548	507	4.38	1.40	48	2.00	4.95	1	548	514	4.38	2.80

An in-depth analysis of the major axis (M) measure was conducted. Table 4 summarizes the results of the ANOVA analysis. Table 4 reveals that feed per tooth and the machining axis are the most significant factors in the major axis (M) measure. This confirms that the geometrical error sources are motion control and control software and can be identified by, as mentioned in Section 1, applying different feeds for the same motion path [18].

Table 4. ANNOVA for major axis (M) measure

Factor	*D.F.*	*SC Sec.*	*SC ajust.*	*Mc ajust*	*F*	*P*
Axial depth of cut per pass	3	129.75	129.75	43.25	1.30	0.286
Feed per Tooth	1	352.08	352.08	352.08	10.60	0.002
Axis machining	1	280.33	280.33	280.33	8.44	0.006
Error	42	1395.08	1395.08	33.22		
Total	47	2157.25				

Figure 10 shows the main effects plots on the major axis (M) measure. When feed per tooth increases, the major axis (M) also increases. On the other hand, when x-axis machining is used the major axis (M) measure is greater than when y-axis machining is used.

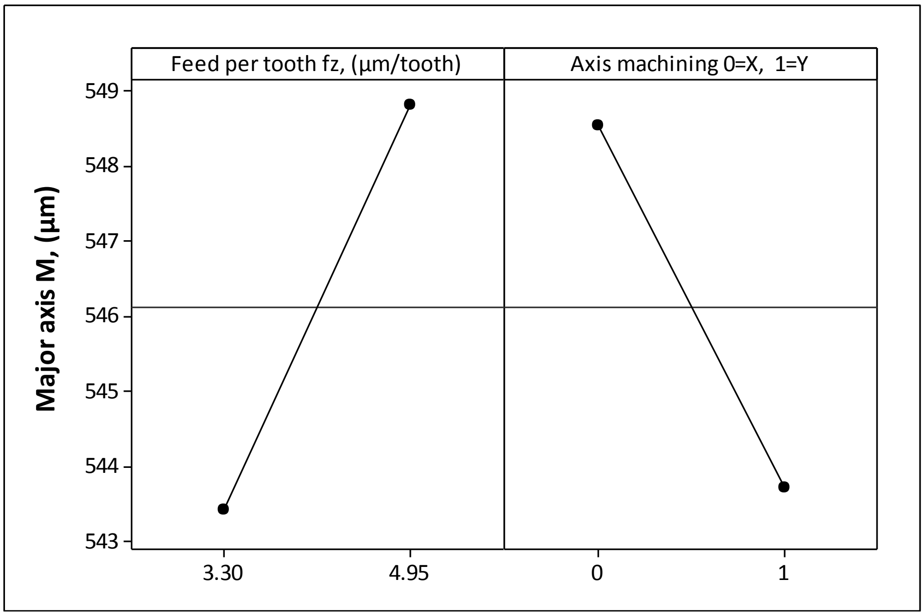

Figure 10 Main effects plot for major axis (M) measure

Figure 11 shows that the values of major (M) and minor axis (m) exceed the desired value of 525µm and 500 µm, respectively. When both graphics are compared, it is evident that the values of the major and minor axes on the X-axis machining direction are larger than the values obtained on the Y-axis machining direction. Figure 12 shows a micro-cavity in the XY plane. It is also worth mentioning that when the axis of machining is the X-axis, the value of the major axis is greater than the value obtained using the Y-axis machining direction. So, and according to the results, it can be concluded that the difference between the X-axis motion and Y-axis motion is what is affecting the accuracy of the final shape.

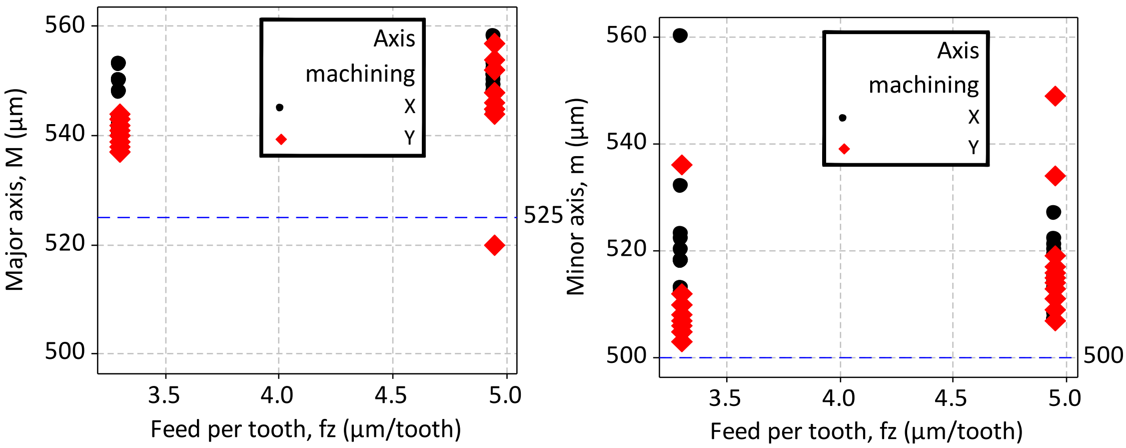

Figure 11 Effect of feed per tooth using X and Y axes machining directions on major and minor axes.

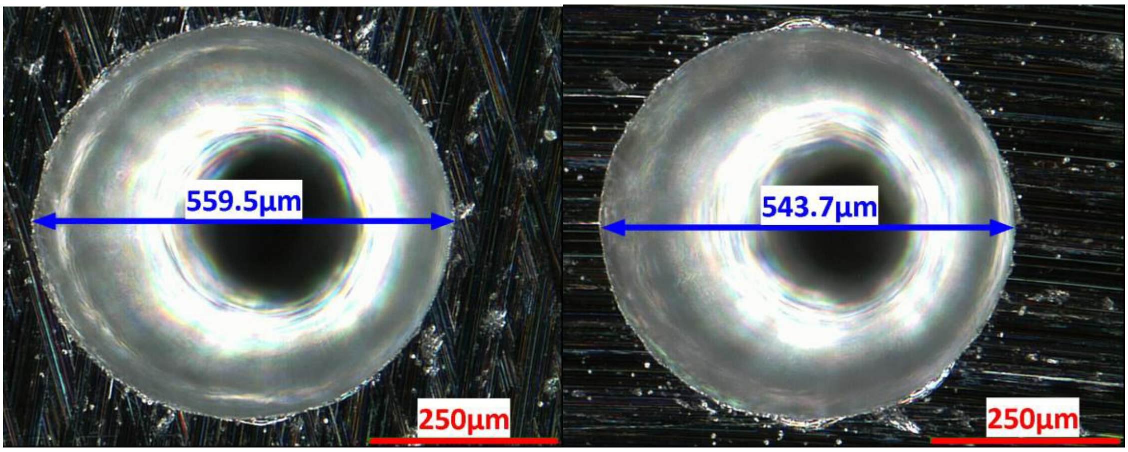

Figure 12 Measure of the major axis (M) a) Micro-cavity performed using X-axis machining (left) and performed using Y-axis machining (right).

These results can be explained by machine kinematics. Figure 13 shows a schematic explanation for the tendency of the ellipses long axes. A spindle motor starts with an initial speed to go from point A to point B, using the path in double line. When the micro-tool arrives at point B, the spindle motor decelerates in order to end at zero speed, however, when working with micro distances another trajectory is machined (triple line) because of the inertia of the spindle and consequently this fails to stop as desired. On a macro-scale, these accelerations and decelerations are not as noticeable because these variations, compared with the dimensional size of the pieces are negligible, but on a micro-scale they are proportionally important. The explanation for this behaviour is that, as distances are short the programmed feed rate is never reached.

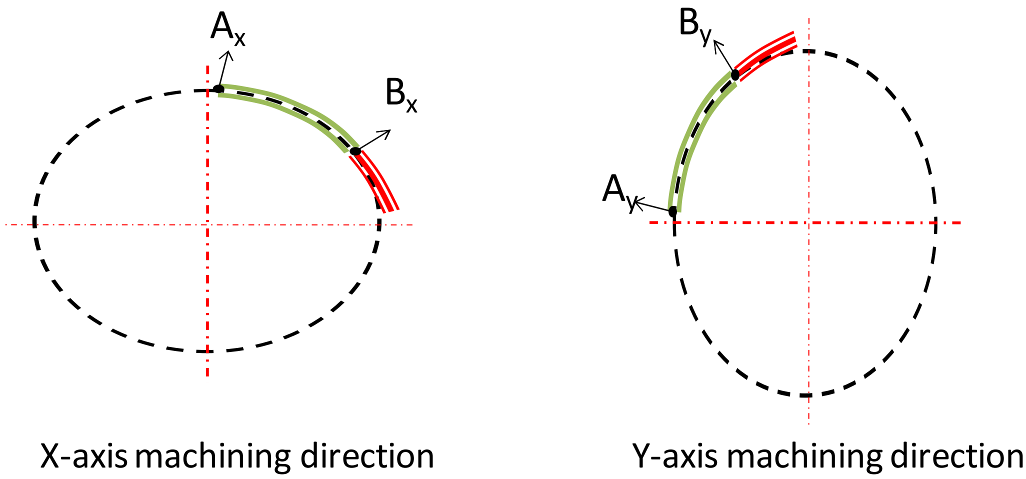

Figure 13 Schematic view of Acceleration/Deceleration effect on the trajectory of the micro tool.

The results obtained by the calculated relative errors infer that the influence of acceleration and deceleration is not the only element that affects the accuracy of the final feature. Figure 14 shows that the errors obtained are not equal when an X-axis direction is used or when a Y-axis machining direction movement is used. The graphics demonstrate that the percentage errors on both axes of the ellipse (major and minor axes) are lowest when it is machined in the Y-axis direction. The results show that the geometrical error is caused mainly by three sources; all of which are related to each other. The kinematic errors caused by the machine's structure and because there are not the same loads in the moving carriages, produce motion control and control software errors.

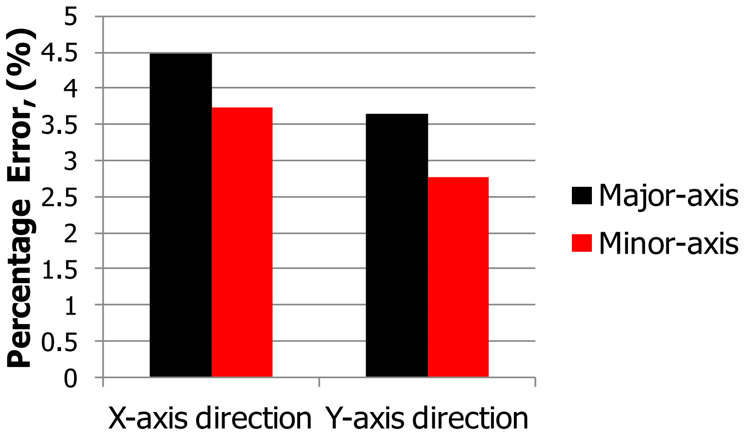

Figure 14 Dimensional errors according to the axis of machining.

According to experimental data by Andolfatto et al. [25], the repartition of the mean value of the error sources along the experimental trajectory, on a macro-scale, are shown in Table 5. The major source of error is the link errors at 86.9%. Table 5 also shows the percentages applied to the mean values of the experimental data in this work. The comparison is made in order to emphasize that while on a macro-scale the errors may be negligible, on a micro-scale it means that the manufactured final product does not comply with the desired dimensions. In addition, the most influential factor on the geometrical error are the link errors and on average these errors affect the end product with 86.9% of the total error. In comparison with some previous research by Chen et al. [3], these authors used a three-axis CNC horizontal machining centre and developed a displacement measurement approach. They found that one of the maximum translational errors is 29 microns. This is evidence that, although on a macro-scale this is insignificant, on a micro-scale this has an enormous affect because the characteristics of the final piece contain details of the same size. Moreover, the Andolfatto et al. [25] study quantifies the dynamic errors as 0.6%, but on a micro-scale this error increases as a result of micro tool deflections and vibrations. Thus, further research should be performed in order to analyze this error source.

Table 5 Repartition of the mean value of the error sources (Adapted from Andolfatto et al. [2011]) and applied to the experimental data of this work.

			x-axis direction		**y-axis direction**	
			Major axis	**Minor axis**	**Major axis**	**Minor axis**
Error sources		**%**	**[μm]**	**[μm]**	**[μm]**	**[μm]**
Contouring errors		1.1	0.259	0.110	0.210	0.163
Quasi-static geometric errors	Link errors	86.9	20.458	8.726	16.620	12.890
	Motion errors	11.4	2.684	1.145	2.180	1.691
	Thermal drift	0	0	0	0	0
Dynamic errors		0.6	0.141	0.060	0.115	0.089

5. Conclusions

This work investigates the machine-tool motion accuracy of a medium CNC machine in the micro-milling of elliptical cavities. Furthermore, it studies the influence of the process parameters and the quality of the geometrical features on the final micro shape features. The methodology of this study includes an analysis of the structure of the machine which used in the tests, as well as a model to test the control motion and control software. Then, an experimental study was performed with a geometry selected to evaluate the error which is produced according to the theoretical principles studied. Furthermore, a brief comparison of the results with previous studies on a macro-scale has been incorporated.

Some specific conclusions can be drawn as follows:

- The present work developed an experimental approach in order to characterize the radial error using a CNC machine instead of specialized machine or in-house micro machine centre in the micro-milling process. Furthermore, this methodology is a practical solution replacing expensive commercial solutions such as laser interferometer, double ball bar, laser Doppler vibrometers, etc.

- Results suggest that CNC standard machine tools are capable of performing micro-milling to produce micro-cavities, but inertial and kinematic values are highly significant when it comes to affecting motion control.

- The dimensions of the cavities obtained were close to the desired values; achieving a percentage of error below 5%.

- It could be seen that, by performing an inspection of the machine tool, the mass moved by the X-axis is greater than the mass moved by the Y-axis. Mass has a direct effect on inertial force thus, the greater the mass, the slower the time response of the system, because X-axis mass is greater than Y-axis mass and this results in a greater error in the X-axis. Experimental results confirm that the difference in axes' motion produces errors in the final micro part. Using a medium milling centre with similar characteristics for micro-milling could be proposed a compensation model.

- Accuracy and final shape are affected by the dynamics of machine tool. At a micro-scale, accelerations and decelerations are significant and cannot be assumed to be negligible, as they would be in the case of macro-scale. Results suggest that accuracy and final shape are mainly influenced by feed per tooth.

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Chapter 7. Analyzing effects of cooling and lubrication conditions on micro-milling of Ti6Al4V.

Chapter 7 presents an experimental work with the aim of to study the effect of cooling and lubrication conditions on micro-milling of Ti6Al4V. The different methods of cooling and lubricating used in this research work include: dry machining, jet application, MQL in feed direction and MQL against direction. Results are obtained by evaluating the performance of the lubrication conditions with respect to accuracy, surface quality, tool wear, burr formation and geometric shape.

This study was presented in an article entitled "*Analyzing effects of cooling and lubrication conditions on micro-milling of Ti6Al4V*", submitted in Materials and Manufacturing Processes in November of 2013 (LMMP-2013-0826).

Analyzing effects of cooling and lubrication conditions on micro-milling of Ti6Al4V

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Abstract

The aim of this work is to characterize the effect of cooling and lubrication conditions on micro-milling of Ti6Al4V. This work is carried out by varying the cooling conditions in feed and against direction conditions in micro-channel manufacturing processes such as dry machining, jet application, and Minimum Quantity Lubrication (MQL). Results are obtained by evaluating the performance of the lubrication conditions in terms of accuracy, surface quality, tool wear, burr formation and geometric shape. According to the experiment results, using MQL when micro-milling Ti6Al4V improves microchannel dimensions, enhances surface finish, reduces tool wear, and has a significant effect on accuracy as well.

Keywords: MQL, micro-milling, tool, wear, roughness

Introduction

Miniaturization brings to the fore a market in need of new low cost, high accuracy and high quality processes capable of manufacturing miniaturized products. Some processes are simply not suitable for micro-product manufacturing because of their limited capabilities (geometric tolerances, shape complexity and the material properties of the product in question). Mechanical micro-machining is emerging as the favored candidate for small scale manufacturing processes (Robinson & Jackson, 2005). One example of an area which can greatly benefit from micro-production is the medical field, as it requires micro-devices for tissue engineering, instruments and minimally invasive devices such as prosthesis, stents and aneurysm clips. Accordingly, there is an increasing need to work with high tolerances, specific textures and fine features.

The micro-milling process is characterized by the call to keep several machining aspects under control in order to avoid creating any diminishment in the quality of the final part. Lubricant use is one of these aspects, as it is a determining factor on final product accuracy and surface finish. Cutting fluid plays an important role because of its capacity to reduce friction and its ability to dissipate the heat generated between the micro tools and the workpiece. Furthermore, it improves chip evacuation. As cutting zones are very tiny, one of the most challenging aspects of the micro-milling scale is effective cooling and/or lubricating fluid delivery. According to Li et al. (2004) the impingement force of the cutting fluids is greater than that of the cutting forces, which are typically only around a few Newtons, but can cause tool deflection or even tool damage, as well as inaccuracies and/or poor surface quality in the final part. To improve cutting fluid penetration into the small cutting zone, a minimum quantity lubrication (MQL) method is considered as the suitable alternative for precisely delivering the lubricant and/or coolant.

Research into the use of lubricants using MQL technique in milling processes is a subject matter which has been extensively investigated by many authors (E.g. Rahman & Kumar, 2001, Rahman et al., 2002, Liu et al., 2005, Lopez de Lacalle et al., 2006, Liao & Lin, 2007, Hong & Ding, 2001, Su et al., 2006, Yuan et al., 2011, Tosun & Huseyinoglu, 2010, Frăţilă & Caizar, 2012). Rahman et al (2001) investigated the use of MQL in ASSAB 718HH steel and found that when the MQL technique was employed burr formation was reduced in comparison to dry machining and flood cooling. In later research (Rahman et al., 2002) they concluded that a substantial decrement in the cutting force of the MQL occurs; unlike in dry machining and traditional flood cooling. Liu et al. (2005) proposed a novel cooling and lubricating method, based on a recent concept of acquiring superior lubricity by using water vapor, for green machining and HSM. They found that the cutting force is decreased, the friction coefficient, the chip deformation coefficient and the surface roughness value is reduced and the cutting temperature is also diminished. Other research (Lopez de Lacalle et al., 2006) confirms that traditional emulsion fluid is wasteful in HSM, because it is not capable of reaching the interior zones of tool teeth. On the other hand, MQL flow does reach the cutting zone and performs a variety of functions such as lubricating, cooling the tool and the work-piece, and evacuating chips.

As was mentioned earlier, medical devices in the healthcare industry is an up and coming area for manufacturing products with micro-milling. Titanium alloy Ti6Al4V has been distinguished as one of the most widely used materials in biomedicine for prosthesis and surgery instruments; as well as in other industries as diverse as aerospace and the automotive industry (Vazquez et al., 2011, Vazquez et al., 2012). One of the cooling approaches studied with Titanium alloy Ti6Al4V is cryogenic cooling. Hong and Ding (2001) evaluated the effectiveness of the cryogenic cooling method in turning experiments, and additionally they developed finite element predictions of the cutting temperatures. The authors backed the use of liquid nitrogen in reducing tool temperature when applied in the proximity of the tool cutting edge (Su et al., 2006). The recommendation is to use MQL with a cooling air temperature of -15°C (Yuan et al., 2011).

The use of cutting coolants in micro-milling is a relatively unexplored topic. Prakash et al. (2001) used the MQL technique with a flow rate of 1mlh-1 and then evaluated the results in terms of tool wear, chip shape, cutting speed and feed rate. The diameter of the tool used in this investigation was 1 mm and they worked with copper. They found that the chips generated during MQL are smaller in contrast to those produced with dry cutting. Additionally, tool life increases with the increase of federate and depth of cut. Similar research was performed by Li and Chou (2010) who studied the efficiency of the minimum quantity lubrication (MQL) method in near micro-milling when compared with any other lubricating element (dry condition). They evaluated tool wear, surface roughness and burr formation. Additionally, they considered the effect of the tool material, oil and air flow rates on tool functioning in MQL cutting. The tests were performed using a meso-scale milling, 0.600 mm diameter end mill and hot work die steel (SKD61) as the workpiece. They concluded that the use of MQL will not only increase the tool life considerably, but will also improve surface roughness and burr formation in comparison to those produced in dry machining. They recommended the following conditions: 1.88 ml/h and 40 l/min of oil flow rate and air flow rate, respectively. The results demonstrate that air flow proportion has a more appreciable effect on tool life than the oil flow proportion under MQL conditions in this study.

An atomization-based cutting fluid application system for micro-milling was developed by Jun et al (2008) using ultrasonic vibration. Results demonstrate that, in comparison to dry conditions, lower cutting forces and improved tool life are achieved when atomization-based cutting fluid is used. In terms of cutting fluid properties, the authors found lower cutting forces when fluid with a lower surface tension and higher viscosity was used. Similar research was performed by Rukosuyev et al. (2010) where they developed a system that consists of a cutting fluid based on ultrasonic atomization. They found that locating the nozzle (with respect to the cutting region) is critical for the system’s cooling and lubricating performance because the spray focuses on a specific point and then diverges. Marcon et al. (2010) investigated the effect of a graphite nanoplatelet based lubricant in micro-milling of hardened steel. By using this lubricant they found a lower tangential force, however, this lubricant has a negative effect on slot depth and produces burnishing in the final product.

In contrast to the MQL technique in conventional milling, there is little research work applying MQL to micro-milling, which means limited progress has been made for the moment. The majority of the studies cover performance in easy-to-cut materials. In comparison, the work presented here deals with the use of minimal lubrication in titanium alloy Ti6Al4V (identified as a difficult-to-cut-material) in order to analyze the performance of different lubrication conditions, evaluate tool wear, burr formation, accuracy and surface roughness. Results will help in industrial application as it is clear what type of lubricant system is better for micro-milling process of small cavities. Furthermore, the tool diameter used in this research is the smallest of all the studies related to the use of MQL and other lubrication techniques in metallic materials.

Experimental set-up

The micro-milling experiment was conducted with the resources listed and detailed in Table 1. A high-speed milling machine and monitoring sensor were also employed (Figure 1).

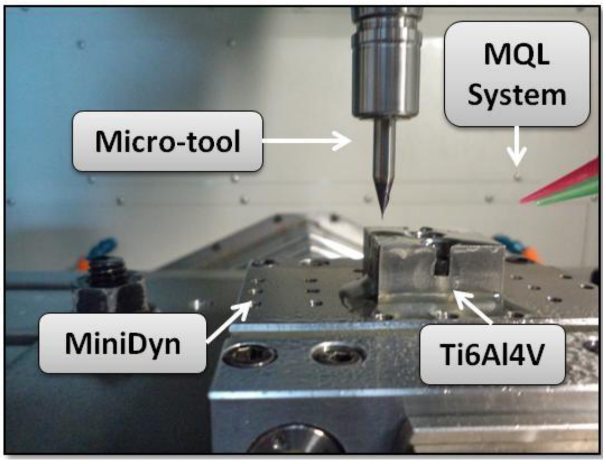
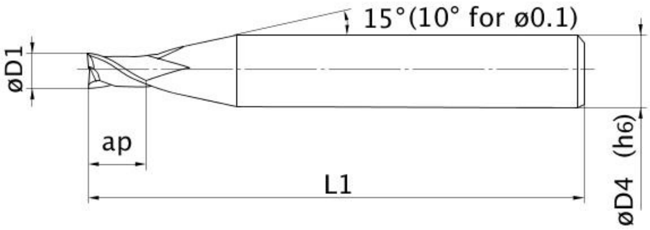


Figure 1: Close view of the experimental set-up.

Table 1: Micro-milling experimental setup.

Resource	**Description**
CAM System	Siemens NX Version 6.
Machine Tool	Vertical Machining Center: Makino F3 with position accuracy of 0.0015 mm. Fanuc 310is controller and Geometric Intelligence Control. Spindle speed up to 30,000 rpm.
Cutting tools	Mitsubishi tungsten carbide cutting tools. Flat end mills with 200 µm in diameter and two flutes More details of the cutting tool are provided in Figure 2.
Cutting tool adapter	Mega micro chuck by BigKaiser®.
Workpiece holding	Erowa clamping system.
Cutting force measurement	MiniDyn 9256C1 connected to a National Instrument data acquisition system (PCI6220).



	Symbol	**Units**	
Corner Geometry		-	S
Coating		-	MS-(AlTi)N
Tool interference corner	*B2*	[°]	15
Cutting diameter	*D1*	[mm]	0.2

Shank diameter	*D4*	[mm]	4
Overall length	*L1*	[mm]	40
Under Shank Length	*L2*	[mm]	7.8
Neck Length	*L3*	[mm]	0.7
Length of cut	*ap*	[mm]	0.3
Number of flutes	*z*	-	2

. Figure 2: Geometric characteristics of the Mitsubishi MS2SSD0020 cutter.

The work-piece material used was titanium alloy T6Al-4V with hardness of 32HRC. This is the material used in medical applications because it has numerous suitable characteristics such as biocompatibility, high strength, low weight and corrosion resistance. In the interest of evaluating the effect of the lubricating conditions, the cutting parameters fixed were previously determined by screening tests (Table 2). The cooling and/or lubrication conditions that were used in the experiments are dry, conventional emulsion, MQL in feed direction and MQL against feed direction. 10 replicas for each machining condition were made. The two directions used in MQL are the lubricant jet inside from behind the tool (feed direction) and the jet inside from ahead (against feed direction) see Figure 3.

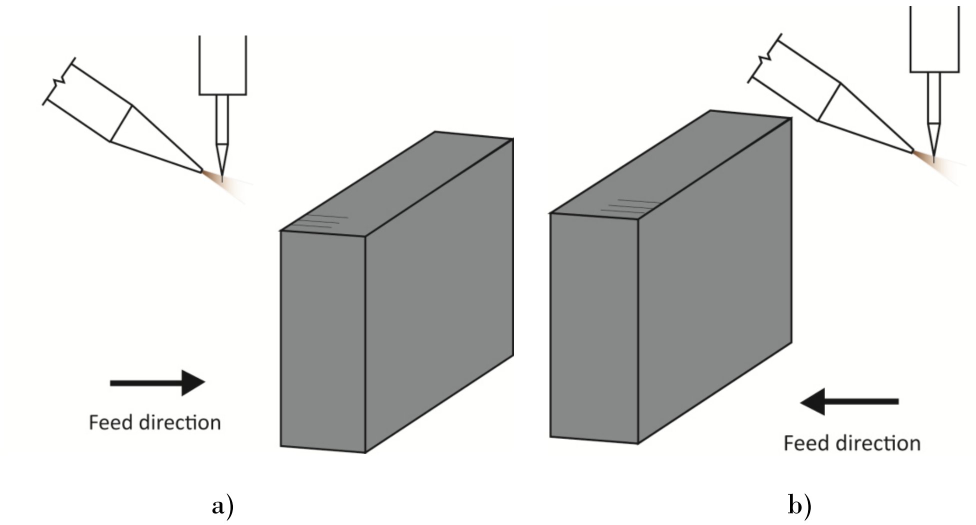


Figure 3: MQL position, a) Feed direction, b) Against feed direction

Table 2: Fixed micro-milling parameters.

Process parameters	***Units***	***Value***
Spindle speed, (N)	min^{-1}	30,000
Feed rate, (F)	mm/min	75
Radial depth of cut/Width, (w)	µm	200
Depth of cut per pass, (a_p)	µm	20
Feed per tooth, (fz)	µm /tooth	1.25

The lubricants used in this study for the conventional emulsion was a vegetable oil (emulsion of a 1:10 oil-to-water ratio) MAK KIT10 ES-AL by LUBRICORP with viscosity of 1.3 cSt. While the minimum quantity lubrication was performed with a vegetable oil TRI-Cool MD1 by TRICO with viscosity of 34 cSt.

The dimensional measurements and surface roughness parameter Ra on the micro-channel bottom region were conducted with a Confocal Microscope System CSM 700 from Zeiss. Two measures for surface roughness were performed: the linear roughness measurement (along a straight line) and the areal roughness measurement (over a rectangular range) in order to compare the results.

In addition, a ZEISS DSM 960A Scanning Electron Microscope and Zeiss Discovery V12 Stereomicroscope were used to analyze tool wear. An ultrasonic cleaner was used to clean the tools beforehand.

Results and discussion

The effects of cooling and/or lubricating conditions in micro-milling of Ti6Al4V on tool wear, burr formation, accuracy, surface roughness and geometric shape are discussed in the following sections.

<u>Tool Wear</u>

Inspecting the small tools in order to determine the tool wear, and considering the tool edge radius is around of 3-4 microns, presented a unique challenge. Tool deterioration causes a reduction of edges and, as a result, its diameter becomes smaller. This, and to simplify the evaluation of the micro-end mills tool wear, was why tool diameters were measured after machining 10 micro-channels for each one under different cutting conditions. Figure 4 shows the resulting tool diameter loss under different lubrication conditions. It is possible to observe that tool wear for jet application increases almost 3 times that of other cooling techniques. The tool diameter loss value in microns is 12.3 µm compared with the minimum value of 2.9 µm achieved with the MQL in feed direction.

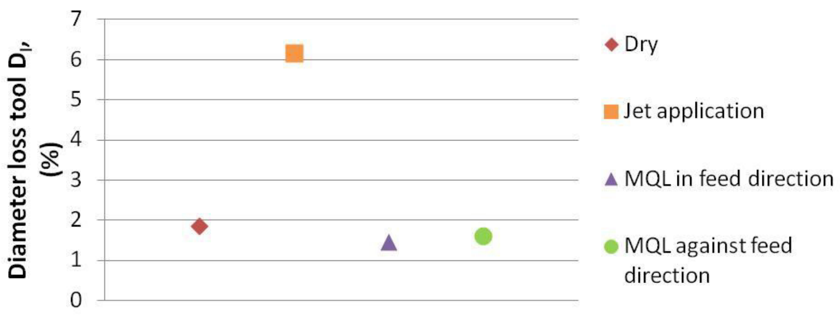
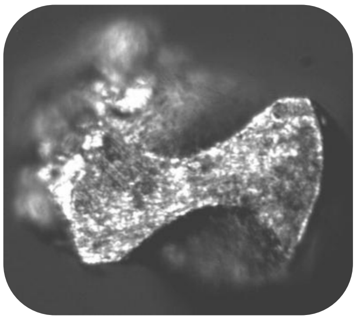
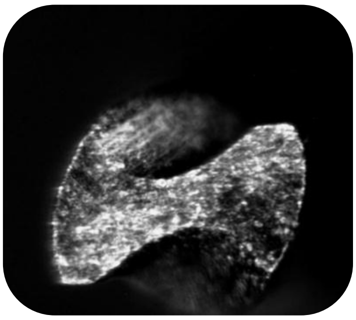
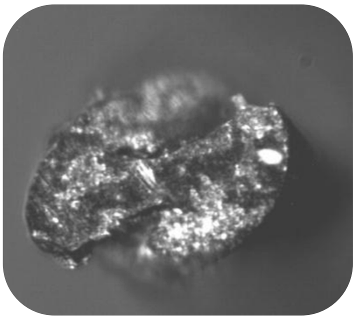
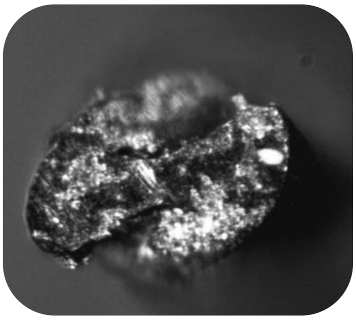
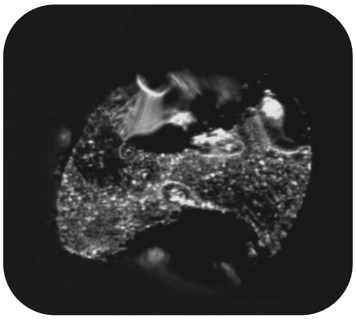
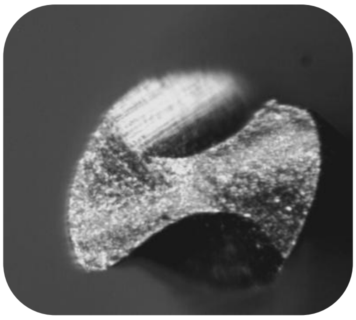
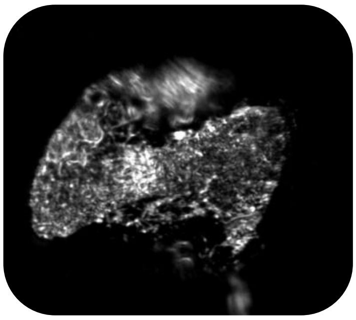
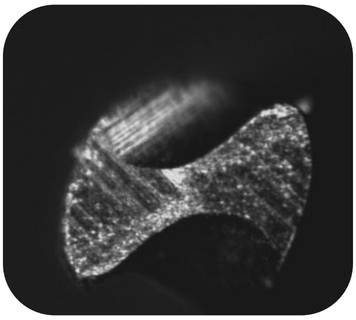


Figure 4: Effect of the cooling technique on tool wear.

In the first column in Table 3, the conditions of the tools immediately after the machining process are depicted. In dry conditions welded chips in one of the flutes can be seen. The same effect appears in the tool lubricated by the jet application. In addition, the jet application does not reduce the temperature in the small cutting zone because the oil-water emulsion causes severe tool wear. Even when the tool has been cleaned in an ultrasonic bath, it is possible to observe metal adhered to the workpiece; demonstrating that the high temperatures promote chip welding. One potential explanation is that, because traditional flood cooling in a micro-scale context causes a disordered flow and does not reach the desired target, in this case the two flutes of the tool, this is possibly causing its deflection. In terms of energy, there is higher entropy in the jet application than in the MQL application and this is why the MQL supply reduces tool wear. Images of the tools for MQL after the process of micro-milling clearly demonstrate that the oil remaining in the tool's edges is basically explained by the properties of cutting fluid. The vegetable oil has a high viscosity and, according to the results, a low surface tension. Previous research by Jun et al. [2008] found that lower cutting forces are obtained when a cutting fluid with the above mentioned properties is used. Once the tools were cleaned, the end mill tool used with MQL in feed direction seems to be in better condition than any of the other tools. The different tool wear results in MQL conditions arise from where lubricant flow falls on the tool, either against a flank surface or the face of the tool. The tool always rotates clockwise, thus when the MQL flow falls on the face of the tool, tool rotation forces the lubricant out, whereas when the MQL flow falls on the flank tool the lubricant stays within. Therefore, the accurate delivery of lubricant to the tiny tool by MQL is more efficient than an uncontrolled stream created by the jet application; moreover, the material which is being machined has low thermal conductivity and therefore does not dissipate heat.

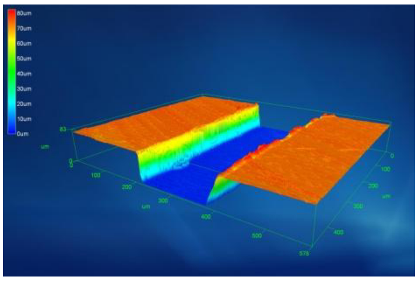
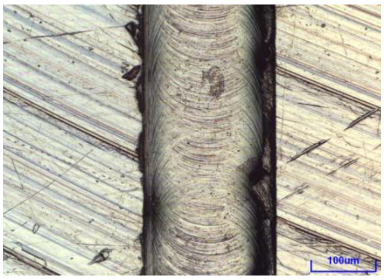
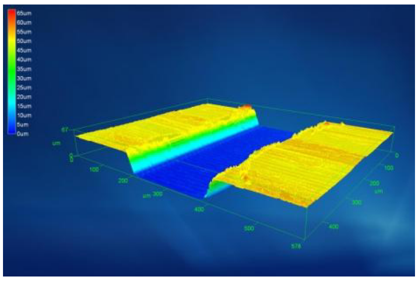
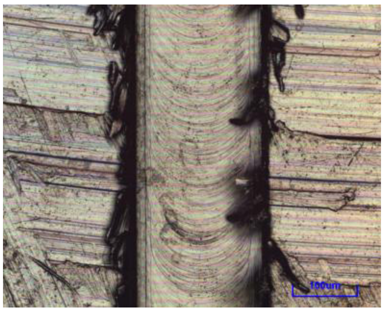
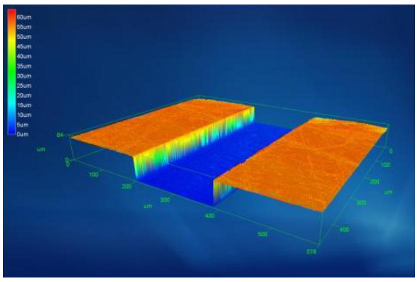
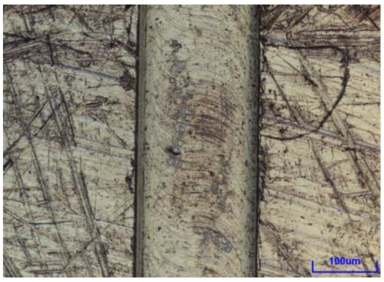
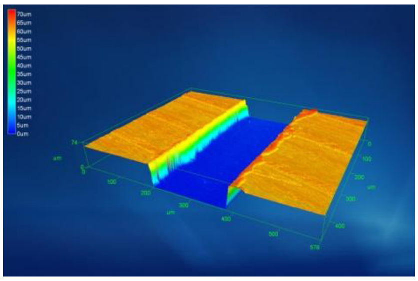
Table 3: Pictures of tool wear according lubrication/cooling method

Tool	After machining	Cleaning tool
Dry		
Jet application		
MQL in feed direction		
MQL against feed direction		

<u>Burr Formation</u>

Two approaches, qualitative and quantitative, were taken to assess burr formation. The quantitative approach measured burr height. Table 4 shows one part of the micro channels, according to the cooling method used. It was found that the top burr formation is observed in all experiments and so it was decided to focus only on this kind of burr because it is highly costly to remove. As Lee and Dornfeld (2002) reported, there are differences between the top burr formations on the two sides of the walls. The wall side where t down milling is performed presents greater burring than the other wall side where up milling is carried out.

Table 4: Pictures of burr formation according to the lubrication/cooling method

Dry		
Jet application		
MQL in feed direction		
MQL against feed direction		

In dry micro-milling, more burr formation on the right side than the left side is observed; although burr formation on the left side is almost non-existent. This is due to the effects of down milling and up milling. However, with the use of the jet application the burr is similar on both sides of the microchannel; this is evidence of increasing tool wear (Lee and Dornfeld, 2002). In addition, top burr dimensions are significantly greater for the jet application method than when machining is performed with the dry and MQL conditions. Results with MQL use are very different in terms of to nozzle orientation. When the nozzle direction is in the feed direction, burr formation is not visible. On the other hand, when the nozzle is oriented against the feed direction, burr formation is similar to that of the dry method results.

Figure 5 shows the quantitative results which take into account burr height. It is clear that the higher burrs, reaching 15 µm burr height, appear when traditional flood cooling, (i.e. the jet application method), is used to machine the micro channels. This value is three times greater than those formed with the MQL method. Even though the burr width measures were not evaluated, it can be concluded from the images that the trend is similar to burr height.

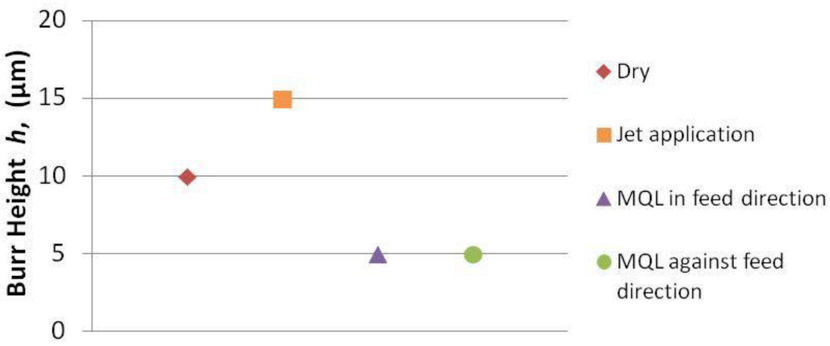


Figure 5: Effect of the cooling method on burr height.

Accuracy

The effect on accuracy of the different lubrication conditions was evaluated through dimensional measurements of channel width. Figure 6 shows the comparison of the results obtained from the lubrication method application. After taking into account when the desired dimension of 200 µm is reached, the best results are achieved when the dry condition is used and when the MQL against feed direction is used. It should also be noted that when the conventional emulsion by jet application is applied, the channel width increases by up to 20% of the desired value. This is because the magnitude of the impact on the jet application method is greater than the cutting forces (Jun et al., 2008) thus causing deflection in the micro tool. Furthermore, the properties of the emulsion fluid may affect penetration into the small cutting zone and not reduce the temperature and evacuation of the chips; resulting in tool damage by welding chips; as reported in the previous section.

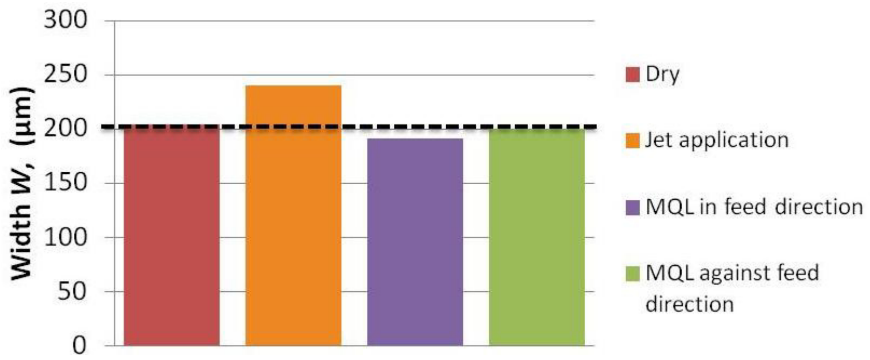


Figure 6: Channel width average at different lubricating method.

Surface Roughness

The effect of the lubricating or cooling conditions on the surface roughness is presented in Figure 7. When the jet application method is compared with the use of MQL, against feed direction reduces surface roughness by 60%. Furthermore, the result of the surface roughness of an area under jet application is almost four times (3.87) rougher than when using the MQL method. Better surface roughness is achieved using the MQL technique in feed direction and against direction in contrast to dry and traditional jet applications. It can be concluded that the difference in surface quality between dry cutting and the jet application is over 20% higher. Differences in surface roughness are mainly caused by tool wear (see previous section). The MQL application results in better interaction between chip and tool, thus reducing tool wear and improving surface quality.

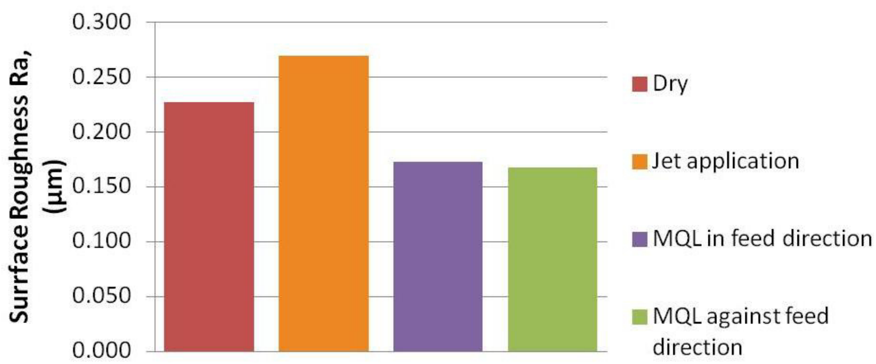
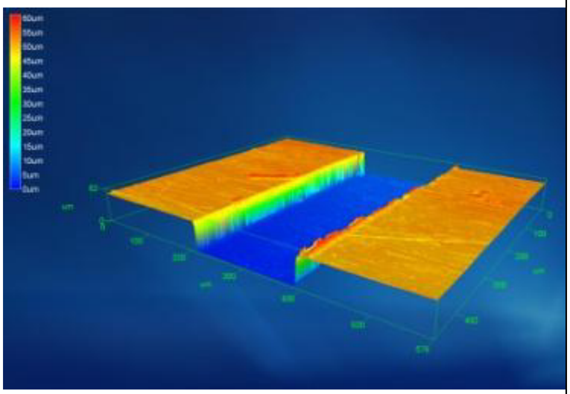
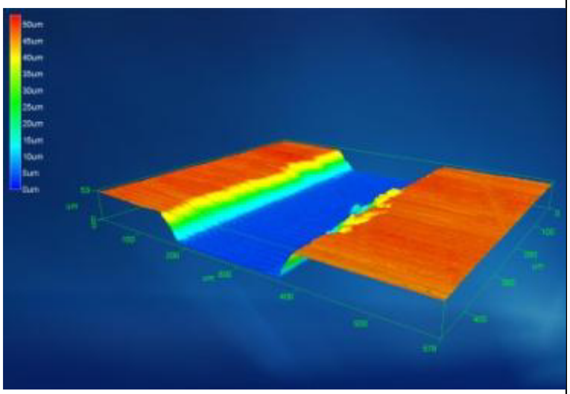
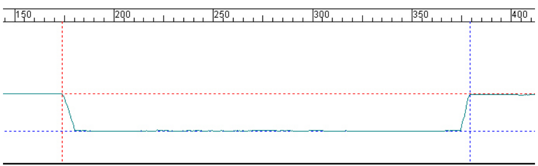
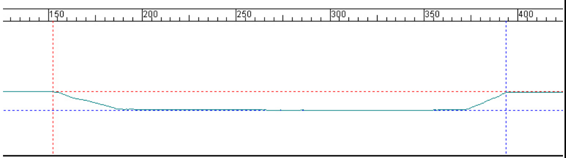


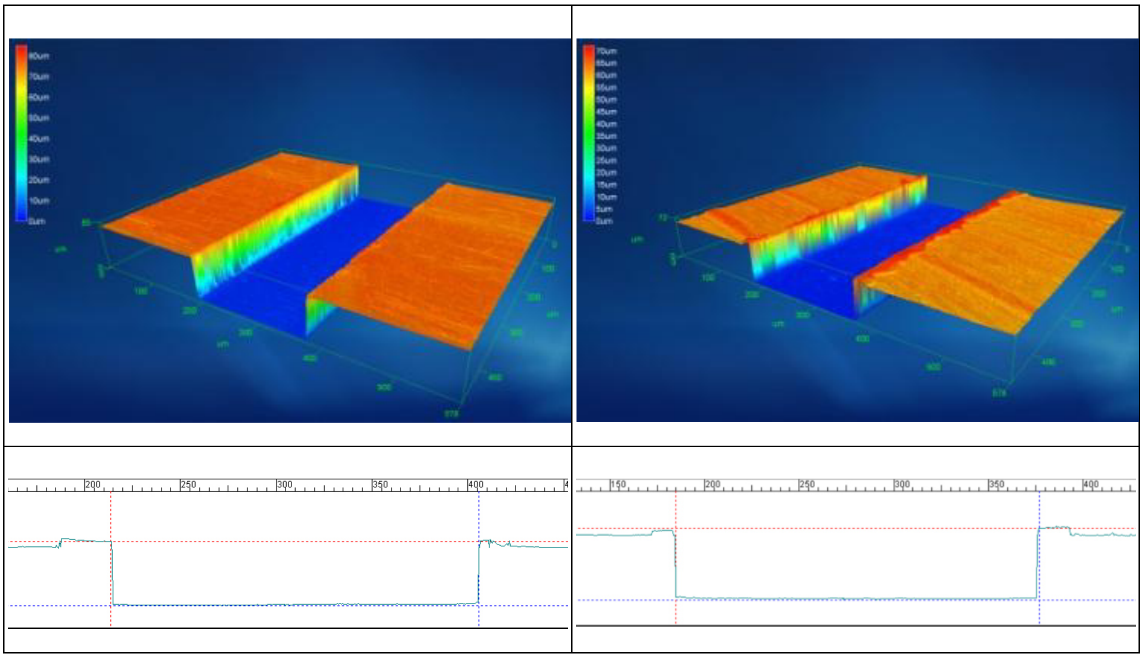
Figure 7: Effect of the cooling method on surface roughness

Geometric shape

Microchannel images are provided in Table 5. The micro channels machined in dry conditions do not have the desired square shape. The microchannel cross sections exhibit an inverted trapezoidal shape where the bottom of the microchannel has slightly less deviation than the dimension target. A similar profile shape is obtained with the jet application method. However, the deviation of the bottom width measure is greater, along with the top width which is also significantly larger, than the machined micro channels under other lubrication conditions. The result of the jet application on the geometric shape of the micro channels is the roundness of the lower corners and the microchannel loses its rectangular profile, resulting in a 150° angle rather than a 90° angle. The inverted trapezoidal shape suggests the jet application is not cooling and lubricating the small inner region and the micro tool is heated with chips welded on it, thus affecting the surface and the quantity of the material removed from the resulting cut depths. According to the images of the micro channels, it is possible to confirm that the use of the minimum quantity of lubricant technique improves quality in terms of geometric shape. The pictures at the bottom of the table show right-angled profiles, the bottom and top width have the same dimensions.

Table 5: Pictures of geometric shape according to the lubrication/cooling technique.

Dry	Jet application
	
	
MQL in feed direction	**MQL against feed direction**



Conclusions

The role of cooling and lubrication conditions in micro-milling of Ti6Al4V has been investigated by evaluating tool wear, burr formation, accuracy, surface finish and geometric shape. The different methods of cooling and lubricating used in this research work include: dry machining, jet application, MQL in feed direction and MQL against direction. Note that, not only was the application of the minimum quantity lubrication studied, but also the direction of the application was studied.

- Some specific conclusions can be drawn as follows:

- The results suggest that the use of traditional cooling conditions diminish the quality of the micro channels no matter what parameter (e.g. dimensions, surface or shape) is considered. The error produced with this technique is about 20%. This could be explained by the disordered flux created by the jet application and it being inefficient in the context of the micro-scale because it does not reach the small cutting zone.

- As for tool wear, the tool used under traditional coolant by jet application presents severe wear, while the best results were achieved under MQL in feed direction; obtaining tool diameter loss value of 1.6% compared to 6.15% under the jet application.

- Burr formation is reduced when the MQL technique is used.

- The desired geometric shape was obtained through dry machining and MQL machining methods, however, when flood machining was used the micro channels tend to be of a trapezoidal shape.

- Finally, the use of a minimal quantity of lubrication in feed direction during the micro-milling process produces better results than traditional cooling techniques (dry machining and jet application).

Acknowledgements

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Chapter 8. Computer Fluid Dynamics analysis for efficient cooling and lubrication conditions in micro-milling of Ti6Al4V

Chapter 8 exposes a comparison between Computational Fluid Dynamic analysis and experimental work evaluating the cooling and lubrication conditions on micro-milling of Ti6Al4V.

This study was presented in an article entitled "*Computer Fluid Dynamics analysis for efficient cooling and lubrication conditions in micro-milling of Ti6Al4V*", submitted in Materials and Manufacturing Processes Journal/LMMP-2014-0155 in January 2014.

Computer Fluid Dynamics analysis for efficient cooling and lubrication conditions in micro-milling of Ti6Al4V

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Abstract

Titanium alloy Ti6Al4V has been extensively used material in industries such as medical field for prosthesis and surgery instruments due to its capacity of biocompatibility. However is considered as difficult-to-machine material due their inherent mechanical and thermal properties producing several too wear and shorter tool life, diminished surface quality and low productivity. The aim of this work is to evaluate the efficiency of Minimum Quantity Lubrication (MQL) in micro-milling with respect to dry machining and jet application. Two-approaches aiming at the study performance of MQL are presented. First, experimental evidence showed that the MQL technique offers better results on the basis of accuracy, tool wear, surface roughness, burr formation and geometric shape. Second, the effect of flow of cutting fluid was analyzed through Computational Fluid Dynamics (CFD) analysis, it was found jet application in the context of the micro-scale cause a disordered flow and not reaches the desired target in this case the two flutes of the tool. These results were accordant with the obtained in micromiling experiments. In addition, recent machining concerns are related to sustainability aiming to reduce or to eliminate the use of cutting fluids, the applicability of MQL in micro-milling represent a substantial reduction in cutting fluid consumption.

1. Introduction

Titanium alloy Ti6Al4V has been recognized as one of the most suitable materials in industries such as: aerospace, automotive and particularly in the field of medicine for instruments and minimally invasive devices like prosthesis and surgery instruments [1-3]. Unfortunately Ti6Al4V material was categorized as difficult-to-machine material, according to Ulutan and Ozel the machining of this material is a compromise between machinability and tool wear challenge [4]. The mechanical and thermal properties include poor thermal conductivity allows to high temperature in cutting zone, chemically reactive result in chipping and premature tool failure and high strength and low modulus of elasticity promote shorter tool life and even tool breakage [5].

Because of this the effort for improve the cooling and lubrication technique in conventional machining conditions of this alloy has been investigated by many authors. Hong and Ding [6] evaluated the effectiveness of cryogenic method in cutting of Ti6Al4V. The authors affirm the use of liquid nitrogen in reducing the tool temperature when applied in the proximity of the tool cutting edge. They compared different methods, such as dry cutting, cryogenic tool, traditional cooling and better results were obtained using simultaneous rake and flank cooling by cryogenic technique. Later research improves the cryogenic machining approach achieving tool life increases compared with others techniques [7]. Su et al [8] suggest that the use of compressed cold nitrogen gas and oil mist is the optimal option providing the best tool in high speed end milling of Ti6Al4V. Similar research was performed by Yuan et al [9] they recommended to use MQL with -15°C cooling air condition.

The use of cutting fluids in micro-milling has limited progress. Marcon et al. [10] investigated the effect of a graphite nanoplatelet based lubricant in micro-milling on H13 tool steel. They found that with the use of this lubricant the tangential force is reduced. However, it has a negative effect on the slot depth and causes burnishing of the machined surface. Similar research was performed by Li and Chou [11], using 600µm diameter micro-end mill and hot work die steel (SKD61) as the workpiece. They found that the use of MQL increases the tool life considerably and additionally improve surface roughness and burr formation in comparison to those produced in dry machining. An atomization-based cutting fluid application system for micro-milling was developed by Jun et al [12] using ultrasonic vibration. The experiments were carried out using 508 µm diameter micro-end mill and aluminum 7075 as the workpiece. Results demonstrate that, in comparison to dry conditions, lower cutting forces and improved tool life are achieved when atomization-based cutting fluid is used.

In this study, application of MQL on micro-milling of Ti6Al4V was conducted using 200 µm diameter micro-end mill in order to evaluate the efficiency of this technique with respect to dry and jett application. Then, the effect of the cooling and lubrication conditions on accuracy, tool wear, surface roughness, burr formation and geometric shape were analyzed. Computational Fluid Dynamics analysis has been used to explain the experimental phenomenon observed. The effect of flow of cutting fluid into the cutting zone (including the micro-channel and the tool tip) was studied simulating the MQL and jet application conditions in micro-milling.

2. Experimental method

The MQL was applied to the tool tip through a two nozzles of 800 µm and 236 µm diameters for air and oil respectively. Both of them have conic shape. The drop size obtained for this setup was around 9 µm diameter it allows to assure the entrance in the cutting zone. The distance from the nozzles to the tool tip was 20 mm. The output air velocity was 1.28m/s. By contrast, the jet application was applied through a nozzle of 6.35 mm diameter. The output velocity emulsion was 6.4m/s. The concentration emulsion was 1:10 parts oil-to-water ratio. The distance from the nozzles to the tool tip was 70 mm. The properties of the cutting fluids are listed in Table 1. The detailed view of the cooling conditions is presented in the Figure 1. Additionally, micro-milling experiments under dry conditions were performed, 10 replicas for each machining condition were made.

Table 1: Properties of the cutting fluids.

Property	**Units**	**MQL Trico-MD1**	**Jet app. MAK KIT10 ES-AL**
Density (20°C) ASTM D1217	(Kg/m3)	950	890
Viscosity	(N s/m2)	0.034	0.0013
Specific gravity	(gr/ml)	0.87	0.97
Flash point	(°C)	600	

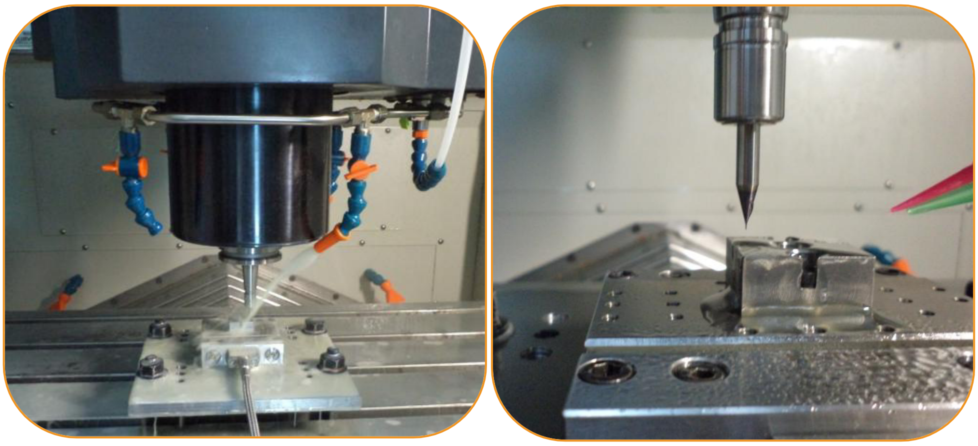


Figure 1: Close view of the experimental set-up of cooling conditions.

A Vertical Machining Center Makino F3 was used to perform the study. The work material was Titanium alloy (Ti6Al4V) with hardness of 32HRC and the micro-end tool was a Mitsubishi tungsten carbide cutting tools with 200 µm in diameter and two flutes. In order to minimize errors Mega micro chuck by BigKaiser cutting tool adapter was employed in all experiments.

Cutting conditions were depth of cut *ap*=0.020mm, feed rate *f*=75mm/min and cutting speed v_c=19m/min.

The dimensional measurements and surface roughness parameter Ra on the micro-channel bottom region were conducted with a Confocal Microscope System CSM 700 from Zeiss. Two measures for surface roughness were performed: the linear roughness measurement (along an straight line) and the areal roughness measurement (over an rectangular range) in order to compare the results. In addition, a ZEISS DSM 960A Scanning Electron Microscope and Zeiss Discovery V12 Stereomicroscope were used to analyze tool wear. An ultrasonic cleaner was used to clean tools after the performed cutting operations.

3.CFD Analysis

As shown in Section1, quite a large amount of research work has been dedicated to the study of flow of cutting fluid in macro-milling while studying the literature available in micro-milling there is a gap of research working with the analysis of cooling and lubricating conditions in micro-milling. Flow of cutting fluid in MQL cutting and jet application cutting were analyzed using ANSYS CFX R14. The simulated steady-state domain is made of 1,189,408 elements. The cutting conditions in the analysis are the same as those in the cutting experiment. The tool tip geometry was simplified as cylindrical body and not incorporates the dual-edge.

In the case of MQL condition, the physical properties of the air and cutting fluid have been assumed as constant. Then, the density (ρ_g) and viscosity (μ_g) of the air were assumed as 1.1614 Kg/m^3 and 1.82x10^{-5} Ns/m^2 respectively. While, the density (ρ) and viscosity (μ) of the fluid were assumed to be 950 Kg/m^3 and 3.4x10^{-2} Ns/m^2 respectively. Boundary conditions of the analysis were given as follows:

By contrast, in the jet application the standard k–ε turbulent flow model is used to model the turbulence. The physical properties of the air and cutting coolant have been assumed as constant. Then, the density (ρ_g) and viscosity (μ_g) of the air were assumed as 1.1614 Kg/m^3 and 1.82x10^{-5} Ns/m^2 respectively. While, the density (ρ) and viscosity (μ) of the fluid were assumed to be 890 Kg/m^3 and 1.3x10^{-3} Ns/m^2 respectively.

4. Results and discussion

4.1 Experiment

Figure 2 shows the resulting tool diameter loss under different lubrication conditions. It is possible to observe that tool wear for jet application increases almost 3 times compared to MQL application. The tool diameter loss value in percentage is 6.15 % compared with the minimum value of 1.6 % achieved with the MQL.

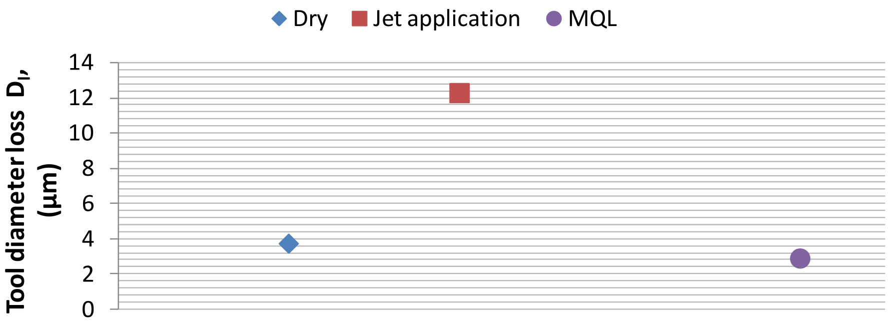
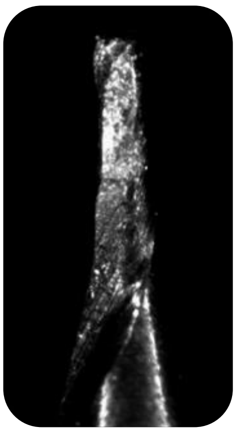
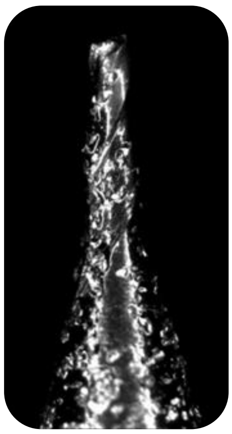


Figure 2: Effect of the cooling technique on tool wear.

In the first row in Table 2, the conditions of the tools immediately after the machining process are depicted. In dry conditions welded chips in one of the flutes can be seen. The same effect appears in the tool lubricated by the jet application. Even when the tool has been cleaned in an ultrasonic bath (second row), it is possible to observe the metal adhered to the workpiece; demonstrating that the high temperatures promote chip welding. Tool pictures for MQL after the process of micro-milling clearly demonstrates that the oil remaining in the tool's edges is basically explained by the properties of cutting fluid. The vegetable oil has a high viscosity and, according to the results, a low surface tension. Previous research by Jun et al. [2008] found that lower cutting forces are obtained when a cutting fluid with the above mentioned properties is used. Once the tools were cleaned, the end mill tool used with MQL seems to be in better condition than all the other tools.

Table 2: Pictures of worn tools according to the lubrication/cooling technique.

	Dry	**Jet app.**	**MQL**
After machining at 32X			

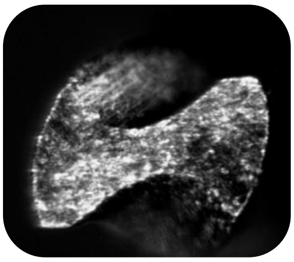
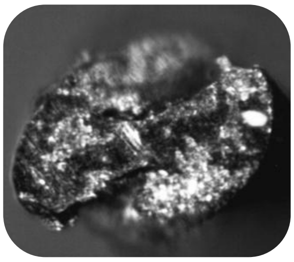
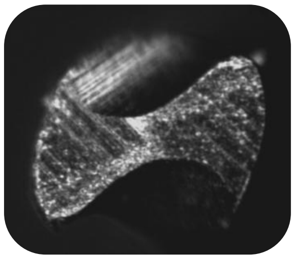
Cleaning tool at 150X			

Figure 3 shows the quantitative results which take into account the burr height. It is clear that the higher burrs, reaching 15 µm burr height, appear when the jet application method, is used. This value is three times greater than those formed with the MQL method. Even though the burr width measures were not evaluated, it can be concluded from the images that the trend is similar to the burr height.

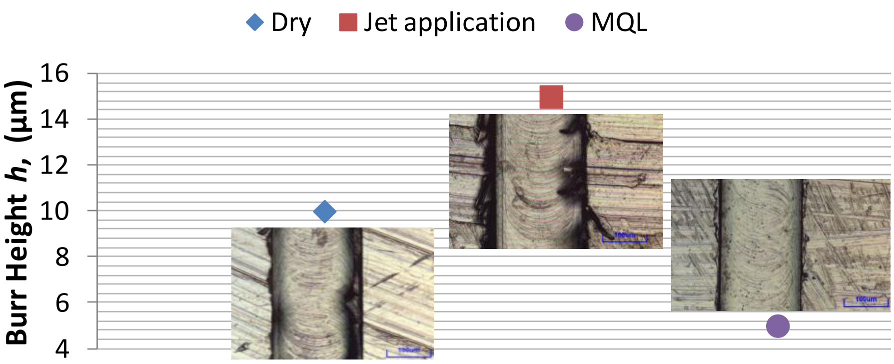


Figure 3: Effect of the cooling method on burr height

Figure 4 shows the comparison of the results of width measure obtained from the lubrication technique application. When taking into account when the desired dimension of 200 µm is reached, the best results are achieved under dry condition and when the MQL is used. It should be also noted that when the conventional emulsion by jet application is applied, the channel width increases by up to 20% of the desired value.

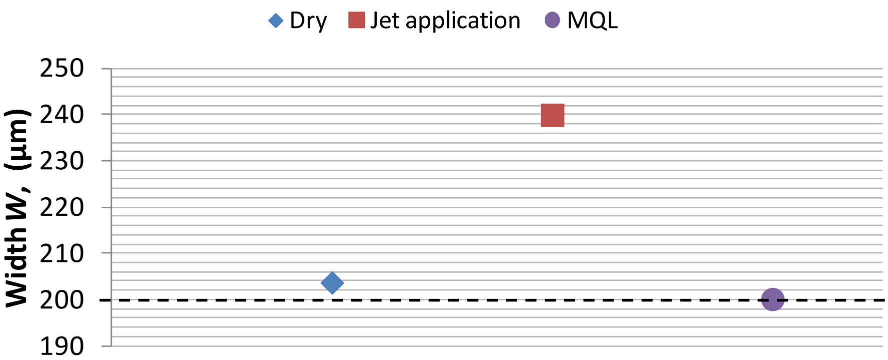


Figure 4: Experimental results of channel width using different lubricating techniques

The effect of the lubricating method on the surface roughness is summarized in the Figure 5. When the jet application is compared with the use of MQL, reduces surface roughness by 60%. Furthermore, the result of the surface roughness of an area under jet application is almost four times (3.87) rougher than when using the MQL method.

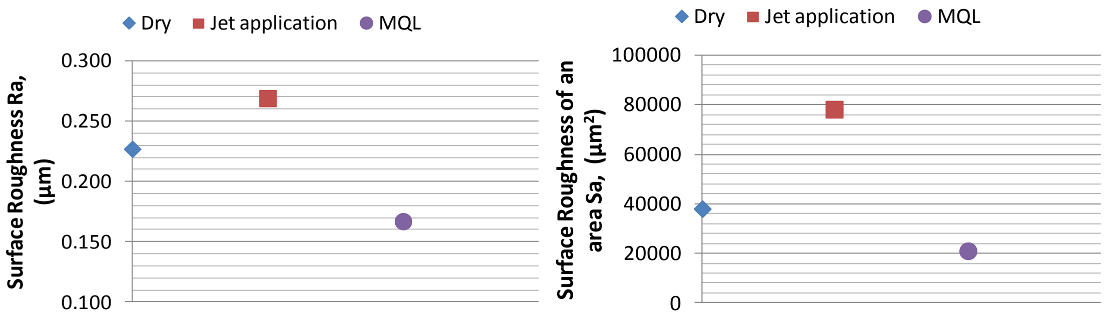
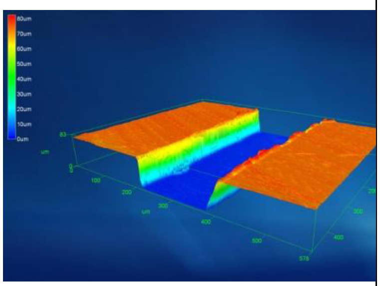
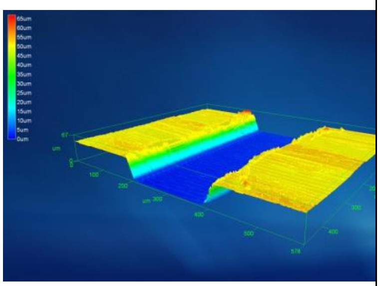
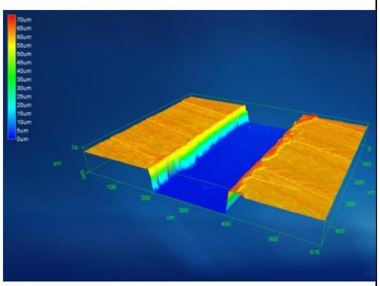


Figure 5: Effect of the cooling technique on surface roughness

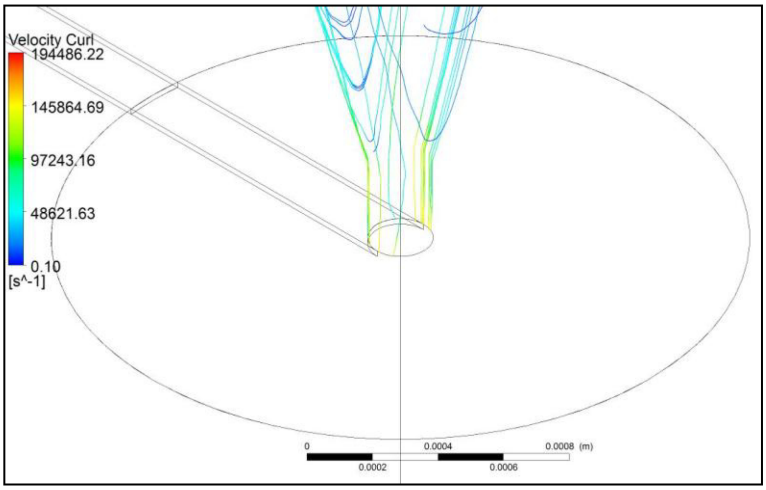
The micro-channel cross sections exhibit an inverted trapezoidal shape where the bottom of the micro-channel has slightly less deviation than the dimension target when dry and jett application conditions are used. The result of the jet application on the geometric shape of the micro channels is the roundness of the lower corners and the micro-channel loses its rectangular profile, resulting in a 150° angle rather than a 90° angle. According to the images in Table 3 of the micro channels, it is possible to confirm that the use of the minimum quantity of lubricant technique improves quality in terms of geometric shape.

Table 3: Pictures of geometric shape according to the lubrication/cooling technique.

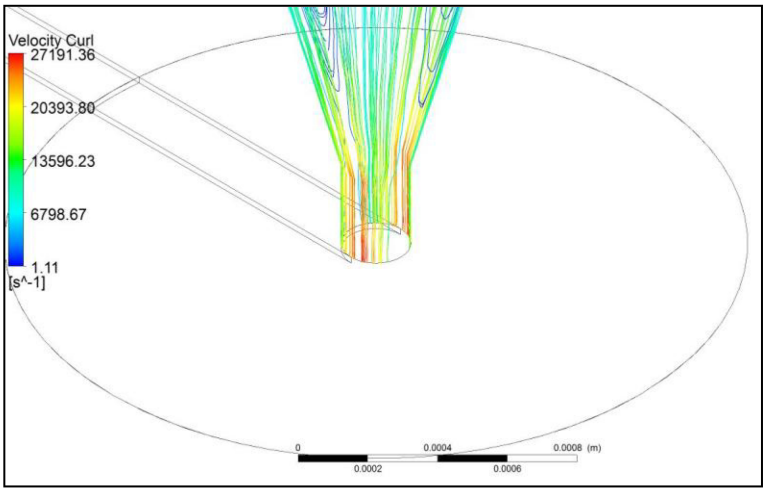
Dry	**Jet app.**	**MQL**
		

4.2 Analysis

Visualized flows of the air from jet application and of the MQL system are shown in Figure. 6 (a) and (b) representing the velocity curl of each method in the tool tip. In the case of jet application the velocity curl is much greater than the MQL method, however, the stream line of the flow velocity demonstrates that it is not reaching all the inner regions of the tool tip. According to the visualization of the velocity curl when cutting fluid is applied through MQL the air copiously penetrates in the tool tip. In order to compare the magnitude of the velocity curl in the cutting zone three different points were selected. The data for the different points are summarized in Table 4. It was found that the velocity curl in the point 1, with the lowest z coordinate value, obtained the smaller value when jet application is used than when MQL is performed. It can be concluded that the flow of air when is used the jet application method could be not reaching efficiently the tiny cutting zone. The significantly greater values of velocity curl in point 2 and 3 under jet application method are evidence of turbulence in the closeness of the tool and, as a result, the oil drops are exploding out of the cutting zone. In contrast MQL technique permits the lubrication and cooling because of reaching the cutting zone.



a)



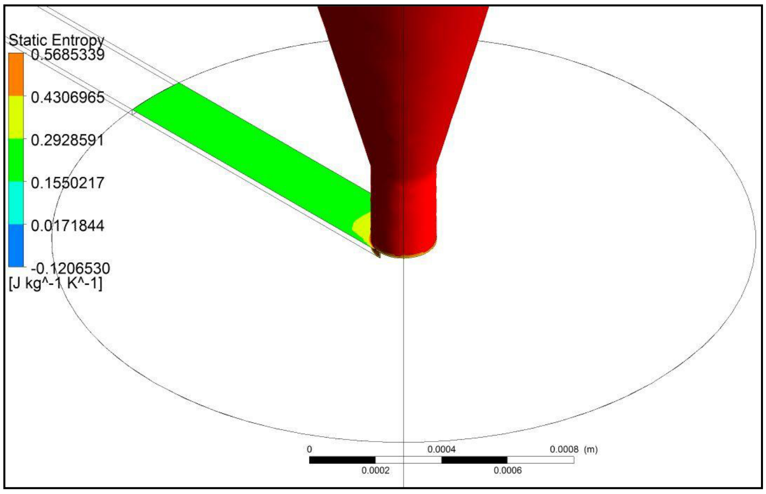
b)

Figure 6: Visualized flows of the air spayed from (a) Jet application and (b) MQL.

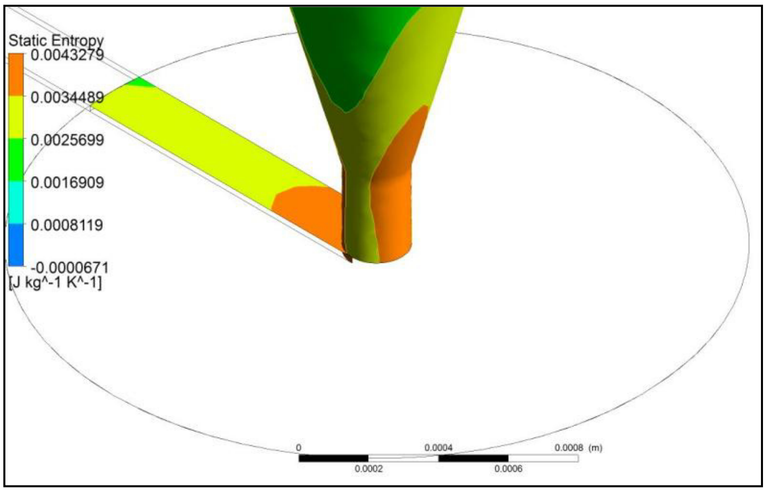
Table 4: The data for the different points near of the cutting zone of the velocity curl.

	Point 1	**Point 2**	**Point 3**	
X coordinate	102.3	100.9	98.2	µm
Y coordinate	-11.1	-19.5	-40.9	µm
Z coordinate	-5.1	24.3	2.2	µm
MQL one fluid	5,938.74	22,466.50	21,339.60	s^-1
MQL –air	5,714.19	21,796.10	20,486.50	s^-1
Jet app	***5,075***	134,351.00	139,581.00	s^-1

One potential explanation of the obtained experimental results is that, because traditional flood cooling in a micro-scale context causes a disordered flow and does not reach the desired target, in this case the two flutes of the tool and it is probably causing the deflection of the micro-tool. For this reason was studied the entropy of the two different machining conditions. Figure 7 indicates that there is higher entropy in the jet application than in the MQL application and this is why the MQL supply reduces tool wear. As seen in the simulation results of the jet application, the entropy in the tool tip was quite large (0.3735480 J kg^-1 K^-1) reaching this value to be 100 times more that the entropy value when MQL is used (0.0037067 J kg^-1 K^-1). Therefore, the accurate delivery of lubricant to the tiny tool by MQL is more efficient than an uncontrolled stream created by the jet application; moreover, the material which is being machined has low thermal conductivity and therefore does not dissipate heat. According to Ezuwgu and Wang [13] around of 80% of the heat generated during the machining of titanium alloys ramains in the tool.



a)



b)

Figure 7: Static entropy field with (a) Jet application and (b) MQL.

5. Conclusions

The effect of the cooling and lubrication conditions on accuracy, tool wear, surface roughness, burr formation and geometric shape were analyzed experimentally. Micro-end mills with 200µm diameter were used to slotting the Ti6Al4V. Then, Computational Fluid Dynamics analysis has been used to explain the experimental phenomenon observed. In the experimental approach dry conditions, jet application and MQL were performed. While in the numerical analysis was included the jet application and MQL method.

From the experimental results, it was found that the MQL technique offers better results on the basis of accuracy, tool wear, surface roughness, burr formation and geometric shape. The use of the traditional cooling conditions diminishes the accuracy of the micro channels producing an error of 20%. As for tool wear, the tool diameter loss can be reduced in almost 4 times using MQL than employing jet application technique. The value of surface roughness (Ra) when MQL is applied is around 0.150 µm compared to 0.269 µm obtained under jet application. Regarding to the geometric shape better results was obtained through dry machining and MQL machining methods, however, when flood machining was used the micro channels tend to be of a trapezoidal shape.

Computational fluid dynamics analysis indicates that jet application in the context of the micro-scale cause a disordered flow, shown as higher values of entropy, and not reaches the desired target in this case the tool tip. In addition, the MQL flow penetrates in the tiny cutting zone and it performs three different actions; it extracts the heat generated during the machining, it reduces friction between the tool and workpiece and it evacuates the chip of the cutting zone. These results were accordant with the obtained in micromiling experiments. Finally, the applicability of MQL in micro-milling represents a substantial reduction in cutting fluid consumption.

Acknowledgements

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Chapter 9. Process planning considerations for micro-milling of mould cavities used in ultrasonic moulding technology.

Chapter 9 presents the proposed process planning for micro-milling of mould cavities using a complex geometry. Several key factors in process planning are addressed.The ultrasonic moulding technology requires this kind of moulds.

This study was presented in an article entitled "*Process planning considerations for micro-milling of mould cavities used in ultrasonic moulding technology*", submitted in Precision Engineering in November 2013 (PRE-S-13-00310).

Process planning considerations for micro-milling of mould cavities used in ultrasonic moulding technology.

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Keywords: micro-milling, process planning, dies and moulds, miniature mould cavities, ultrasonic moulding.

Abstract

The current trend in miniaturization of products and components requires appropriate technologies for the manufacture of miniature dies and moulds. The work presented here deals with the process planning of micro-milling for the production of miniature mould cavities, required in ultrasonic moulding. Several aspects of process planning are addressed, including cutting tool geometry selection, segmentation of cavity geometry, minimum chip thickness, chordal tolerance, and type of interpolation. The case study involves the successful micro-milling of a complex aluminium mould cavity for ultrasonic moulding. The part geometry is a miniature classical guitar model. The proposed process plan is demonstrated through the micro-milling of the mould cavity and silicone replicas of the miniature guitar models. In general terms, good surface finish and geometric definition was obtained. In a randomly located set of geometric features, the dimensional error was below 5% for most features (32 out of a total of 40).

1 Introduction

Miniaturization of products and associated components is a current technological trend in a wide range of applications such as automotive, biomedical, biotechnology, optical and sensors [1-4]. The production of these miniaturized components requires replication technologies based on processes such as hot embossing, microforming, microinjection moulding, and resin casting [5, 6]. In turn, these replication technologies require tooling in the form of dies and moulds with geometries and features specifically oriented to microfabrication. When micro parts are manufactured, in many cases, a large amount of the material are wasted to produce the necessary sprue, runners and gates to assure a good part quality [7]. When expensive materials are manufactured, this can cause a cost disadvantage. The ultrasonic moulding process has the potential to become a suitable small scale manufacturing process. The work presented here deals with the process planning for micro-milling of moulds for ultrasonic moulding technology.

1.1 Related Work

Recent research associated with the micro-milling process has focused on issues such as machine tool design [8-13], miniature cutting tools [14-16], process mechanics [17, 18], surface finish [19] and CAM systems [20-22]. However, in the research literature there is relatively little attention to the micro-milling process planning issue, i.e. integrating a sequence of operations with different cutting tools, associated tool paths and process parameters.

In the micro-milling process, cutting tool edge radius is comparable in size relative to the chip thickness found along the various angular positions of the miniature end mill. Therefore, the feed per tooth vs. cutting tool edge radius ratio is a significant factor to monitor. Related investigations show that the micro-milling process is only stable when the feed per tooth is higher than 30% of cutting tool edge radius [23-27]. If the feed per tooth is below the recommended value, the ploughing effect dominates the process. In addition to the feed per tooth factor, the cutting tool deflection in micro-milling can also cause geometrical errors in the workpiece [25].

In the context of dies and moulds for conventional production processes, the process planning of milling operations is a challenging task. Cakir et al. have developed a system for guiding the die and mould makers taking into account the tool type, workholding strategy, machining strategy, machining tolerances, etc [28]. Similar work was developed by Ciurana et al. they developed a model that integrate process planning and production planning starting in the design phase to the production request to the client delivery [29]. Analyzing the deflection forces Lopez de Lacalle et al. applied a new technique for the best selection of the milling toolpaths on complex surfaces [30]. Regarding to process planning for moulds by high speed machining Lopez de Lacalle et al. proposed a method of generating NC programs [31].

In contrast to conventional mould making, for miniature mould manufacturing, the micro-milling process planning has limited progress. Popov et al. have developed guidelines for micro-milling pockets and thin ribs. Testing was conducted in brass. The best results were obtained using a tool diameter smaller than the pocket width (avoiding slotting operation) and small z depth increments (7 µm). The roughing operation was conducted with flat end mill (150 µm in diameter) at feed per tooth of 0.8 µm. The finishing operation was conducted with ball-nose end mill (200 µm in diameter) at feed per tooth of 0.9 µm [32]. Dimov et al. studied the influence of tool path type in the surface finish of copper micropockets with hexagonal shape. The best results were obtained for tool paths that follow the periphery of the micropocket, using a flat end mill (150 µm in diameter) [33]. Litwinski et al. conducted a similar study, considering two different types of tool paths: direction parallel (zig-zag) and contour parallel pretending to minimize different typical feature such as surface roughness, top burr formation and bottom burrs [34]. Ozel and Liu developed strategies for selection of micro-milling process parameters in the manufacture of miniature aluminium pockets. In this study, cutting tool run out is considered as a significant factor. Separate roughing and finishing operations are recommended with flat end mill (508 µm in diameter) [35].

1.2 Objective

In terms of workpieces geometries, the research literature shows many examples of micro-milling for channels or grooves [25] [36] [37], thin webs [32] and pockets [33] [35]. In comparison, the work presented here deals with the process planning of micro-milling for the production of 3D shapes in metallic moulds. Several aspects of process planning are addressed, including cutting tool geometry selection, type of interpolation, chordal tolerance, and segmentation of cavity geometry. The case study shows the successful manufacturing of a complex aluminium mould cavity for ultrasonic moulding.

2 Case study: micro-milling of miniature mould cavity

2.1 Test part: miniature mould cavity for ultrasonic moulding

In order to study the relevant factors of process planning in micro-milling, a miniature mould cavity was constructed. The selected part geometry is an acoustic guitar (see Figure 1), which provides a wide range of geometric features such as round channels, square channels, level changes, slopes and draft angles. Figure 1A shows the standard components of guitars. These components were adapted to create a miniature guitar model (as shown in Figure 1B). Finally, the mould cavity was modelled based on the miniature guitar model (as shown in Figure 1C). The total cavity projected area is 8.2 by 21.9 mm. The workpiece material for the miniature mould cavity was aluminium 7075 T6 (90 HRB) due to its high machinability and applicability for ultrasonic moulding moulds.

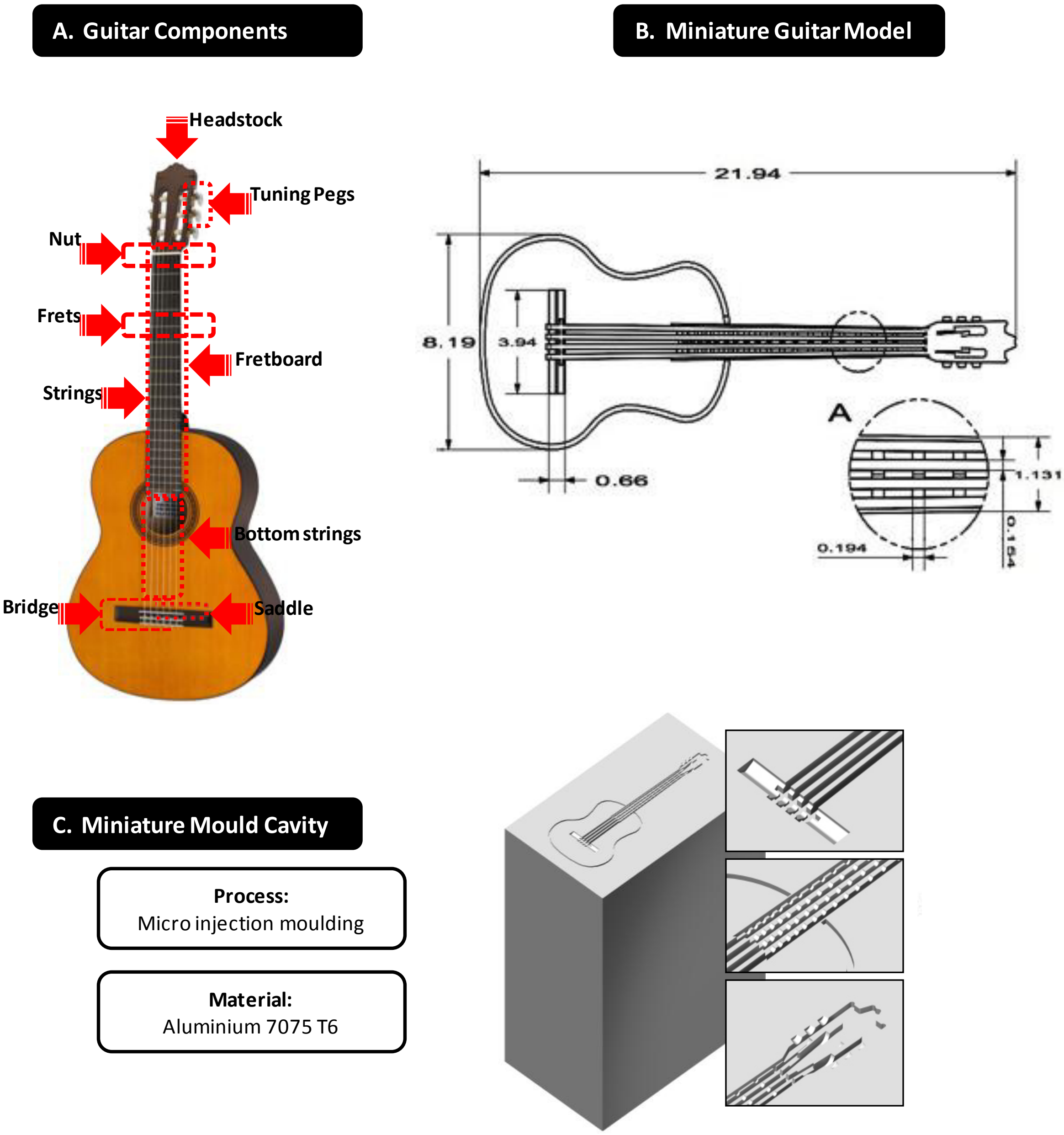


Figure 1: Test part: miniature mould cavity for ultrasonic moulding.

2.2 Experimental Set Up

The micro-milling experimentation was conducted with the resources listed in Table 1. A high-speed milling machine and various types of micro-end mills were utilized.

Table 1: Micro-milling experimental setup.

Resource	**Description**
CAM System	Siemens NX Version 6.

Machine Tool	Deckel-Maho 64V Linear (3-axis, vertical spindle) with positioning accuracy of 20 and 10 µm in Y and Z directions respectively and 8 µm in X direction. Fanuc 180i controller. Spindle speed up to 12,000 rpm.
Cutting tools	Mitsubishi tungsten carbide cutting tools. Flat end mills with 100 and 200 µm in diameter and two flutes. Ball-nose end mills with 100 µm in diameter and two flutes. More details of the cutting tools are provided in Figure 2 and 3.
Cutting tool adapter	Heat shrink type.
Cutting tool length and diameter calibration	Non-contact Laser System supplied by Mida
Workpiece holding	Erowa clamping system.

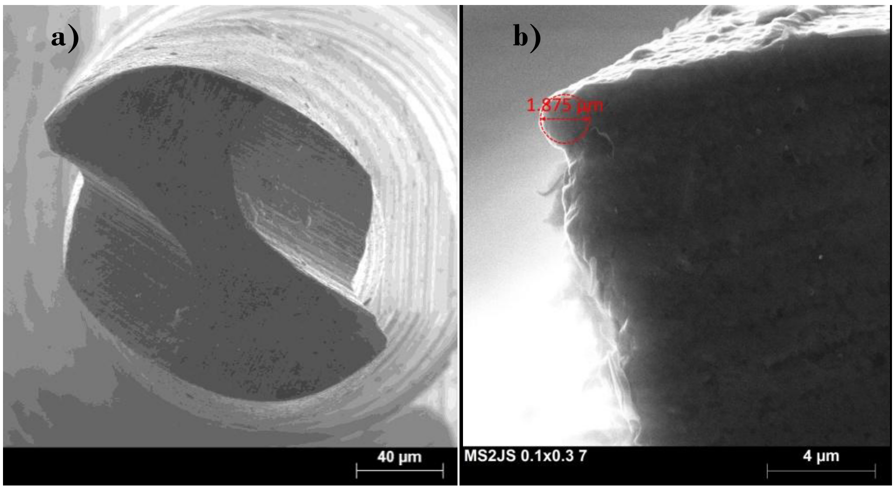
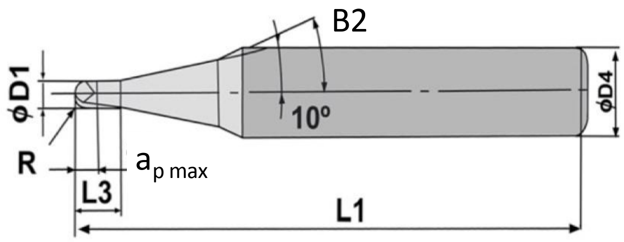


Figure 2: Cutting tools: a) Close-up image of two fluted micro flat end mill with 200 µm in diameter and b) 1.875 µm edge radius of micro flat end mill with 100 µm in diameter



No.			T01	T02	T03
Model			VC2PSBPR0005	MS2JSD0010	VF2XLD0020N010
Type			Ball nose end mill	Flat end mill	Flat end mill
Coating			VC	MS	VF
Cutting diameter	*D1*	[mm]	0.100	0.100	0.200
Ball Radius	*R*	[mm]	0.050	0	0
Shank diameter	*D4*	[mm]	6	4	4
Overall Length	*L1*	[mm]	50	40	45
Under shank length	*L3*	[mm]	-	-	1
Length of cut	$a_{p\,max}$	[mm]	0.2	0.3	0.3
Tool interference corner	*B2*	[°]	20	10	12
Number of flutes	*Z*		2	2	2

Figure 3: Miniature cutting tools dimensions

2.3 Process Plan for Micro-milling of Miniature Mould Cavity

As indicated in the related work section, the research literature has relatively few recommendations regarding the process planning in the manufacture of miniature mould cavities through the micro-milling process. The approach followed in this study involved two iterations of process planning. The first iteration provided some reference information. The second iteration was built based on the first iteration results. In addition, various sources of recommendations from research literature and general mouldmaking practice were adapted to create the process plan in the second iteration.

2.3.1 First Iteration

The process plan for the first iteration, as indicated in Table 2, was conducted with a single micro flat end mill. In this process plan, the smallest feature in the workpieces was used as a reference to specify the flat end mill with 100 m in diameter. The complete cavity geometry was used as a reference for the tool path generation. The micro-milling operation in the first iteration was conducted with spindle speed of 12,000 rpm. In the **Cut Pattern** (CP) parameter (see Table 2), “Follow Periphery” mode offsets the tool from the outermost edge that is defined by the part or blank geometry. The “Follow Part” mode creates concentric offsets from all specified part geometry. In the **Order** (O) parameter, “Depth First” mode means the tool path cuts all levels in one hole before proceeding to the next hole. The “Level First” mode means the tool path will cut at the same level for the whole part before proceeding to the next level.

After a qualitative analysis of mould cavity geometric features, the process plan for the second iteration was created. No detailed measurements were conducted in regards to the first iteration process plan.

Table 2: First iteration process plan: integrated geometry approach.

Guitar component	*Tool Geometry and Diameter* D [mm]	*Radial Depth of Cut* a_e [%D]	*Axial Depth of Cut* a_p [μm]	*Final Depth* H [μm]	*Feed per Tooth* fz [μm]	*Feed Rate* Vf [mm/min]	*In/Out Tol.* T_i / T_o [mm]	*Cut Pattern* CP	*Order* O	*Cut Direction* CD	*Inter-polation* INT
Complete cavity geometry	Flat mill 0.100	25	2	249	1.67	40	0.001 0.001	Follow part	Level first	Up milling	Circular

2.3.2 Second Iteration

The second iteration for the process plan was generated taking into account the results of the first iteration and additional sources of micro-milling process recommendations. For the second iteration, the operations were divided into roughing and finishing phase (as industrial practice indicates for conventional mouldmaking). The micro-milling operations for roughing and finishing phase are indicated in Table 3 and 4, respectively. All micro-milling operations were conducted at 12,000 rpm for spindle speed.

The down-milling cut direction is used to avoid the chatter and provide a stable cutting condition because it is using a tool with a long neck (reference: VF2XLD0020N010) that can promotes vibrations and deflections. Additionally, this technique is recommended for delicate features and materials with low hardness.

Table 3: Second iteration process plan: segmented geometry approach (Roughing Phase).

Guitar component	*Tool Geometry and Diameter* D [mm]	*Radial Depth of Cut* a_e [%D]	*Axial Depth of Cut* a_p [μm]	*Final Depth* H [μm]	*Feed per Tooth* fz [μm]	*Feed Rate* Vf [mm/min]	*In/Out Tol.* T_i / T_o [mm]	*Cut Pattern* CP	*Order* O	*Cut Direction* CD	*Inter-polation* INT
Fretboard	End mill 0.200	50	4	104	3.75	90	0.001 0.001	Follow periphery	Level first	Down milling	Circular

Table 4: Second iteration process plan: segmented geometry approach (Finishing Phase).

Guitar component	*Tool Geometry and Diameter* D [mm]	*Radial Depth of Cut* a_e [%D]	*Axial Depth of Cut* a_p [μm]	*Final Depth* H [μm]	*Feed per Tooth* fz [μm]	*Feed Rate* Vf [mm/min]	*In/Out Tol.* T_i / T_o [mm]	*Cut Pattern* CP	*Order* O	*Cut Direction* CD	*Inter-polation* INT
Headstock	End mill 0.100	50	1	166	0.63	15	0.001 0.001	Follow periphery	Depth first	Down milling	Circular
Tuning Pegs	Ball nose end mill 0.100	50	1	166	0.50	12	0.001 0.001	Follow periphery	Depth first	Down milling	Circular
Nut	End mill 0.100	50	1	249	0.63	15	0.001 0.001	Follow periphery	Depth first	Down milling	Circular
Frets	Ball nose end mill 0.100	50	2	166	0.50	12	0.001 0.001	Follow periphery	Depth first	Down milling	Circular
Strings	End mill 0.100	50	1	249	0.63	15	0.001 0.001	Follow periphery	Level first	Down milling	Circular
Bottom Strings	End mill 0.100	50	2	249	1.67	40	0.001 0.001	Follow periphery	Depth first	Down milling	Circular
Bridge	End mill 0.100	25	2	249	1.67	40	0.010 0.010	Follow part	Level first	Down milling	Circular
Saddle	End mill 0.100	50	2	249	0.50	12	0.003 0.003	Follow periphery	Level First	Down milling	Circular

2.4 Metrology

Dimensional measurements in the X-Y plane were performed with a Stereo Microscope Discovery 12 from Zeiss (150x magnification) to collect the digital images and Quartz PCI© Software for image processing. The depth measurement was performed with an indirect method. Silicone rubber, with low linear shrinkage (0.4%), was cast into the miniature mould cavity to create part replicas. Then, transverse cuts were done in order to observe the part cross sections (as shown in Figure 4). A Zeiss DSM-960 scanning electron microscope (SEM) was used for qualitative study through images. The silicone part replicas were coated with an ultrathin gold coating by electrodeposition before SEM imaging.

The measurement of surface roughness parameter R_a on the micro-channel bottom surface was conducted with a Confocal Microscope System CSM 700 from Zeiss©, with a cut off of 0.08 mm, in accordance with ISO/DIS 4287/1E.

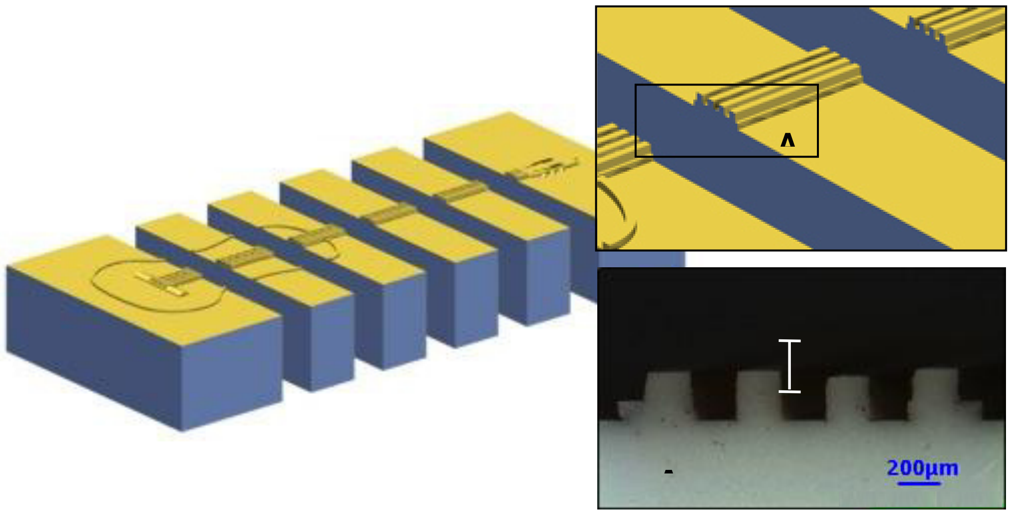


Figure 4: Depth measurements through cross sections in silicone part replicas.

3 RESULTS AND DISCUSSION

In this section, results and discussion are presented. First, some general qualitative and quantitative results are described. Next, a series of specific recommendations for micro-milling of miniature mould cavities are discussed.

3.1 Qualitative Results, Dimensional Error and Surface roughness.

The miniature guitar replicas obtained from the miniature mould cavity have good general appearance. Figure 5 shows sample SEM images of the miniature guitar replicas. In selected areas of the part, some cutting tool marks can be observed. However, the overall geometric definition is satisfactory. It should be noted that the miniature mould cavity received no secondary surface finish processing after the micro-milling process.

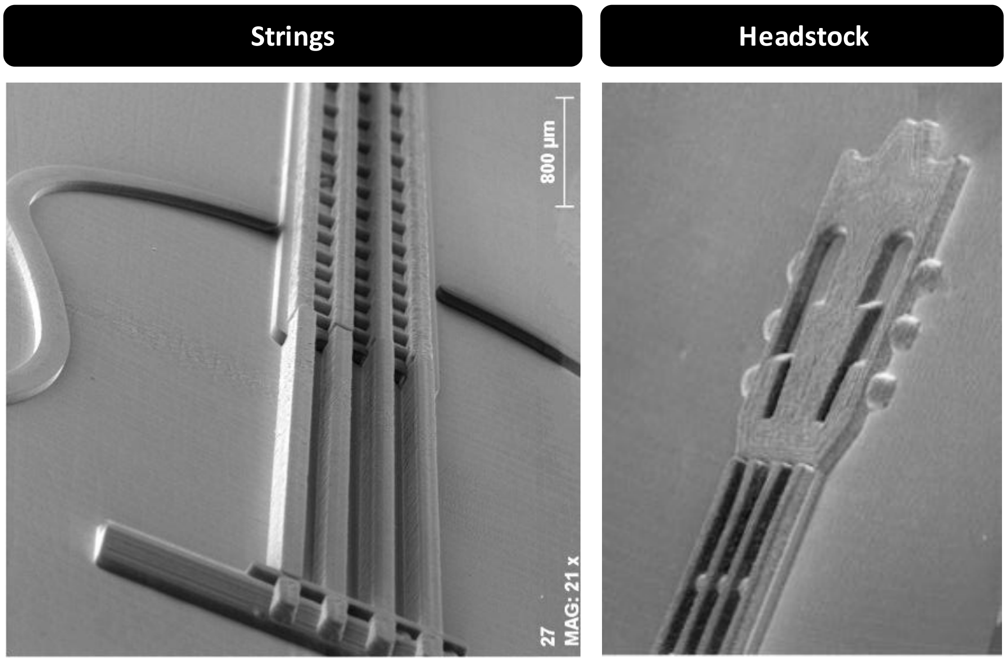


Figure 5: Silicone miniature guitar replicas based on miniature mould cavity.

Due to the generic nature of the miniature mould cavity geometry, a set of randomly located geometric features was defined to evaluate dimensional error. Table 5 summarizes the results for X-Y plane dimensions and for depth dimensions (Y-Z plane).

For the X-Y plane dimensions, 55% of the geometric features have a dimensional error below 2%, while 75% of these features show an error below 5%. The depth dimensions show smaller dimensional errors compared to the X-Y plane dimensions. In this case, 75% of the measured geometric features show a depth dimensional error below 2%, while 85% of these features have an error below 5%. In the X-Y plane, the maximum dimensional error was 12.6%. The maximum dimensional error in depth direction was 10.84%.

Surface roughness R_a was measured in the headstock of the guitar mould cavity, three different measures were performed and the average was: 1.15 µm.

Table 5: Dimensional error in X-Y and Y-Z plane (depth).

X-Y Plane				**Y-Z Plane (Depth)**			
Geometric Feature	**Nominal Dimension**	**Actual Dimension**	**Dimensional Error**	**Geometric Feature**	**Final Depth**	**Actual Depth**	**Dimensional Error**
	L	**L_a**	**ε_L**		**H**	**H_a**	**ε_H**
	[mm]	**[mm]**	**[%]**		**[μm]**	**[μm]**	**[%]**
1	3.942	3.947	0.13	1	0.249	0.249	0.00
2	1.743	1.739	0.23	2	0.249	0.252	1.20
3	0.124	0.127	2.42	3	0.249	0.224	10.04
4	0.664	0.692	4.22	4	0.249	0.255	2.41
5	0.167	0.170	1.80	5	0.249	0.262	5.22
6	0.164	0.157	4.27	6	0.249	0.222	10.84
7	0.167	0.166	0.60	7	0.249	0.250	0.40
8	0.155	0.165	6.45	8	0.249	0.246	1.20
9	0.151	0.152	0.66	9	0.249	0.251	0.80
10	0.155	0.161	3.87	10	0.249	0.247	0.80
11	0.127	0.143	12.60	11	0.249	0.248	0.40
12	0.120	0.121	0.83	12	0.249	0.252	1.20
13	0.127	0.138	8.66	13	0.249	0.250	0.40
14	0.198	0.184	7.07	14	0.249	0.245	1.61
15	0.198	0.187	5.56	15	0.249	0.245	1.61
16	0.198	0.198	0.00	16	0.249	0.248	0.40
17	0.440	0.449	2.05	17	0.249	0.248	0.40
18	3.738	3.745	0.19	18	0.249	0.242	2.81

3.2 Recommendations for Micro-milling of Miniature Mould Cavities

The proposed process plan for micro-milling of miniature mould cavity generated good results, as shown in the previous section. Next, a more detailed discussion of some key process plan factors follows.

3.2.1 Integrated vs. Segmented Geometry Approach for Tool Path Generation

For mould cavities in conventional scale, tool path generation through CAM systems is a mature technology. In the conventional scale, the CNC programmer has flexibility in choosing cutting tools with different geometries and sizes. However, in the micro-scale, the cutting tool rigidity and strength are a major issue. Therefore, the process plan calls for maximizing the miniature cutting tool diameters.

When the micro-end mill size is close to the dimensions to the intended microgeometry, the tool path generation is more challenging, compared to conventional scale CNC programming.

In order to tackle these challenges, the process plan was established with the following considerations: a) segmented geometry approach for the tool path generation, b) roughing and finishing phases, and c) combination of micro flat and ball-nose end mills

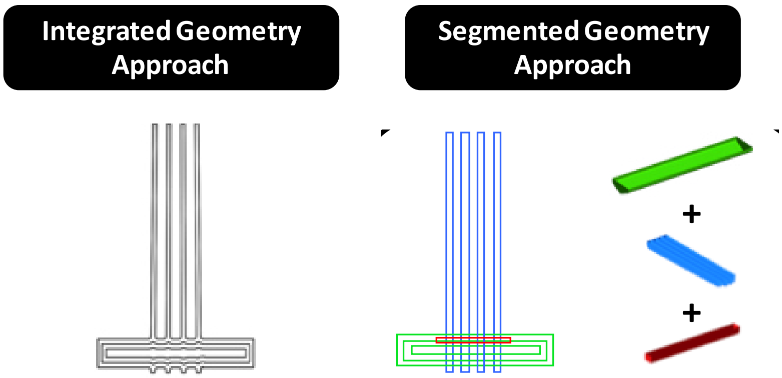


Figure 6: Integrated vs. segmented geometry approach in tool path generation.

In the first iteration of the process plan, the complete cavity geometry was used as reference for tool path generation (considering a single cutting tool). The generated tool path contains rounding at some areas with sharp change in feed direction (as shown in Figure 6). This rounding effect was reflected in a poor geometric definition of corners. In the second iteration, tool paths were generated with a segmented geometry approach, as shown in Figure 6. The segmented geometry approach requires a series of independent CNC programs. However, geometric definition in these intricate areas was improved (see Figure 7).

The use of a roughing operation (as indicated in Table 3) in the fretboard area of the miniature guitar helped in simplifying some of the CNC programs for the following finishing operations (as recommended by Ozel and Liu [35]). The reason to not adopt this approach in the rest of geometry is because exist thin walls than after roughing phase can cause vibrations in the finishing machining resulting in a poor wall surface quality. Finally, a combination of flat and ball-nose end mills in several sizes (100 and 200 m in diameter) provided enough flexibility in order to achieve the intended miniature mould cavity. Figure 7 shows selected areas of the miniature guitar replica as illustration of the level of detail achieved.

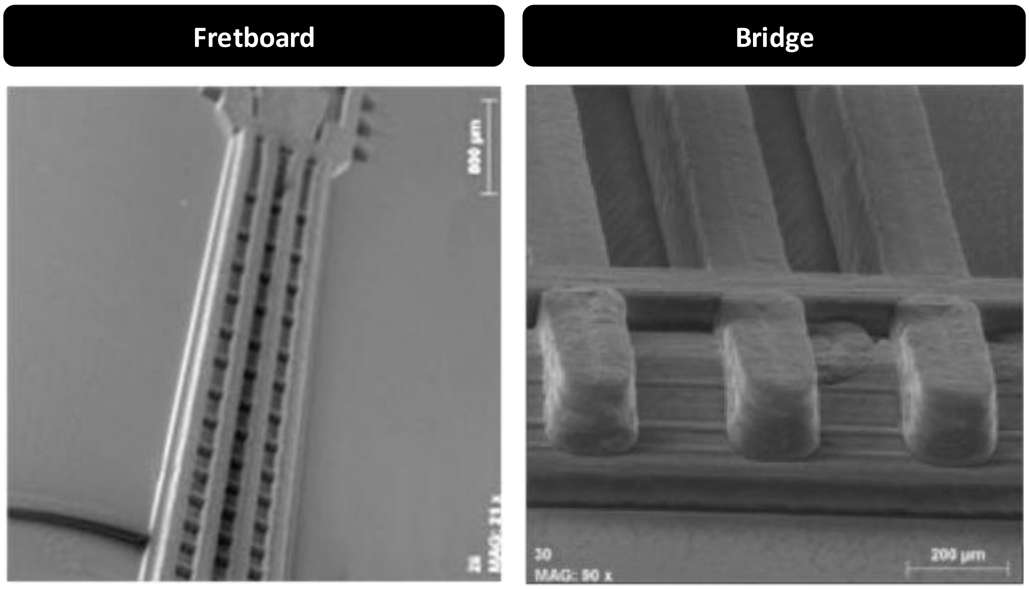


Figure 7: Selected areas of the miniature guitar replica showing acceptable geometric definition.

3.2.2 Feed per Tooth/Feed rate and Tool Edge Radius

In the micro-scale, the minimum chip thickness for chip formation is a critical factor [2]. Several authors recommend a minimum chip thickness of 20 to 40% relative to the tool edge radius (*r*). More particularly, Kim et al. recommend having a feed per tooth larger than the tool edge radius in micro-milling. However, in many cases such condition is not possible due to limitations in micro-end mill strength. In those cases, Kim et al. recommend a minimum feed per tooth of at least 30% relative to the tool edge radius [24].

According to Jin and Altintas the tool edge radius for a micro flat end mill with 200 µm of diameter is 3.7 microns [38] —manufactured by the same tool supplier used in this work—. The micro flat end mill with 100 µm of diameter was measured and the edge radius is 1.87 microns (Figure 2b). Based on this cutting tool geometry, the proposed process plan specifies feed per tooth of 3.75 µm for the roughing operation. In the finishing operations, the feed per tooth was set to 0.50, 1.67 and 0.63 µm depending on the specific area of the miniature mould cavity. Therefore, the minimum feed pert tooth is approximately 27% of the tool edge radius.

At the micro-scale, the dynamics of machine tools are an important factor. Due to the following error inherent in any machine tool control system, rounding of corners might be significant in the range of feed rates used for micro-milling.

In the first iteration, micro-milling was conducted at 40 mm/min. In the second iteration, only the roughing operation is conducted at 90 mm/min. Then, the finishing operations use 12 and

15 mm/min for most cavity areas. Figure 8 shows the influence of feed rate in the geometric definition of the headstock area in the miniature mould cavity. At the higher feed rate, some rounding can be appreciated in areas where the cutting tool has sharp changes in feed direction. At lower feed rates, productivity is lower, but acceptable quality is achieved in the final miniature mould cavity.

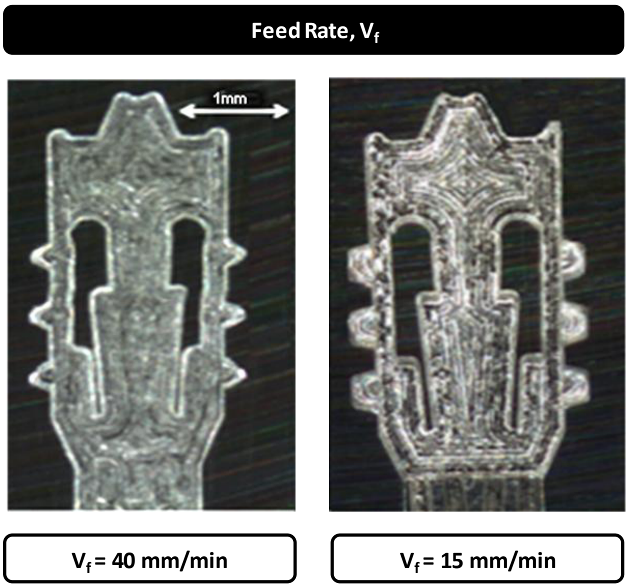


Figure 8: Influence of feed rate on miniature mould cavity geometry.

3.2.3 Radial Depth of Cut (Stepover Distance) and Axial Depth of Cut

The appropriate selection of radial depth of cut (stepover distance), a_e, is also related to the minimum chip thickness issue. The use of radial depth of cut below 50% of tool diameter will reduce the effective chip thickness in the process due to the trochoidal motion of the cutting edge (see Equations 1 and 2 for approximate expressions of angular position for maximum chip thickness). For example, considering 100 µm in tool diameter, feed rate (f_z) of 1 m, and a_e/D of 25%, the maximum chip thickness (h_{max}) will be 0.87 m. If a_e/D goes to 10%, the maximum chip thickness drops to 0.60 m.

$$\phi_{max} = cos^{-1}\,(2\frac{a_e}{D} - 1) \tag{1}$$

$$h_{max} = f_z\, sin(\phi_{\max}) \tag{2}$$

On the other hand, if radial depth of cut is too large, poor surface finish might be generated. In this study, using 50% of diameter for radial depth of cut produced good results. In specific cases were the tool size is a limitation with respect to the cavity geometry dimension as, a radial depth of cut lower than 50% is necessary.

In micro-milling, tool strength is a severe limitation for process planning. Due to this factor, the proposed process plan used axial depths of cut ranging from 1 to 4 µm (similarly to the recommendation of Popov et al. [32]). The small values of axial depth of cut result in long machining times. However, this condition is key in order to maintain the integrity of micro-end mills.

3.2.4 Chordal Tolerance and Interpolation Type

In micro-milling, one of the adopted solutions to minimize the error is the use of tight CAM chordal tolerances. However, extremely small chordal tolerance can produce CNC programs with minute tool path segments beyond the processing capability of the controller.

In both process plan iterations, the in and out tolerances were selected according with the capability of machine tool and CAM software. The use of 1 µm for chordal tolerance produced good results. In the case of the saddle area, the chordal tolerance was set to 3 µm, considering that the cavity geometry was open and therefore larger tool path segments could be tolerated.

In general, CNC programs with circular interpolation have a fewer number of processing blocks avoiding potential data starvation in the machine tool controller. Additionally, when circular interpolation produces a more continuous contour instead a series of facets improving final surface quality. In miniature geometric features, the influence of linear vs. circular interpolation can be more dramatic, compared to conventional scale machining. Figure 9 shows a simulation that illustrates this point.

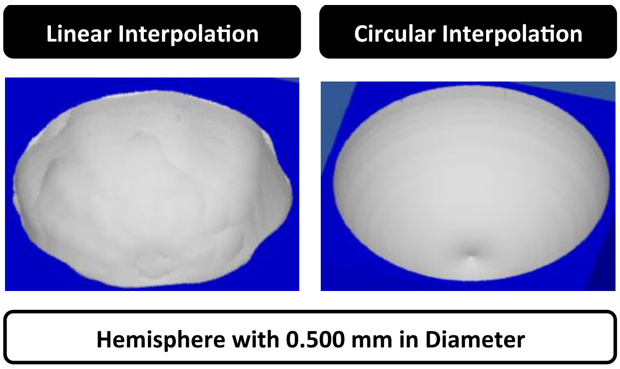


Figure 9: Linear vs. circular interpolation in miniature geometric features.

3.3 Summary of process planning for micro-milling of mould cavities for ultrasonic moulding

The methodology can be applied to process planning of complex miniature mould cavities with micro geometric features up to 120 µm. Figure 10 resume the proposed process planning approach.

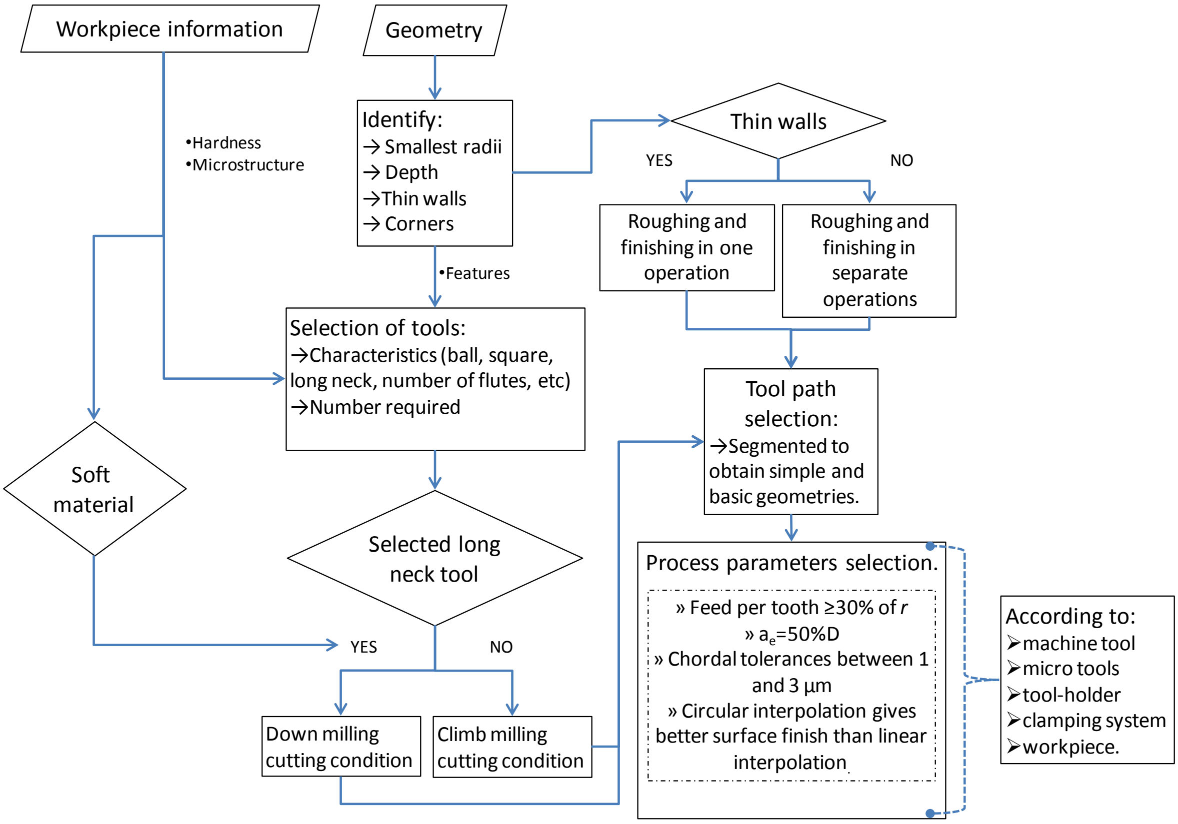


Figure 10: Proposed process planning for micro-milling of mould cavities for ultrasonic moulding.

4 CONCLUSIONS

This work investigates several aspects of process planning for micro-milling of dies and moulds. The case study involved the construction of a mould cavity for ultrasonic moulding of a miniature classical guitar, incorporating a wide range of geometric features. The successful manufacturing of the miniature mould cavity was achieved based on process planning in two iterations and the exhaustive consideration of factors such as cutting tool geometry selection, minimum feed per tooth, radial depth of cut, axial depth of cut, feed rate, in and out tolerances, and type of interpolation. The quality of the mould cavity was measured through silicone replicas of the miniature guitar. In general terms, good surface finish and geometric definition was obtained. In a randomly located set of geometric features, the dimensional error was below 5% for most features (32 out of a total of 40).

Based on the successful process plan for micro-milling for a miniature mould cavity, the following specific conclusions can be drawn:

- The geometry of the miniature mould cavity should be segmented in order to have several CNC programs and achieve better geometric definition.

- The use of roughing and finishing phases, together with micro ball-nose and flat end mills in several sizes, helps in reducing complexity of some CNC programs.

- Feed per tooth should be kept to a minimum of 30% relative to the tool edge radius.
- Radial depth of cut should be 50% in order to avoid thinning of the chip thickness.
- Feed rate should be monitored in order to avoid rounding of corners associated to servo following error.
- Chordal tolerance should be between 1 and 3 μm
- Circular interpolation gives better surface finish than linear interpolation

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Chapter 10. Swarm intelligent selection and optimization of machining system parameters for microchannel fabrication in medical devices.

Chapter 10 presents a multicriteria decision making for material and process parameters selection for response variables by using particle swarm optimization (PSO) method. The dimensional accuracy and the surface roughness are the main responses studied.

This study was presented in an article entitled "Swarm intelligent selection and optimization of machining system parameters for microchannel fabrication in medical devices", published by Materials and Manufacturing Processes in April 2012 (Vázquez *et al.*, 2012).

Vázquez, E., Ciurana, J., Rodriguez, C. A., Thepsonthi, T., & Özel, T. (2011). "Swarm intelligent selection and optimization of machining system parameters for microchannel fabrication in medical devices". *Materials and Manufacturing Processes*, 26(3), 403-414

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Abstract

Current technology trends in medical device industry calls for fabrication of massive arrays of microfeatures such as microchannels on to nonsilicon material substrates with high accuracy, superior precision, and high throughput. Microchannels are typical features used in medical devices for medication dosing into the human body, analyzing DNA arrays or cell cultures. In this study, the capabilities of machining systems for micro-end milling have been evaluated by conducting experiments, regression modeling, and response surface methodology. In machining experiments by using micromilling, arrays of microchannels are fabricated on aluminium and titanium plates, and the feature size and accuracy (width and depth) and surface roughness are measured. Multicriteria decision making for material and process parameters selection for desired accuracy is investigated by using particle swarm optimization (PSO) method, which is an evolutionary computation method inspired by genetic algorithms (GA). Appropriate regression models are utilized within the PSO and optimum selection of micromilling parameters; microchannel feature accuracy and surface roughness are performed. An analysis for optimal micromachining parameters in decision variable space is also conducted. This study demonstrates the advantages of evolutionary computing algorithms in micromilling decision making and process optimization investigations and can be expanded to other applications.

Keywords

Medical device; Microchannels; Micro\-end milling; Particle swarm optimization

Chapter 11. Conclusions and outlook.

Chapter 11 presents the conclusion of the Thesis, summarizes the main contributions presented and points out possible further works arising from the research exposed. The list of publications is presented at the end of this chapter.

11.1 Conclusions

The focus of this Thesis is to take advantage of the knowledge of macro-milling and micro-milling to improve the performance of the micro-milling process in order to achieve manufacture micro-products using a conventional CNC machine.

For this reason the issues worked in this Thesis includes as first approach an experimental analysis that allows the characterization of the process understanding the relations between the process parameters and machining conditions on response variables (accuracy, surface finishing and geometric shape). Chapter 3 and Chapter 4 worked with a simple geometry (micro-channel) using different materials such as: aluminium, copper, stainless steel and titanium alloy.

The work carried out in Chapter 3 and Chapter 4 has led to the following conclusions:

- These studies find better results when micro-channels were carried out in aluminium compared with copper.
- In aluminium and stainless steel workpiece, the average micro-channel width better controlled using higher feed rates.
- In all materials the use of coolant provides better results in terms of micro-channel bottom surface roughness.

The Chapter 5 presents a similar study employing micro-cavities as final shape desired. This study would be the basis for the following analysis. In Chapter 6, is developed a more in-depth analysis evaluating the machine tool motion carrying out elliptical cavities and applying the theoretical principles.

The significant findings of these studies can be summarized:

- The results suggest that accuracy and final shape are mainly influenced by feed per tooth and coolant.
- In general, using lower values of feed per tooth generate better results.
- Accuracy and final shape are affected by the dynamics of machine tool. At a micro-scale, accelerations and decelerations are significant and cannot be assumed to be negligible, as is the case of macro-scale. Results suggest that accuracy and final shape are mainly influenced by feed per tooth.

The machining conditions are also studied through the analysis of the influence of the cooling and lubrication on micro-milling of Ti6Al4V. Chapter 7 and Chapter 8 present experimental work and the study of the effect of flow of cutting fluid through Computational Fluid Dynamics (CFD).

According to Chapter 7 and Chapter 8 these are the significant findings:

- The experimental results, it was found that the MQL technique offers better results on the basis of accuracy, tool wear, surface roughness, burr formation and geometric shape. The explanation is founded by CFD analysis.
- Computational fluid dynamics analysis indicates that jet application in the context of the micro-scale cause a disordered flow, shown as higher values of entropy, and not reaches the desired target in this case the tool tip.

Once understanding the relations between process parameters as well as machining conditions and quality of the final micro-pieces with simple geometries, the next step, presented in Chapter 9, is to produce a micro-product using complex 3D geometries and proposes a planning process in order to reach this goal.

Based on the successful process plan for micro-milling for a miniature mould cavity, the following specific conclusions can be drawn:

- The geometry of the miniature mould cavity should be segmented in order to have several CNC programs and achieve better geometric definition.
- Feed per tooth should be kept to a minimum of 30% relative to the tool edge radius.
- Radial depth of cut should be 50% in order to avoid thinning of the chip thickness.

Moreover a multi-objective optimization models are used for selecting the proper process parameters combination for getting the best results in several responses. In Chapter 10, Experimental models based on quadratic regression are developed for surface roughness and cross-sectional geometry error. An evolutionary computational approach (PSO) is applied to the decision making problem in micro-machining parameters.

Regarding to Chapter 10 the significant conclusion is:

- MOPSO provides Pareto frontiers of nondominated solution sets for optimum micro-milling process parameters, providing a resourceful and efficient means to the decision maker.

With the knowledge provided by these studies the state of the art of the micro-milling process is enhanced and enriched. In addition, proves the capacity of the conventional machines to produce micro-products with complex geometries ensuring acceptable accuracy and surface quality.

11.2 Main contributions

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

- The effect of key process parameters on the dimensional accuracy, geometric feature and surface roughness have been investigated for micro-milling on aluminium, copper, stainless steel and titanium alloy using micro-channels and micro-cavities as desired geometries.
- The characterization of the radial error using a CNC machine instead of specialized machine or in-house micro machine centre in the micro-milling process. Furthermore, this methodology is a practical solution replacing expensive commercial solutions such as laser interferometer, double ball bar, laser Doppler vibrometers.

- A multi-objective particle swarm optimizer for micro-channels by micro-milling. It provides Pareto frontiers of non-dominated solution sets for optimum micro-milling process parameters, providing decision makers with a resourceful and efficient means of achieving it.

- Successful process plan for micro-milling for a miniature mould cavity using complex 3D geometry. The methodology can be applied to process planning of complex miniature mould cavities with micro geometric features up to 120 μm.

- The effect of cooling and lubrication conditions on tool wear, burr formation, accuracy and surface roughness for micro-milling on Titanium alloy Ti6Al4V considered as difficult-to-machine

- Computational Fluid Dynamics analysis for cooling and lubricating conditions for micro-milling on Titanium alloy Ti6Al4V was performed and validated with experimental work.

11.3 Further work

In this section shows suggested future work to continue in research of micro-manufacturing technologies.

- Testing of micro-milling for other materials commonly used for biomedical applications such as polymers (i.e. PEEK).

- Improve micro-tools in order to reduce premature tool failures.

- Research on flexible and economical sensing methods for monitoring and controlling the micro-milling process.

- Integrated approach to design and machining of micro-milling.

- CAD/CAM system must be optimized to support the micro-milling requirements (Micro-stocks, close tolerances, optimized milling strategies).

11.4 Thesis results

The following list contains the publications presented as chapters of this PhD thesis.

Vázquez, E., Rodríguez, C. A., Elías-Zúñiga, A., & Ciurana, J. (2010). An experimental analysis of process parameters to manufacture metallic micro-channels by micro-milling. The International Journal of Advanced Manufacturing Technology, 51(9-12), 945-955.

Vázquez, E., Gómez, X., & Ciurana, J. (2012). An experimental analysis of process parameters for the milling of micro–channels in biomaterials. International Journal of Mechatronics and Manufacturing Systems, 5(1), 46-65.

Amaro, A., Gomar, J., Vázquez, E., Ciurana, J., & Rodríguez, C. (2012). Experimental Analysis of Process Parameters to Manufacture Micro-Cavities by Micro-Milling. Advanced Materials Research, 498, 91-96.

Vázquez, E., Gomar, J., Ciurana, J., & Rodríguez, C. (2014). Evaluation of the machine-tool motion accuracy using a CNC machining centre in micro milling processes. Accepted in International Journal of Advanced Manufacturing Technology. DOI: 10.1007/s00170-014-5787-6

Vázquez, E., Gomar, J., Ciurana, J., & Rodríguez, C. (2013). Analyzing effects of cooling and lubrication conditions on micro-milling of Ti6Al4V. Submitted in Materials and Manufacturing Processes Journal/ LMMP-2013-0826.

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Vázquez, E., Amaro, A., Ciurana, J., & Rodríguez, C. (2013) Process planning considerations for micro-milling of mould cavities used in ultrasonic moulding technology. Submitted in Precision Engineering/ PRE-S-13-00310

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Additional relevant publications but not included as chapters:

Books:

Vázquez, E., de Ciurana, Q., & González, C. Á. R. (2010). *Micro-machining Technologies for Micromechanical Components*. Girona, España. Universitat de Girona. Servei de Publicacions. ISBN: 9788492707331

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Gomar, J., Amaro, A., Vázquez, E., Ciurana, J., Rodríguez, C. (2011) Micro-machining of 3D geometries for medical applications. 4th Manufacturing Engineering Society International Conference (MESIC 2011). Cádiz, España.

Gurguí, D., Vázquez, E., Ferrer, I. (2013) Influence of the Process Parameters to Manufacture Micro-cavities by Electro Discharge Machining (EDM). 5th Manufacturing Engineering Society International Conference (MESIC 2013). Zaragoza, España.

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