Machining of ceramics and ecological steels using a mill-turn centre equipped with an ultrasonic assisted tooling system

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Abstract

Today, there is a large demand for the machining of simple and/or complex shaped components made of difficult to cut materials such as ceramics. Recently, there is also a demand to machine new type of steels, having restrictions in chemical composition (e.g. lead and sulphur free) in order to comply with recent governmental EU regulations. This paper first describes on-going and planned research activities on the machining (turning) of these advanced materials. For the machining of various ceramic materials, an ultrasonic assisted tooling system has been designed, manufactured and integrated within the available Mori Seiki NL2000Y/500 mill-turn centre. The developed system has been tested through initial machining experiments on aluminium and ZrO_2. Second, this paper also briefly describes other on-going and planned research and education activities in which the Mori Seiki NL2000Y/500 is involved. It includes advanced NC-programming of multi-axis machine tools, energy efficient machining of ecological steels and the development of training programs for 3rd years mechanical engineering students.

Keywords: Ultrasonic Assisted Machining, Tool path generation, ceramics

1 INTRODUCTION

Manufacturing industries are nowadays facing new challenges in the machining of difficult to cut materials. These materials include various ceramic materials such as ZrO_2, Al_2O_3, B_4C, SiC,.. and also steels with a strong reduction of hazardous elements such as lead or sulphur.

Ceramic components find their applications where high hardness and good resistance against heat, chemicals, erosion and wear are required. Today the most common manufacturing processes used to machine these ceramic materials (in their final state) are grinding and Electrical Discharge Machining (EDM). Compared to grinding, NC-controlled Wire EDM, die sinking EDM as well as milling EDM allow to machine complex ceramic shapes in one set-up [1]. EDM is however only feasible under the condition that the ceramic has a maximum electrical resistivity of about 1 Ωm. To obtain a certain electrical conductivity, second phases are added such as TiN, WC or TiCN, which result in so called ceramic composites.

Ultrasonic assisted machining is another process which is gaining industrial interest for the machining of ceramic components. In ultrasonic assisted machining, a small amplitude vibration (f ~ 15…40 kHz) is added to the tool movement. Quite some research efforts are done in the area of ultrasonic assisted turning (UAT). Literature reports about several systems generating vibrations either in one direction (1D) or even in two directions (2D) [2,3]. Ultrasonic assisted turning (UAT) has several advantages such as diamond turning of ferrous materials, ductile machining of brittle and hard materials (with a higher critical depth of cut) and in general lower cutting forces [4,5].

Since 2006, the K.U.Leuven research group (Lauwers) started research on multi-axis ultrasonic assisted grinding (ÚAG) of ceramic components. This process allows to machine complex shapes similar to conventional multi-axis milling. As there is also a demand from the regional industry to machine ceramic parts with an overall axi-symmetric shape, it has been decided to start research on ultrasonic assisted turning at K.U.Leuven. This objective is also supported by the aim that it will generate knowledge about ultrasonic assisted turning, a process where tools are used with a defined cutting edge. At present, the research results on the UAG equipment at K.U.Leuven, are not always straight forward, due to several reasons: generation of an ultrasonic vibration is limited (most often a maximum amplitude of about 1 µm is generated) and not repeatable. In addition, the grinding process in itself is more complex (compared to processes based on a defined cutting edge), because there are quite some influencing parameters, which makes it often difficult to draw clear conclusions (e.g. influence of tool wear on material removal mechanism, surface roughness).

This paper describes first the development of an ultrasonic tool holder system which has been integrated within a 4-axis turn-mill centre (Mori Seiki NL2000Y/500). Next, other on-going and planned research and educational activities in which the Mori Seiki NL2000Y/500 is involved, are described. This includes research on advanced tool path generation for multi-axis machine tools, development of education programs for mechanical engineering students and the energy efficient machining of ecological steels.

2 DEVELOPMENT OF AN ULTRASONIC ASSISTED TOOL HOLDER SYSTEM

2.1 Specifications and design

Based on a detailed literature review and the experiences obtained in ultrasonic assisted grinding, it was decided that a maximum amplitude of 10 µm within a frequency range of 18 tot 40 KHz should be sufficient. In addition to these mean specifications, the following was stated:

- The ultrasonic tool holder system should be able to generate vibrations in different directions (cutting direction, feed direction,…).
- The system should be robust, flexible and easily to be integrated within the Mori Seiki NL2000Y/500.

- Generated vibrations may not influence the machine tool
- Machining should be possible with and without vibration.
- The system should be resistant against environmental conditions such as cooling and chips.

For reasons of simplicity and time constraints, it was opted to design an ultrasonic tool holder system with one directional vibration (1D). The average operating frequency has been set to 20 kHz. Figure 1 shows a general scheme to build up an ultrasonic tool holder system. It consists of an ultrasonic generator, the converter (generating the ultrasonic vibration), the booster (connection between convertor and sonotrode) and the sonotrode. A change in vibration direction will be obtained in a manual way and this by changing the sonotrode configuration (see further).

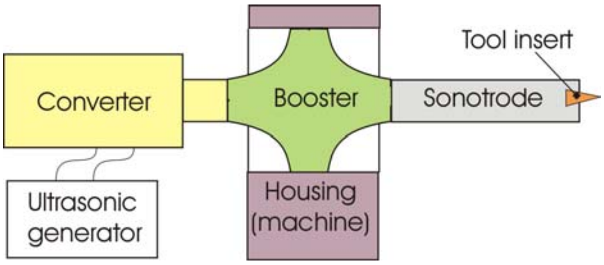


Figure 1: Schematic overview of the ultrasonic tool holder system.

In order to have a better understanding of the description of the different components, Figure 2 shows an exploded view of the final designed system.

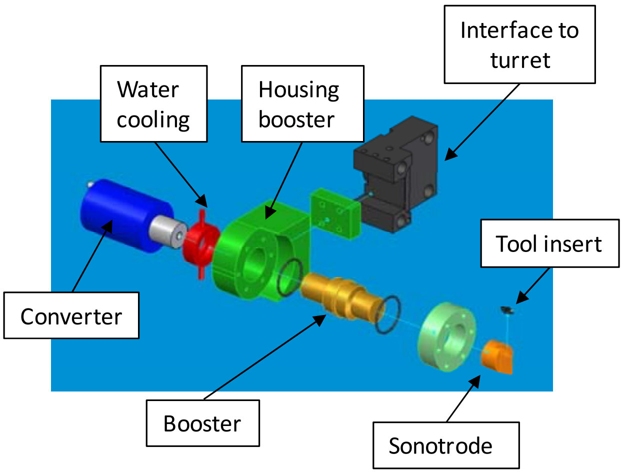


Figure 2: Exploded view of the designed ultrasonic tool holder system.

A commercially available ultrasonic generator and converter has been acquired from MPI Ultrasonics. The generator (Mastersonic, MSG.X00.OW, MMM, 600W) can generate frequencies in a large frequency domain. The so called MMM technology (Multi frequency, Multimode, Modulated) [6] allows to drive different resonating elements within a mechanical structure with high efficiency. The available PC-interface allows a user friendly control. The converter (type MPI-20kHz-3kW-MH-AC-WC) is based on piezo actuation with maximum input power of 3KW. Connections for water cooling are foreseen.

The booster is used to transfer (with or without amplification) signals from the converter to the sonotrode. Within this design, an amplification factor of 1 is selected. Typical materials chosen for booster components are titanium (used in case of high frequency ranges) and aluminimum (lower frequency ranges and prototypes). Within this design, aluminium (6000 series) has been selected.

Important in booster design is to make sure that the connection towards the machine is made at a non-vibrating position (node). Different designs have been made and simulated by FEM in order to check the mode shapes at resonance. Figure 3 shows the booster design and a detail of the connection within the housing part. The housing part is then connected via an interface element to the turret of the machine. Figure 4 shows the FEM simulation of the booster design. The resonance frequency of this component is 19,8 kHz. The connection element towards the housing is positioned at a node.

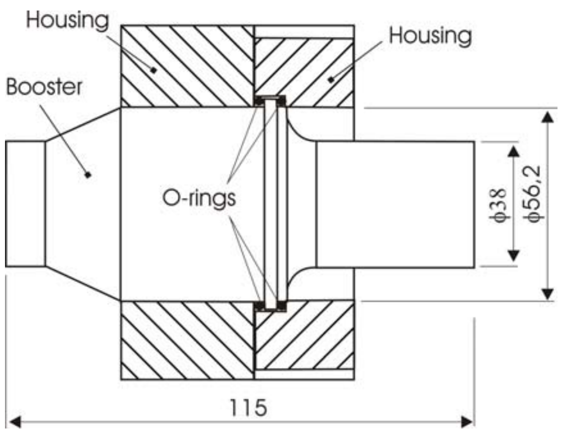


Figure 3: Booster design and integration within the housing.

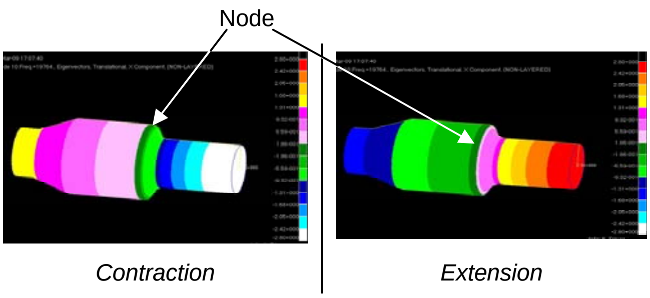
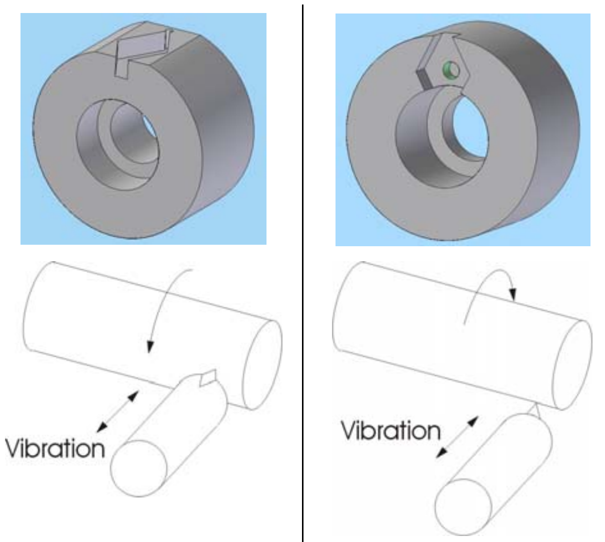


Figure 4: FEM analysis of the booster design.

The sonotrode should be designed as such that it has his resonance frequency in the same range as the booster. Therefore, the length of it should be in the same order of the booster or it should be very short, so the influence of it is negligible. Within this research, a short sontrode was chosen in order to have a more compact system. Two designs have been proposed in order to have a "manual" change of the vibration direction in respect to the cutting speed direction (Figure 5).



Vibration perpendicular to cutting speed direction | *Vibration along cutting speed direction*

Figure 5: Different sonotrode designs to obtain different vibration configurations

2.2 Manufacturing and integration of the tool holder system

The different components (except the converter and the generator) has been produced in house, partially using the available Mori Seiki NL2000Y/500. Figure 6 shows the implementation of the system into the machine. Cooling of the piezo-driven convertor is performed using the available cooling channels of the machine.

Figure 6: Implementation of the ultrasonic tool holder system within Mori Seiki NL2000Y/500.

2.3 Tool holder performance

The tool holder performance has been measured using maximum power of the generator (= 600W). The vibration amplitude at the tool tip has been measured using an Eddy Current sensor. Figure 7 shows the evolution of this amplitude for different frequency values. The highest amplitude is measured at a frequency of about 17600 Hz.

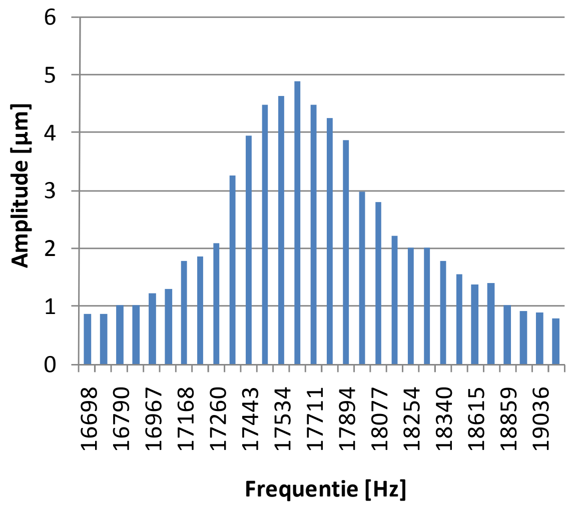


Figure 7: Measurement of tool tip amplitude as a function of the frequency.

3 ULTRASONIC ASSISTED TURNING: EXPERIMENTS

In order to test the tool holder system, first machining experiments have been machined on aluminium (Ø: 65 mm). Different samples are machined by cylindrical turning by varying the cutting speed and by setting the ultrasonic vibration on or off (vibration perpendicular to cutting speed). The cutting depth has been set to 400µm and the feed rate to 300µm/rotation. For each sample, the surface roughness profile has been measured along the part axis (using Taylor Hobson equipment). Based on the surface profile, an estimation of the vibration frequency and the amplitude is made. For example, Figure 8 shows the surface roughness profile for a sample machined with a cutting speed of 300m/min. The profile shows a wave length of 3,6mm, which corresponds to a frequency of 17998 Hz.

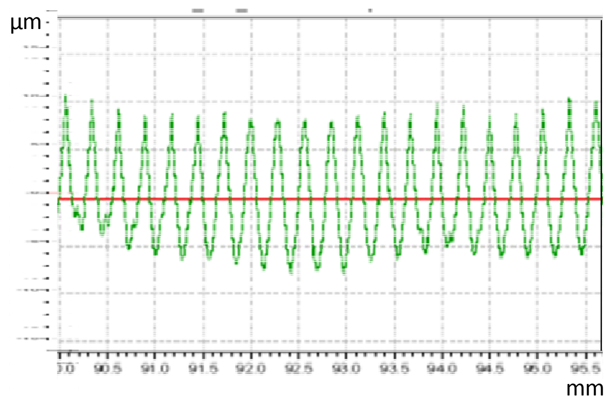


Figure 8: Measured surface roughness profile (v_c: 300m/min)

Table 1 shows the results (roughness Ra, frequency, estimation of vibration amplitude) for different settings of the cutting speed and with or without vibration. The ultrasonic vibration results in higher surface roughness. Under these conditions, the process can be seen as texturing.

Table 1: Experimental results.

	v_c [m\min]	Ra [µm]	F [Hz]	Amplitude [µm]
C	10	0,55	-	-
U	10	1,07	18530	1,8
C	75	0,76	-	-
U	75	1,08	18319	3
C	150	0,59	-	
U	150	0,98	17998	5,5
C	300	0,52	-	-
U	300	3,75	17998	8
C	900	0,60	-	-
U	900	2,04	17390	4,25

C: classical (no vibration) / U: ultrasonic vibration

Next to aluminium, additional machining tests were performed on ZrO_2. Sintered cylindrical parts of ZrO_2 (Ø: ~ 65 mm, length: 30 mm) were mounted on cylindrical aluminium bar for easy clamping. As there is not much known yet about the machining of this material, initial settings were chosen as follows: v_c: 200 m/min, feedrate: 10µm/min, a_p: 10µm. At present, not much experiments could be performed. Planned research includes further testing of the ultrasonic tool holder system for the machining of various ceramic materials.

4 OPTIMISED TOOL PATH GENERATION FOR MULTI-AXIS MACHINE TOOLS

4.1 Tool path generation by minimization of tool rotary movements

The efficient NC-programming of multi-axis machine tools is known to be very hard and time consuming. The way a part is machined is not unique and the efficiency of several strategies is often difficult to estimate without computer support. New methodologies and concepts for tool path planning and generation for multi-axis milling of complex shaped surfaces/components are being worked out at K.U.Leuven. The multi-axis machine tool itself has an important influence on the machining performance. Due to differences in speed and the acceleration profiles of linear and rotary axis, the way a part (e.g. complex shaped surface) is machined can strongly influence the machining time.

Tool path evaluation algorithms, taking into account the machine dynamics (acceleration and speed profiles) have been already presented in last years MTTRF paper [7]. It was shown that for the machining of complex shaped surfaces, a machine based estimated machining time for operations planning is much more accurate, certainly compared to for example an estimated machining time based on tool path length and a programmed feed.

During last year, new tool path generation algorithms have been developed for the machining of complex shaped surfaces using multi-axis machine tools. This research work has been carried out in the frame of the on-going EU-project NEXT (www.nextproject.eu). Optimisation is based on a minimisation of the rotary movements (which are often slower compared to the linear axes).

The developed algorithm works as follows. After the selection of a machining strategy (e.g. zig, zig-zag), the machining of a complex shape consists of tool path tracks. At present, the optimisation is performed on track level. In each tool contact point, a range of gouge free tool posture is proposed. This means that a tool posture is defined by the tool contact point and a range of inclination angles (Figure 9). The range of inclination angles can be represented as an arc within the workpiece coordinate system. The minimum gouge free inclination angle is being defined for maximum material removal, while a maximum gouge free inclination angle can be set by the user (e.g. 45°).

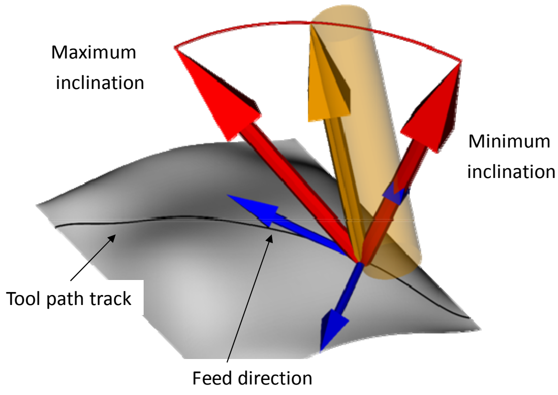


Figure 9: Optimized tool posture with a given range of possible inclination angles.

A tool path is now generated by finding the best inclination angles (for each tool posture) through minimization of the rotary movements of the machine tool along a tool path track. Therefore, the tool postures, together with the possible range of inclination angles, are mapped by inverse kinematics calculation to machine axes values. As an example, Figure 10 shows the change in rotary axes values based on a change in inclination angle (Figure 9).

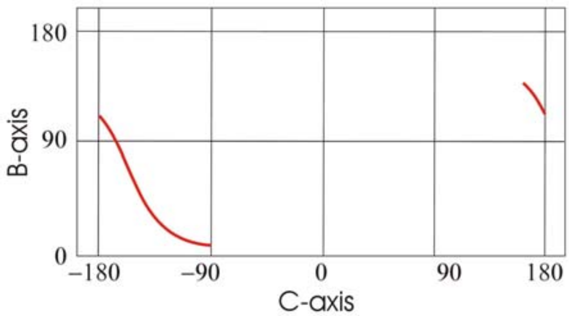
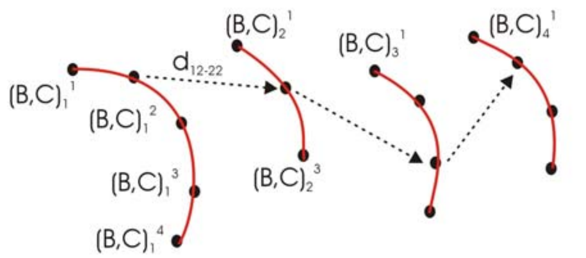


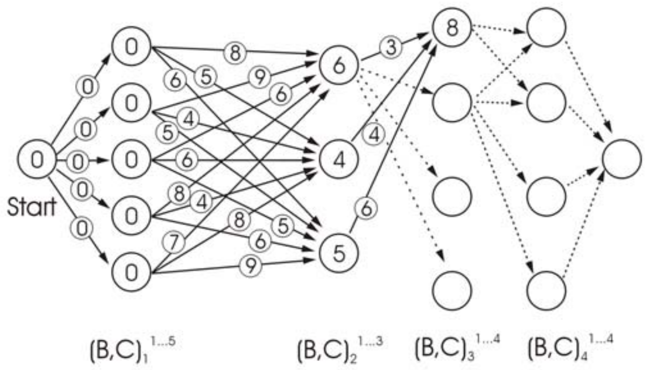
Figure 10: Representation of inclination angle range in machine axes values (change of machine axes values driving the rotary axes movements).

A "near" optimal path is now found by finding the best inclination angle for each tool posture, so the amount of rotary movements are minimized along a tool path track. The optimisation algorithm works as follows (Figure 11). For each tool posture, the given range of inclination angles is segmented into a limited set of values (e.g. every 1 degree) which are then represented in a graph. Each node in the graph represents a tool posture with a specified angle. In

Figure 11, each column of nodes in the graph is related to one tool contact point (e.g. the 1st column of nodes is related to the first tool contact point, etc,..). The links between nodes are attributed by a "distance", which is related to the amount of rotary movements required to move from one tool posture to another one. For example, Figure 11, the distance $d_{12\text{-}22}$ is the amount of rotary movements to move the tool from $(B,C)_1^2$ to $(B,C)_2^2$. The shortest path in the graph is now found by applying the Dijkstra's algorithm [8]. The procedure starts with the first node (starting node), which gets a value of zero. The nodes in the next column get a value which is related to the value in the previous nodes increased with the distance between the nodes. For example, the value of the node $(B,C)_2^2$ is calculated as the minimum of 4 values $[((B,C)_1^1 + d_{11\text{-}22}); ((BC)_1^2 + d_{12\text{-}22}); ((BC)_1^3 + d_{13\text{-}22}); ((BC)_1^4 + d_{14\text{-}22})]$. The values of the nodes in the next column are calculated in the same way. Figure 11,b explains the procedure using some arbitrary values for distances between nodes. The node in the last coloumn, having the lowest value, will define the optimal tool path by simple back tracking.



(a)



(b)

Figure 11: (a) presentation of different tool posture with range of inclination angels, (b) graph representation and finding optimal path.

The algorithm has been applied to machine a complex shaped surface shown in Figure 12. The part has been machined by a zig-strategy, on the one hand applying a constant inclination angle of 20º and on the other hand, a optimised inclination angle with minimum rotary movements. The cumulative amount of rotations are shown for both strategies. For the optimized strategy, less rotary movements are required to obtain the part with more or less the same surface quality. The higher amount of tool rotations in the non-optimized strategy are caused by large axes movements close a singular point.

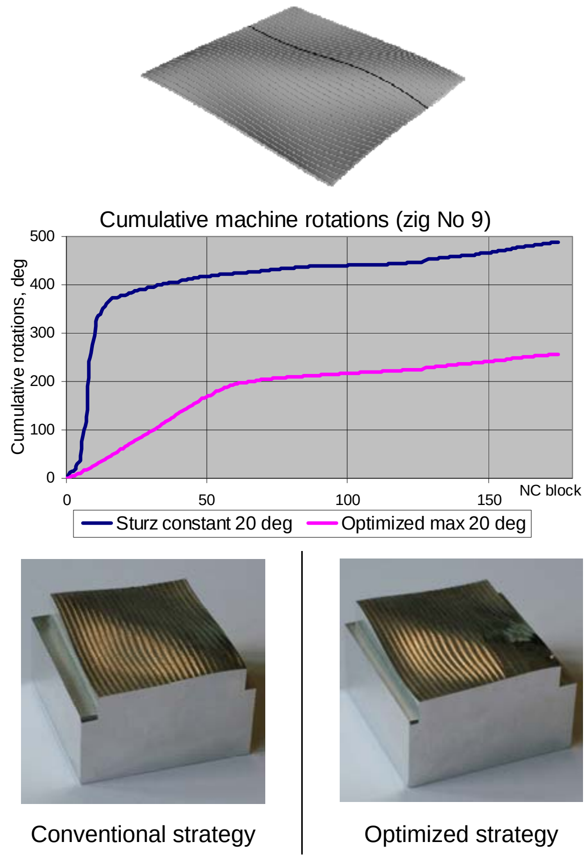


Figure 12: Machining of complex shaped surface

4.2 Planned research

Planned research includes the validation of some of the developed tool path planning and generation algorithms on the available Mori Seiki NL2000Y/500 machine. Also for this machine, parts with a number of features on different faces, can often be machined in different ways. The sequence in which the features are machined can result in different "real" machining times.

5 DEVELOPMENT OF EDUCATION PROGRAMS

The Mori Seiki NL2000Y/500 is also actively used within various education programs. Last year, a new "lab session" has been developed for 3rd years Bachelor students (mechanical engineering, 180 students) [9]9. This lab session has several objectives: introduction of NC-controlled machine tools, introduction to operations planning, part programming at the machine control and using CAM systems and finally the machining of the parts. Figure 13 shows the CAD-models of parts used within the lab session.

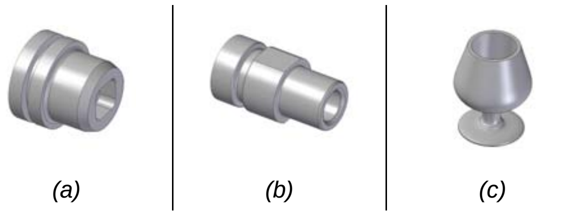


Figure 13: Part geometries used for education programs.

The parts (a) and (b) are programmed directly at the feature based machine control. These parts require turning as well as milling operations. The third part (c), a “mini DUVEL beer glass” is programmed using the available ESPRIT CAM software.

Besides the above lab session, the Mori Seiki NL2000Y/500 has also been used in other courses such as “production machines and systems” and the course “project work”.

6 PLANNED RESEARCH ON ENERGY EFFICIENT MACHINING OF ECOLOGICAL STEELS

Until now the application of innovative and environment friendly materials as well as the consideration of energy consumption during manufacturing has often been neglected [10]. Due to sharply increasing energy and raw material costs the subject of economical efficient manufacturing processes is issued like never before. For example, new EU-regulations (e.g the EU direction 2000/53/EG) force European companies to use ecological-friendly materials. All this has certainly an impact on the manufacturing of components made of these materials . As an example, tool steels with a lower amount of sulphur and lead have to be used, but they are more difficult to machine. Research (simulation, experimental investigation,..) is required for the development of process models and technology. Planned research at K.U.Leuven includes an experimental investigation of these so called ecological tool steels, to be carried out in the available Mori Seiki NL2000Y/500.

In addition, research will be performed on the calculation of energy consumption and related costs for manufacturing processes. Special attention will be given to regional SME’s, because they have to be made aware of the importance of knowing their energy foot print. Within this research, energy costs will be calculated for the above processes.

7 CONCLUSIONS

This paper described different research and education aspects in which a turn-mill centre (Mori Seiki NL2000Y/500) is being used. A large part of the research has been devoted to the design, manufacturing and integration of an ultrasonic tool holder system. The tool holder performance has been proven and initial cutting experiments have been performed. Planned research on this topic includes the development of machining technology for the machining of various ceramic materials.

In addition, work has been done on the development of advanced tool path generation algorithms for multi-axis machine tools. Innovative is the use of machine information for finding optimal tool paths. In this work, multi-axis tool paths haven been optimized through minimization of rotary axes movements. Planned research includes the validation of these algorithms (tool path planning and tool path generation on a turn-mill centre.

This paper also described the development of education programs, including topics like operations planning, part programming and real machining. Planned experimental research on the machining of ecological steels has been briefly presented.

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KATHOLIEKE UNIVERSITEIT
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Machining of ceramics and ecological steels using a mill turn centre equipped with an ultrasonic assisted tooling system

Overview of research & education activities performed on the by MTTRF provided turn-mill centre

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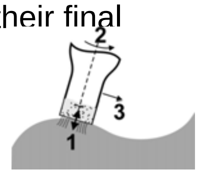
Introduction

- Overview of last years research and education activities related to the by MTTRF provided turn-mill center: Mori Seiki NL2000Y/500
  - Development of an ultrasonic assisted tool holder system
    - Objective: UAT of ceramic components !
  - Development of advanced tool path generation algorithms for multi-axis machine tools
  - Development of education programs (students 3rd Bachelor, Mechanical Engineering)

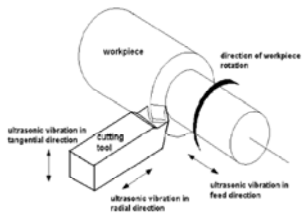
Introduction – Why UAT

- Why the development of an "Ultrasonic Assisted Tooling System" to machine ceramic materials
  - Manufacturing industry is facing new challenges in the machining of various ceramic materials such as ZrO_2, SiC,…
- Feasible technologies to machine ceramics in their final state
  - Grinding
    - Conventional grinding is less flexible
  - EDM
    - Material should be electrical conductive
  - Ultrasonic Assisted Machining
    - Multi-axis Ultrasonic Assisted Grinding (UAG
      - Machining of complex shapes
      - Research at KULeuven started in 2006
    - Ultrasonic Assisted Turning (UAT)



Introduction – Why UAT

- UAT is not new !
  - Different systems have been developed
    - Various vibration systems: 1D, 2D
- Research objective is supported by:
  - Regional industries are interested in the machining of axi-symmetric ceramic components
  - Having a better understanding of Ultrasonic Assisted Machining using tools with a defined cutting edge

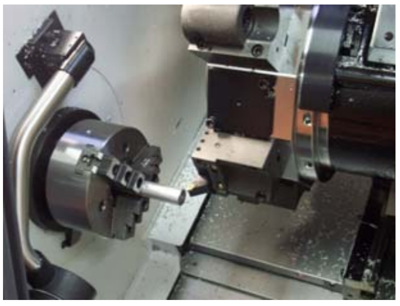


Overview

- Introduction
- Development of an ultrasonic tool holder system
  - Specifications and design
  - Manufacturing and integration
  - Tool holder performance
- Ultrasonic Assisted Turning
  - Initial experiments
  - Planned research
- Tool path generation for multi-axis machine tools
- Development of education programs
- Planned research on machining of ecological steels
- Conclusions

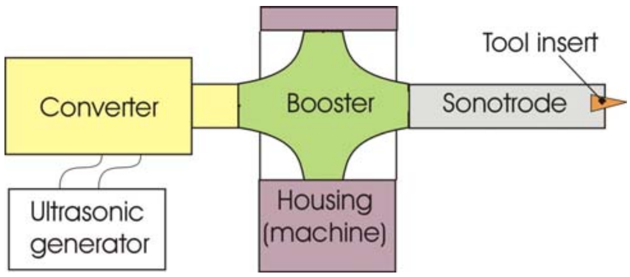
UATooling System Specifications & Design

- Specifications
  - Amplitude up to 10µm
  - Frequency range: 18..40kHz
  - Vibrations in different directions
  - Robust, flexible and easy integration within Mori Seiki NL2000Y/500
  - Isolation
  - Machining with/without vibration
  - Resistance against environmental conditions
    - Coolant
    - Chips
    - …



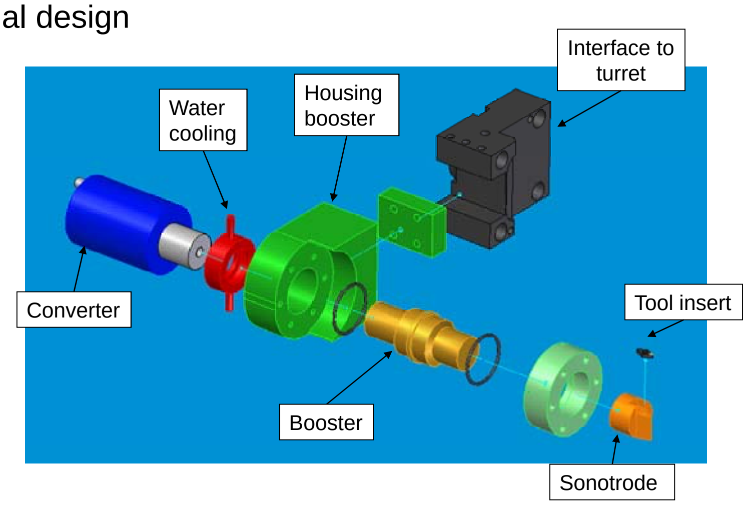
UATooling System Specifications & Design

- Vibration directions: **one** or more ?
  - One directional system has been selected
  - Average operating frequency: 20kHz
- General scheme of a one directional system



UATooling System Specifications & Design

- Final design

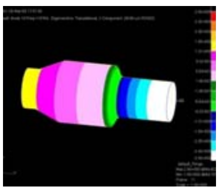


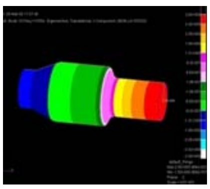
UATooling System Specifications & Design

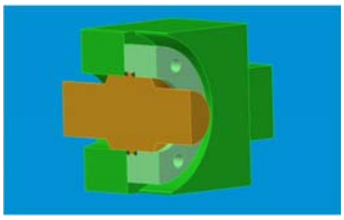
- Generator
  - Mastersonic (commercial)
  - MMM technology (patented)
  - Max. Power: 600W
- Converter
  - Piezo-actuated
  - Max. 3KW
  - Water cooled

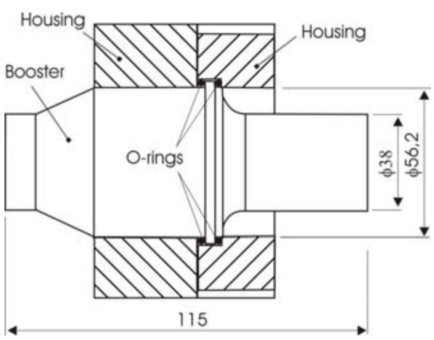
UATooling System Specifications & Design

- Booster
  - Amplification factor (gain): 1
  - Possible materials
    - Titanium
    - Aluminium (lower frequencies, prototypes,..)
  - Connection to the housing
  - FEM simulation
    - Resonance: 19,7 kHz



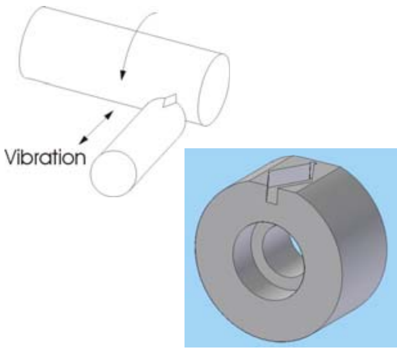


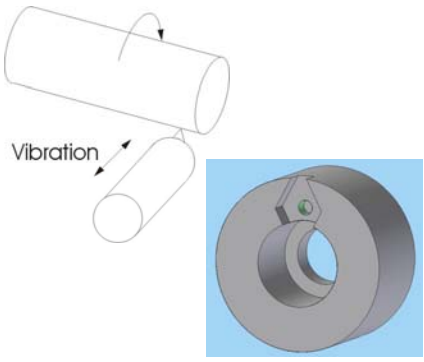




UATooling System
Specifications & Design

- Sonotrode
  - Short length has been choosen (compact design)
  - Two different versions for changing the vibration direction compated to the cutting speed direction





UATooling System
Manufacturing & Integration

- In house manufacturing by a team of students

UATooling System Manufacturing & Integration

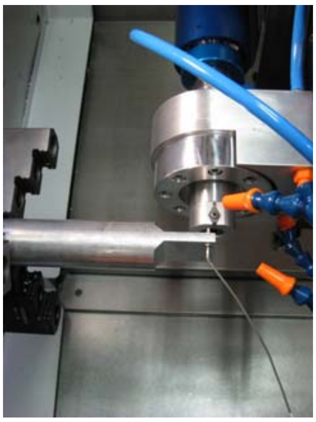
- Integration within the Mori Seiki NL2000Y/500

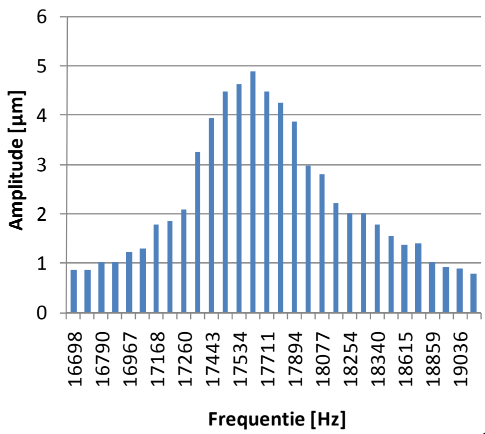
Generator within the machine tool cabinet

PC control of ultrasonic generator

UATooling System Manufacturing & Integration

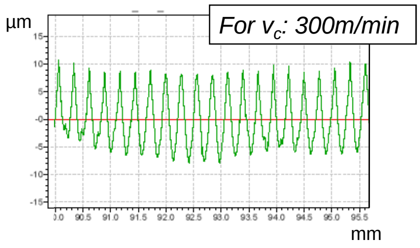
- Tool holder performance
  - Amplitude meausered with Eddy Current Sensor





UAT – Initial Experiments

- Initial experiments on aluminium
  - Test of ool holder system
  - Conditions
    - ∅ 65mm, a_p: 400µm, f: 300 µm/rotation
    - Ultrasanic on/off
    - Different v_c
  - Estimation of frequency and amplitude based on surface roughness profile
    - Frequency: 17998 Hz
    - Amplitude: ~



	v_c [m\min]	Ra [µm]	f [Hz]	Ampl. [µm]
C	10	0,55	-	-
U	10	1,07	18530	1,8
C	75	0,76	-	-
U	75	1,08	18319	3
C	150	0,59	-	-
U	150	0,98	17998	5,5
C	300	0,52	-	-
U	300	3,75	17998	8
C	900	0,6	-	-
U	900	2,04	17390	4,25

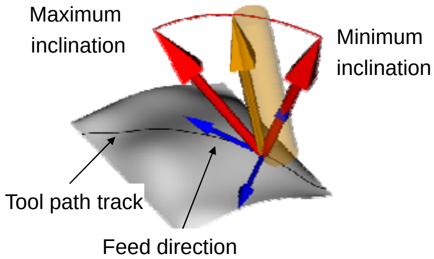
C: classical (no vibration) / U: ultrasonic

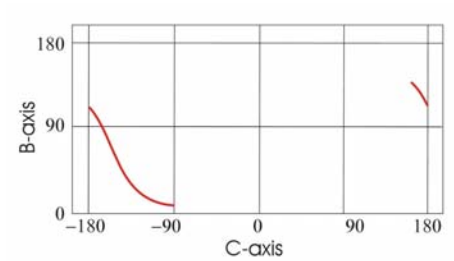
UAT – Planned research

- A few machining experiments on ZrO_2 has been performed.
- Planned research:
  - Further testing of ultrasonic tool holder system
  - Development of process technology for well known ceramic materials
    - ZrO2, SiC,..
    - In co-operation with industry

Tool path generation for multi-axis machine tools

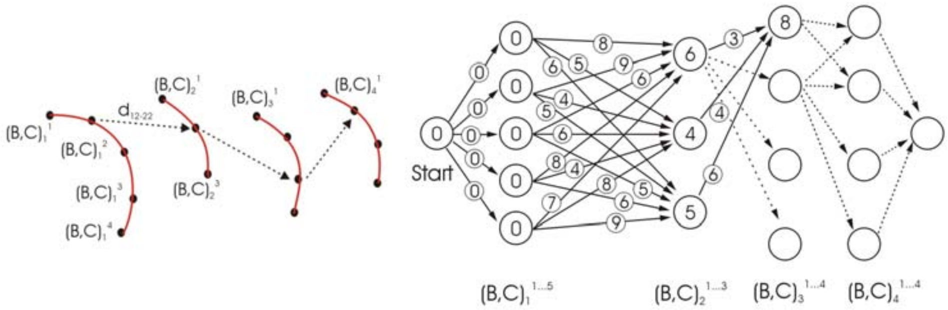
- Tool path generation by minimizing the number of rotary movements of the machine tool
  - In each tool contact point → tool posture defined by the tool contact point and a range of possible inclination angles
    - Minimim gouge free inclination
    - Maximum inclination angle
  - Transformation of tool posture to machine axis values



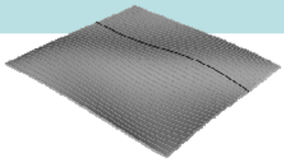


Tool path generation for multi-axis machine tools

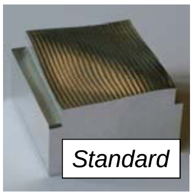
- Optimised tool path (track by track) by finding the best inclincation angles so the amount of rotary movements is minimized
  - Transformation of tool postures into a graphe
  - Finding optimal solution by applying Dijkstra's algorithm

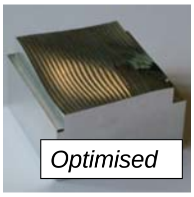


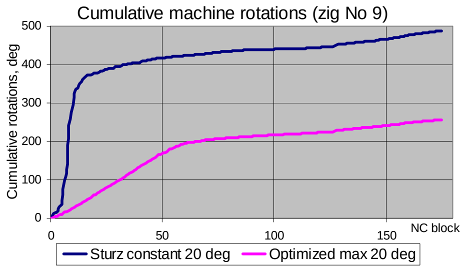
Tool path generation for multi-axis machine tools



- Results
  - Both strategies result in more or less the same surface quality



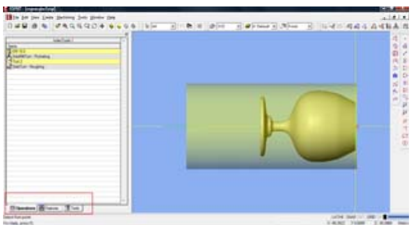




- Planned research
  - Further development of tool path planning and generation algorithms
  - Validation of some algorithms on the 4-axis turn-mill centre

Development of education programs

- The Mori Seiki NL2000Y/500 is used in several education programs
- Lab session developed with the following objectives
  - Introduction to NC-controlled machines
  - Introduction to operations planning
  - Part programming
    - At machine control
    - Using ESPRIT CAM system



Energy efficient machining of ecological steels

- Today
  - Innovative and environment materials as well as the consideration of energy consumption often neglected
  - New EU regulations related to ecological materials are comping up
- Planned reserach (to be performed on Mori Seiki NL2000Y/500)
  - Experimental investigation of the machining of these materials
  - Research on development of methods to calculate the energy consumption of manufacturing processes
  - Find ways to reduce the energy consumption

Conclusions

- Ultrasonic Assisted Turning
  - A ultrasonic tool holder system has been developed and implemented
  - Initial experiments performed
  - Planned research aims the development of process technology for the machining of ceramic materials
- Multi-axis tool path planning & generation
  - New tool path generation algorithm developed which minimizes the amount of rotary axes
  - 100% time reduction
  - Validation on 4-axis turn-mill centre planned for the next research period
- Education programs developed
  - Followed by about 180 students !
- Research on energy efficient machining of ecological steels will be start-up

Publications, Presentations & Dissemination

- As the UAT tool holder is just implemented, publications are planned for the next research period
- Presentations
  - B. Lauwers, Shaping of Ceramics by Electrical Discharge Machining (EDM) and Ultrasonic Assisted Machining: Chances and Limits, Technology Day at Berliner glass, 23/04/2009, Berlin
- Course books
  - B. Lauwers, J.P. Kruth, Lab session “Multi task machining and process planning”
- Various visits to K.U.Leuven

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- MPI Ultrasonics
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