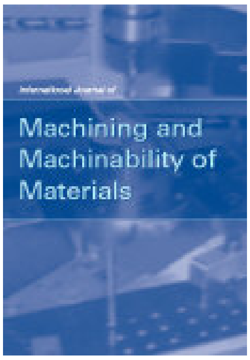

International Journal of Machining and Machinability of Materials

ISSN online: 1748-572X - ISSN print: 1748-5711
https://www.inderscience.com/ijmmm

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Amir Baraati, Hélder Morais, Ricardo Torcato

DOI: 10.1504/IJMMM.2024.10061015

Article History:

Received:	14 April 2023
Last revised:	21 August 2023
Accepted:	26 August 2023
Published online:	18 March 2024

Data analysis and optimisation of cutting parameters for CNC rotary grinding of a crystal glass

Amir Baraati*

School of Design, Management and
Production Technologies Northern Aveiro,
University of Aveiro, Portugal
and
FEUP – Faculty of Engineering of the University of Porto, Portugal
Email: a.baraati@gmail.com
*Corresponding author

Hélder Morais

School of Design, Management and
Production Technologies Northern Aveiro,
University of Aveiro, Portugal
Email: heldermorais@ua.pt

Ricardo Torcato

School of Design, Management and
Production Technologies Northern Aveiro,
University of Aveiro, Portugal
and
EMaRT Group – Emerging Materials, Research, Technology, Portugal
and
CICECO Aveiro – Institute of Materials,
University of Aveiro, Portugal
Email: ricardo.torcato@ua.pt

Abstract: Change fuelled by digitisation, mobilisation, augmentation, disintermediation, automation is a science fact. Manufacturing as a business is reinvented by digital transformation and becomes extremely valuable, predictable and desirable. Machining and finishing complex geometries of crystal glasses in industry at a mass production level with consideration of sensitivity analysis of crystal part material has been interesting, and academic institutions have been pioneers in investigating research activities related to developing, optimising, and measuring the process, cutting parameters, and final geometry. In this study, conventional grinding and ultrasonic assisted grinding process with the same cutting tools, have been compared and determined the optimum cutting parameters with minimum cutting forces for achievement minimum surface roughness. Optimisation was focused on the mechanical characterisation and analysis of the cutting forces in CNC machining of superior crystal glass ($Pb \geq 30\%$). Finally, data analysis of trends to find the correlation and coincidence between theory and experiments has been done.

Keywords: CNC machining; crystal glass; performance measurement; optimisation.

Reference to this paper should be made as follows: Baraati, A., Morais, H. and Torcato, R. (2024) 'Data analysis and optimisation of cutting parameters for CNC rotary grinding of a crystal glass', *Int. J. Machining and Machinability of Materials*, Vol. 26, No. 1, pp.38–57.

Biographical notes: Amir Baraati received his Bachelor's degree from Buali-Sina University, and Master's degree from Azad University in Iran. He has solid experience in design and manufacturing with many international companies like: Siemens, VAI, SMS-siemag, Danieli, Sino steel, SDM. Since 2020 he has joined to the Faculty of Engineering of University of Porto in Portugal as a PhD student and a researcher. Currently, he is collaborating with ESAN institution in Oliveira de Azemeis in Portugal. His research interest is data analysis of industrial data.

Hélder Morais is a Senior Technician in the School of Design, Management and Production Technologies North Aveiro, with a Master's degree in Product and Digital Technology from this place, with a dissertation on setting parameters and cutting strategies for machining crystal glass. The skills developed during his lifework and master thesis allows him to effectively support in jobs related with additive and subtractive manufacturing (CAD, CAM), provide support in R&D and innovation projects in collaboration with companies carried out in that institution and gives support in practical courses in the Workshop of that place.

Ricardo Torcato is an Adjunct Professor of University of Aveiro, with professional and scientific activity in the areas of product development, material selection and production systems. He has industrial experience in design methods and manufacturing processes of moulds for plastic injection. He is currently Vice-Director of the Master's degree in Product and Digital Technology and Professor of disciplines in the areas of product design, manufacturing technologies and CAD and CAM modelling.

This paper is a revised and expanded version of a paper entitled 'Cutting parameters optimization for CNC rotary ultrasonic grinding of a crystal glass' presented at CARV 2023 9th Changeable, Agile, Reconfigurable and Virtual Production Conference, Alma Mater Studiorum – University of Bologna, 20–23 June 2023.

1 Explore

1.1 Introduction

There are two main practical problems that engineers face in a manufacturing process. The first is to determine the values of the process' parameters that will yield the desired product quality (meet technical specifications) and the second is to maximise manufacturing system performance using the available resources. The decisions made by manufacturing engineers are based not only on their experience and expertise but also on conventions regarding the phenomena that take place during processing. In the machining field, many of these phenomena are highly complex and interact with a large number of factors, thus preventing high process performance from being attained. To overcome these problems, the researchers propose models that try to simulate the conditions during machining and establish cause and effect relationships between various factors and desired product characteristics. Furthermore, the technological advances in the field, for instance the ever-growing use of computer-controlled machine tools, have brought up new issues to deal with, which further emphasise the need for more precise predictive models (Benardos and Vosniakos, 2003).

Both ductile and brittle materials can be machined by this process, but the material removal is different in both the cases, i.e., by Ductile fracture and Brittle fracture respectively. When it comes to brittle materials, conventional machining processes cannot be used due to a number of limitations of the material. Thus, non-conventional machining is a rather preferable choice for brittle materials (Shanmugam et al., 2022).

In the grinding process as well as in internal grinding, the grinding wheel is gradually worn. In addition, some metal chips may adhere to the wheel surface. This results in the reduction in the cutting ability, the increase in the cutting forces and vibrations and, as a result, reduces the surface quality (Huu and Muthuramalingam, 2021).

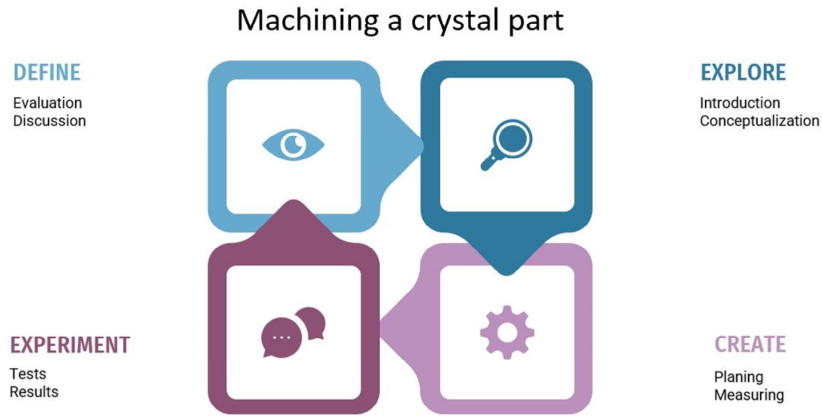
The vibration can effectively re move the chip release to enhance the machining stability. It improves the productivity and the machining quality in the EDM process. The vibration can effectively remove the chip release to enhance the machining stability. It improves the productivity and the machining quality in the EDM process. The mechanism of the electrical discharge machining (EDM) process can be enhanced by incorporating vibration in the machining process. The vibration can effectively remove the chip release to enhance the machining stability. It improves the productivity and the machining quality in the EDM process (Nguyen and Thangaraj, 2021). The higher strength materials can be used machined with complex forms using unconventional machining processes. The EDM process produces lower heat affected zone than laser beam machining (LBM) process (Phan et al., 2022).

Crystal glass pieces are generally obtained by blowing or injection processes. Through these processes it is difficult to obtain an adequate surface finish, being necessary to resort to finishing operations. Currently, for subtractive finishing operations, manual cutting and grinding tools are essentially used. Due to the complexity of the pieces, it is essential to resort to specialised labour, which implies high production times and costs. The automation of the finishing process can allow a reduction in production times and costs. In this sense, it is intended to investigate CNC machining technology, namely grinding, of crystal glass in order to define the best strategies and tools to use (Ferreira, 2020).

Surface roughness is a widely used index of product quality and in most cases a technical requirement for mechanical products. Achieving the desired surface quality is of great importance for the functional behaviour of a part. On the other hand, the process dependent nature of the surface roughness formation mechanism along with the numerous uncontrollable factors that influence pertinent phenomena, make almost impossible a straight forward solution. The most common strategy involves the selection of conservative process parameters, which neither guarantees the achievement of the desired surface finish nor attains high material removal rates (Benardos and Vosniakos, 2003).

This study has been presented in four sections: explore, create, experiment, and define (Figure 1).

Figure 1 Process for this study (see online version for colours)



1.2 Conceptualisation

To find correlations between cutting parameters for machining the crystal glass, conventional and ultrasonic assisted machining have been used.

1.2.1 Conventional machining

The main objective is to remove the maximum amount of material in the shortest time with the intended surface finish, without endangering the integrity of the tool. Strategies are based on machining parameters. One of the main difficulties in machining is to keep the cutting forces constant in order to extend the tool life. Hence, it is important to optimise the cutting parameters. One of the factors that influence machining time is the depth of cut (a_p). The greater the depth of cut, the shorter the machining time. However, a greater depth implies a greater bending of the tool.

Figure 2 Process for computer aided manufacturing (CAM) programming (see online version for colours)

1.2.2 Computer aided manufacturing

In CAM software, 3D machining strategies typically fall into two groups: roughing and finishing. The main objective of the roughing step is to remove material quickly. At this stage it is essential to leave an excess thickness for machining in the subsequent finishing stages. Typically, when machining complex geometries, the roughing stage consists of a sequence of re-roughing strategies, where the tool diameter is reduced until a constant over-thickness is reached. In the finishing stage, strategies adapted to the geometry of the part are used in order to obtain the desired dimensions and surface finish. These strategies usually use a lower feed and a_p and consequently a lower cutting force (Correia, 2005). The process steps for CAM programming are shown (Figure 2).

1.2.3 Ultrasonic assisted machining

Ultrasonic vibration cutting applied to machining hard and brittle materials has high efficiency. Ultrasonic vibration cutting is governed essentially by three parameters that directly influence the cutting force: cutting speed, frequency and amplitude of tool vibration. Ultrasonic vibration cutting compared to conventional machining is more effective: it enables reduction of cutting force, reduction of tool wear, improvement of surface finish, greater stability of the tool applied to difficult-to-machine materials such as Ni-based alloys and Ti, ceramics, glasses and tungsten carbide (Babitsky et al., 2003; Nath and Rahman, 2008). Zhang et al. (2014) carried out an experimental research to study the influence of rotary ultrasonic machining (RUM) on the surface roughness of optical glass. The results of the study revealed that surface roughness increased with increasing ultrasound power and feed speed, and with decreasing spindle rotation speed (Mitrofanov et al., 2004).

1.2.4 Crystal glass

Lead glass (crystal glass) is a glass that has a low melting temperature, high density and a high refractive index. This type of glass is used as a radiation protector, in high-end bottles and glasses, in lamps, decoration pieces, among others. Aluminium silicate glass has low thermal expansion, high glass transition temperature and can withstand high temperatures and can be used in thermometers, kitchen utensils, flue tubes and ovens (Ferreira, 2014; Giacomini, 2012). Grinding optical glass with high machining parameters (high cutting speed and increments) easily causes damage below the surface due to material characteristics. The serious subsurface damage (SSD) is characterised by a layer below the surface that presents micro-cracking from 10 to 100µm (Li et al., 2016). It is possible to machine some glasses in an equivalent way to ductile metals if the axial depth of cut (a_p) and the radial depth of cut(a_e)of the cut is reduced (Giovanola and Finnie, 1980).

1.2.5 Tools

There are specific tools on the market for machining rigid and brittle materials such as drills, milling cutters and reamers. Usually, this type of tool has in the cutting area a diamond or cubic boron nitride coating. Li et al. (2020a) studied the wear of a diamond disc in the optical glass grinding process. Based on this study, a model was developed that aims to simulate topography variations and tool wear. The microscopic differences observed in the grains of the tool caused by its wear are the main cause for the different morphologies observed on the disc. Wear can be caused by micro and macro fractures, pullouts, or by the frictional forces involved (Li et al., 2020b).

Table 1 Chemical composition of the crystal glass

Na2O	*MgO*	*Al2O3*	*SiO2*	*P2O5*	*SO3*	*K2O*	*CaO*	*TiO2*	*Cr2O3*	*Fe2O3*	*NiO*	*BaO*	*MoO2*	*BrO2*
1.432	0.048	0.141	50.753	0.057	0	12.386	0.141	0	0.042	0.048	0	1.397	0.002	0.003
TlO2	ZnO	Rb2O	SrO	PbO	La2O3	Nd2O3	Sb2O3	Ga2O3	Bi2O3	ZrO2	SeO2	CoO	CeO2	LOI
0.270	0.191	0.066	0.026	31.655	0.005	0.008	0.238	0.282	0.114	0.043	0.004	0.013	0.101	0.630

2 Create

2.1 Specimen

The specimens used for the tests had the approximate dimensions of 95 × 65 × 15mm. The material used was produced by the company Vista Alegre Atlantis and is called superior crystal glass. Table 1 shows the chemical composition of the crystal glass by FRX (X-ray fluorescence). Mechanical properties: density (kg/m3): 3.129 ± 0.01 , Vickers hardness (Hv): 456 ± 24, Refractive index: 1.571 ± 0.002.

2.2 Machining procedures

This work has carried out using a 5-axis machining centre DMG Mori DMU50 with a maximum spindle speed of 10,000 rpm and a magazine of 16 tools. Conventional machining tests and ultrasonic assisted tests were carried out on parallelepiped specimens. To optimise the number of experiments with keeping the quality of work, Taguchi method was used, resulting in nine experiments for each tool. To carry out the ultrasonic assisted tests, the acrow ultrasonic tool holder was used (Figure 3). This tool holder is designed for machining materials such as hard metal, SiC, PEEK, zirconia, quartz, boron nitride, between others. This device works at a frequency of 20 to 60kHz which can be translated into an oscillating movement with a frequency greater than 20,000 times per second. The use of ultrasound makes it possible to extend tool life as well as improve surface finish on materials considered difficult to machine.

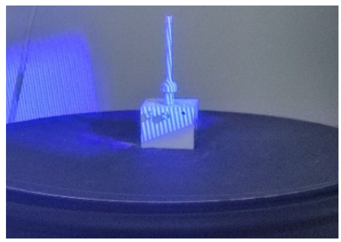
This equipment is accompanied by an ultrasound frequency generator which is located on the outside of the machine (CNC). The ultrasonic generator adjusts the frequency automatically when connected to the tool holder with the tool mounted. The weight of the tool holder can vary between 2.4 to 3.4 kg. The recommended maximum rotation is 6,000 rpm. The manufacturer indicates that the use of a frequency of 24 kHz with an amplitude of 2–10 microns is equivalent to a rotation of 240,000 rpm (Sirris, https://sirris.be/fr/node/48729). This system is normally applied to ceramics used in the semiconductor industry, ceramic bearings, titanium, ceramic teeth and bone screws (Sirris, https://sirris.be/fr/node/48729; Li et al., 2020a).

Figure 3 Tool holder for ultrasonic assisted machining (acrow ultrasonic) (see online version for colours)

2.3 Dimensional measurement of the tools

To carry out the dimensional control, the Carl Zeiss Comet L3 2 5M Scanner has used. The camera lens used has 500 mm. In terms of procedures, it is necessary to calibrate the equipment according to the lens used, introduce the CAD model in Colin, define the strategies that, in the case of tools, use the rotating plate, clean up the imperfections resulting from the process, generate the mesh and export the file. Comparison of the CAD model with the scanned model has performed in the Colin software (Figure 4).

Figure 4 Measurement of initial dimension of the tools (see online version for colours)



2.4 Force measurement

The most used equipment for measuring shear forces in these processes are piezoelectric dynamometers (Risbood et al., 2003; Tounsi and Otho, 2000). Piezoelectric transducers produce load signals proportional to their deformation (Castro et al., 2006). The most common application of dynamometers is on a static plate or base placed between the workpiece and the CNC machine table. However, these sensors can limit the dimensions of the part, given that their dynamic response is influenced by the geometry and weight of the part. These types of devices present better performance when developed for applications such as micromachining (Tounsi and Otho, 2000). Alternatively, piezoelectric rings can be applied to the spindle or rotating dynamometers can be used which are fixed between the spindle and the tool (Jun et al., 2002). However, the low frequency tool/spindle resonance disturbs the cutting force signals that these sensors acquire. These devices collect the force measurement in a global way and not the force of each tooth/insert of the tool (Totis et al., 2010). Accelerometers are devices whose function is to measure the acceleration of movement of a structure or vibration. The movement of a charge creates pressure on the piezoelectric material producing an electrical signal proportional to that charge. Since charge is proportional to force and mass does not change, then charge will be proportional to acceleration. Two types of piezoelectric accelerometers are available. The accelerometer with high impedance output and the accelerometer with low impedance output. In high impedance accelerometers, the electrical charge is directly connected to the measuring instruments. This type of device can be used in applications where temperatures exceed 120°C, as it is not possible to use low impedance models. Low impedance accelerometers are made up of a load accelerometer and a small electronic circuit, which incorporates a FET transistor that converts the load into a low impedance voltage, enabling easier interaction with standard instrumentation. This type of accelerometer is the most used in industry, can operate with voltages from 18 to 24 V and 2 mA and generally has an output signal based on 0 to +/–5 V (https://br.omega.com; Sinha Ray, 2013).

Piezoelectric sensors are used in most cutting force measurement systems on the market. These sensors allow the measurement of multi-axis forces in processes such as milling, turning, drilling and grinding. This technology allows obtaining high precision, high rigidity, reduced size and large range of scale. They present as disadvantages a high cost, need for calibration when changing the part and assembly restrictions (Staroiski, 1994; De Oliveira et al., 2012).

The dynamometer used in this study is a Kistler type 9139AA using piezoelectric sensors allowing the measurement of shear forces in the XYZ directions. This device allows the reading of forces ranging from –30 to 30kN (Figure 5).

Figure 5 Kistler 9139AA dynamometer

2.5 Measurement of surface finish

After machining the glass, it is necessary to assess its surface finish in order to assess irregularities and imperfections. For this, roughness analysis is one of the most used methods. Table 2 summarises various techniques for measuring roughness (Gong et al., 2019; Tavares Oliveira, 2005; Henke et al., 2022).

Table 2 Various technics for measuring the roughness

Method	*Quantitative*	*Three-dimensional data*	*Resolution (nm)*		*Limitations*
			Spatial	*Vertical*	
Instrument stylus	Yes	Yes	15–100	0.1–1	The type of contact can damage the surface
Optical methods					
Conical cut	Yes	No	500	25	Destruction of samples; time-consuming preparation
Profilometry	Yes	Sim			
Sectional light	Limited	Sim	500	0.1–1	Qualitative
Specular reflection	No	No	10^5–10^6	0.1–1	Semi-quantitative
Diffuse reflection (dispersion)	Limited	Yes	10^5–10^6	0.1–1	Smooth surface (<100 nm)
Optical interference	Yes	Yes	500–1,000	0.1–1	
Scanning tunnelling microscopy (STM)	Yes	Yes	0.2–1	0.02	Requires surface with conductivity; Scanning of small areas

Table 2 Various technics for measuring the roughness (continued)

Method	*Quantitative*	*Three-dimensional data*	*Resolution (nm)*		*Limitations*
			Spatial	*Vertical*	
Microscopic atomic force (AFM)	Yes	Yes	0.2–1	0.02	Scanning of small areas
fluid/electric	No	No			Semi-quantitative
Electronic microscope					Expensive
Reflection/replication	No	Yes	5	10–20	
Backscatter signal integration	Yes	Yes	5	10–20	Instrumentation, time-consuming process, data limitation, needs conductive surface, scan small areas
Stereo microscopy	Yes	Yes	5	50	

The rugosimeter makes it possible to measure the surface roughness of the parts, facilitating the control of the surface quality and making it possible to verify whether or not the part complies with the values defined in the drawings. To carry out the measurements, the rugosimeter runs over the surface of the part with a contact point. The movements of the contact tip are captured by sensors that amplify and convert the signals, facilitating the determination of roughness values (Usinagem ultrassônica: Novos porta-ferramentas para materiais duros e frágeis, 2021; Guedes, 2014).

There are mainly two types of roughness metres: one that only provides the reading of the roughness parameters (most used in production) and another that, in addition to this reading, allows recording data according to the selected parameters or characteristics (Figure 6).

Figure 6 Roughness measurement tool TR220

3 Experiment

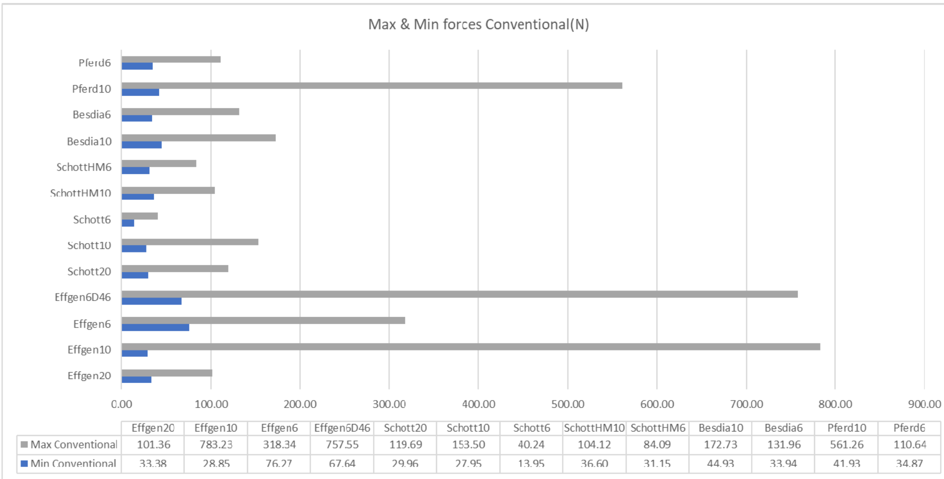
3.1 Design of experiments

After making flat the surface of the specimens, and measure the flatness by visual checking on the fixture, machining started. The parameters of the machining that were selected by Taguchi method were inserted in the CNC machine. Data from the force sensor was collected for each tool with different parameters for analysing.

3.2 Conventional machining experimental results

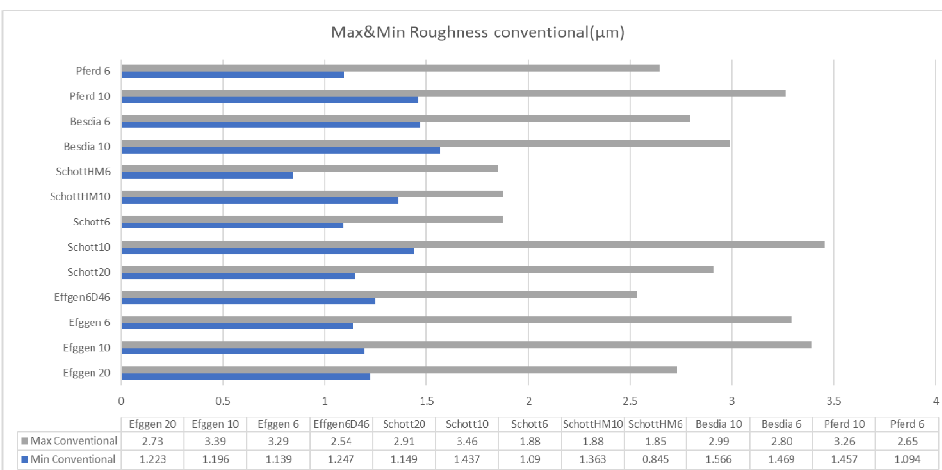
Results obtained from experiments for force and roughness are shown in Figure 7 and Figure 8.

Figure 7 Min and Max forces for conventional grinding (see online version for colours)



	Effgen20	Effgen10	Effgen6	Effgen6D46	Schott20	Schott10	Schott6	SchottHM10	SchottHM6	Besdia10	Besdia6	Pferd10	Pferd6
Max Conventional	101.36	783.23	318.34	757.55	119.69	153.50	40.24	104.12	84.09	172.73	131.96	561.26	110.64
Min Conventional	33.38	28.85	76.27	67.64	29.96	27.95	13.95	36.60	31.15	44.93	33.94	41.93	34.87

Figure 8 Min and max roughness for conventional grinding (see online version for colours)

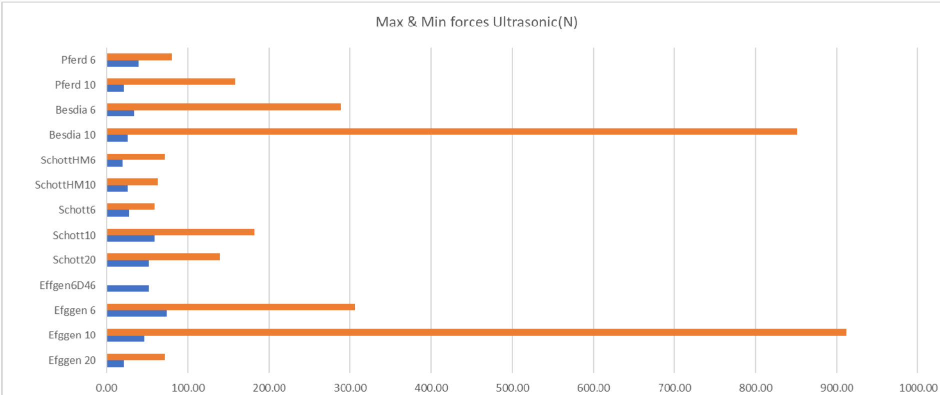


	Efggen 20	Effgen 10	Effgen 6	Effgen6D46	Schott20	Schott10	Schott6	SchottHM10	SchottHM6	Besdia 10	Besdia 6	Pferd 10	Pferd 6
Max Conventional	2.73	3.39	3.29	2.54	2.91	3.46	1.88	1.88	1.85	2.99	2.80	3.26	2.65
Min Conventional	1.223	1.196	1.139	1.247	1.149	1.437	1.09	1.363	0.845	1.566	1.469	1.457	1.094

3.3 Ultrasonic assisted machining experimental results

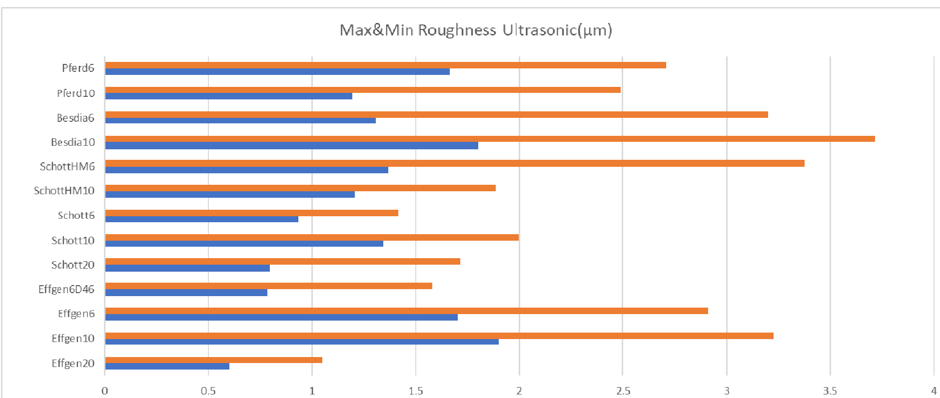
Results obtained from experiments identify the values of the force and roughness are shown in Figure 9 and Figure 10.

Figure 9 Max and min forces for ultrasonic assisted grinding (see online version for colours)



	Effgen 20	Efggen 10	Efggen 6	Effgen6D46	Schott20	Schott10	Schott6	SchottHM10	SchottHM6	Besdia 10	Besdia 6	Pferd 10	Pferd 6
Max Ultrasonic	72.06	911.65	306.38	0.00	139.82	182.24	59.07	63.34	72.06	851.21	288.49	158.30	80.82
Min Ultrasonic	21.47	46.09	74.50	51.87	51.87	58.97	27.73	26.23	19.44	26.22	33.82	21.35	38.83

Figure 10 Max and min roughness for ultrasonic assisted grinding (see online version for colours)



	Effgen20	Effgen10	Effgen6	Effgen6D46	Schott20	Schott10	Schott6	SchottHM10	SchottHM6	Besdia10	Besdia6	Pferd10	Pferd6
Max Ultrasonic	1.05	3.23	2.91	1.58	1.72	2.00	1.42	1.89	3.38	3.72	3.20	2.49	2.71
Min Ultrasonic	0.599	1.901	1.705	0.781	0.795	1.342	0.934	1.208	1.366	1.8	1.311	1.195	1.666

4 Define

4.1 Evaluation of the results

There were some differences between theory and results obtained from experiments. Trends and data analysis are discussed in this part.

4.2 Analysis and discussion

4.2.1 Min and max forces

Regarding forces results, minimum value was recorded for the Effgen20 in conventional and the Schott6 in ultrasonic and maximum value was recorded for the Effgen6 for both grinding methods. For maximum force results, minimum value was recorded for the Effgen20 in both conventional and ultrasonic and maximum value was recorded for the Effgen10 for both grinding methods. There was no transparency with theory and experimental results to show the minimum and maximum force for ultrasonic are lower than conventional method. However, the most effective reasons to identify this result are tools material, tools dimension and also vibration and that was not measured in this study (Figure 11, Figure 12 and Figure 13).

After comparing the free tool length and min force, eight tools met the theory and it shows the 62% transparency of results with theory (Figure 14).

Figure 11 Comparison of minimum forces for conventional and ultrasonic assisted machining (see online version for colours)

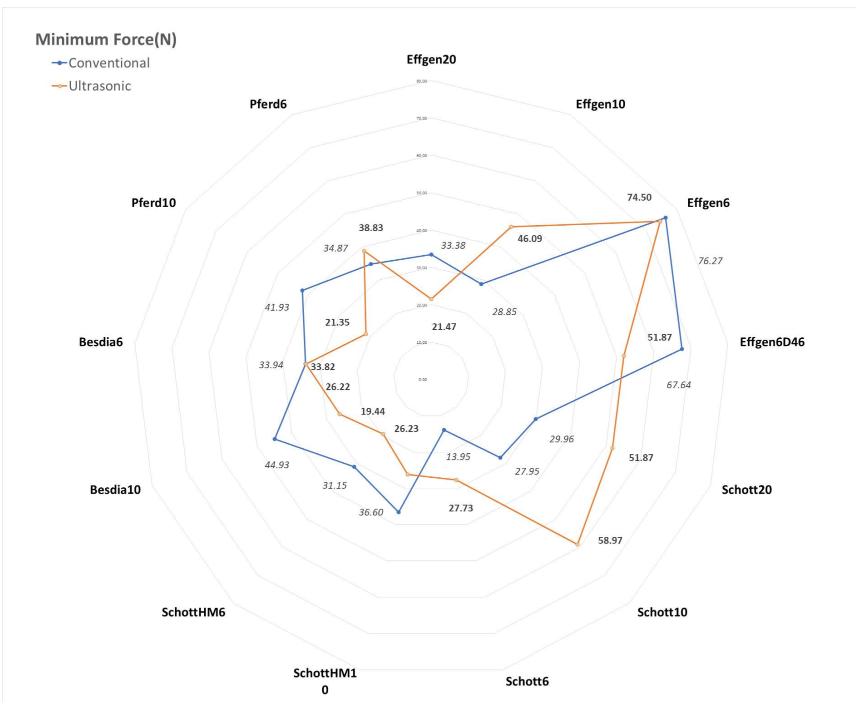


Figure 12 Comparison of maximum forces for conventional and ultrasonic assisted machining (see online version for colours)

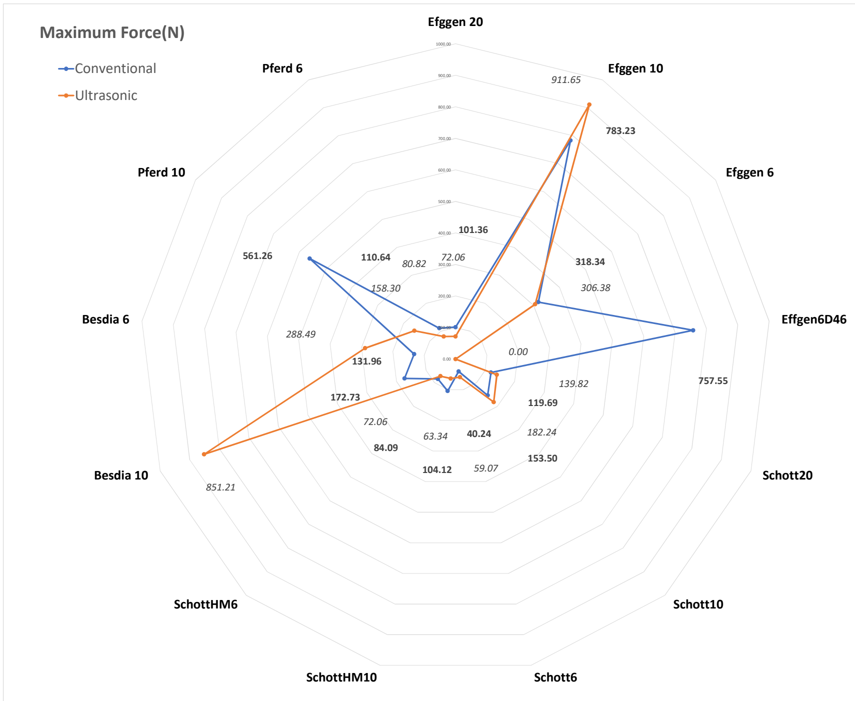
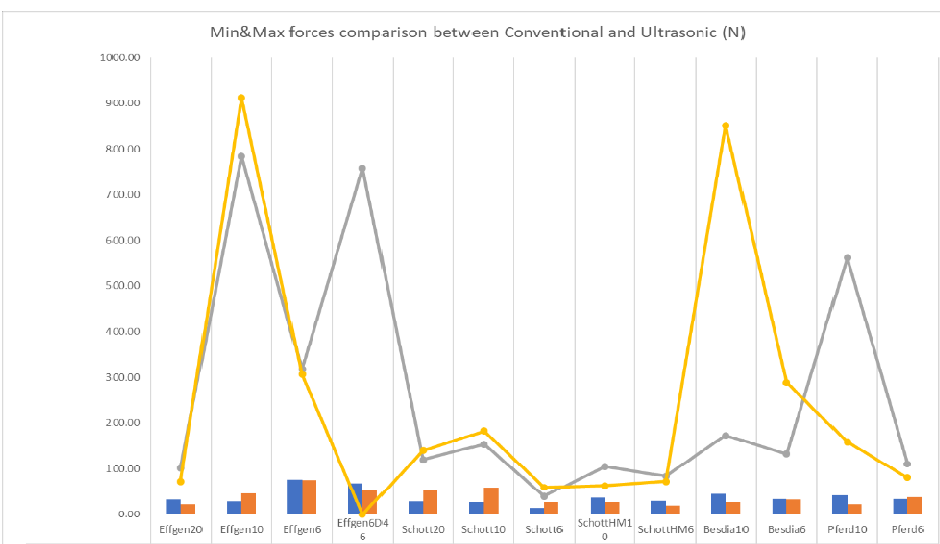
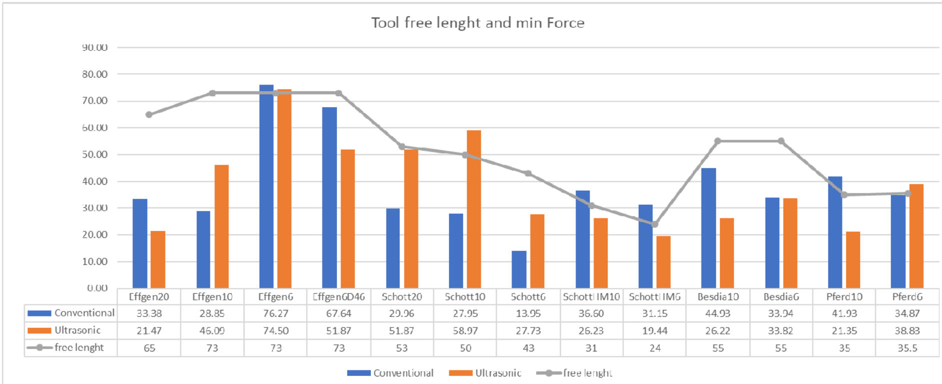


Figure 13 Comparison of maximum and minimum forces for conventional and ultrasonic assisted machining (see online version for colours)



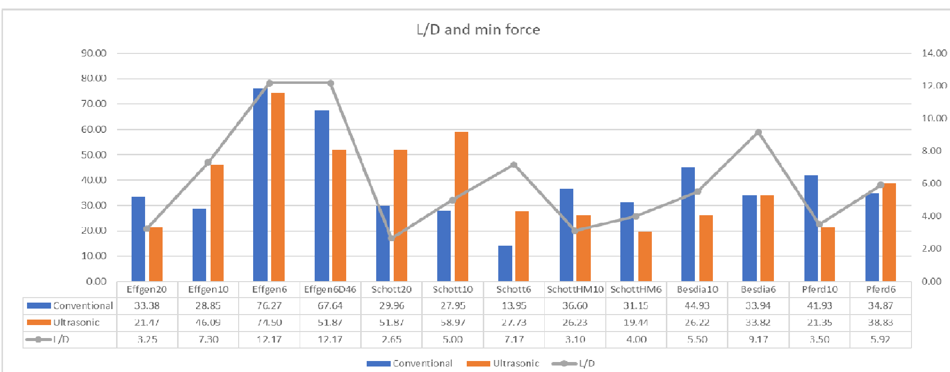
	Effgen20	Effgen10	Effgen6	Effgen6D46	Schott20	Schott10	Schott6	SchottHM10	SchottHM6	Besdia10	Besdia6	Pferd10	Pferd6
Min Conventional	33.38	28.85	76.27	67.64	29.96	27.95	13.95	36.60	31.15	44.93	33.94	41.93	34.87
Min Ultrasonic	21.47	46.09	74.50	51.87	51.87	58.97	27.73	26.23	19.44	26.22	33.82	21.35	38.83
Max Conventional	101.36	783.23	318.34	757.55	119.69	153.50	40.24	104.12	84.09	172.73	131.96	561.26	110.64
Max Ultrasonic	72.06	911.65	306.38	0.00	139.82	182.24	59.07	63.34	72.06	851.21	288.49	158.30	80.82

Figure 14 Comparison between tool free length and min force for conventional and ultrasonic assisted machining (see online version for colours)



In addition, after comparing the ratio of the tool free length per diameter of the tool and reverse ratio the previous conclusion was achieved and 62% of the results coincided with the theorical results (Figure 15).

Figure 15 Comparison between tool free length per diameter and min force for conventional and ultrasonic assisted machining (see online version for colours)



4.2.2 Minimum and maximum roughness

For minimum roughness results, minimum value was recorded for the SchottHM6 in conventional and the Effgen20 in ultrasonic and maximum value was recorded for the Pferd10 for conventional and Effgen10 for ultrasonic grinding. For maximum roughness results, minimum value was recorded for the SchottHM6 in conventional and Schott6 in ultrasonic and maximum value was recorded for the Schott10 for conventional and Besdia10 for ultrasonic grinding. There was no transparency with theory and experimental results to show the minimum and maximum force for ultrasonic are lower than conventional method. However, the most effective reasons to identify this result are tools material, tools dimension and also vibration and that was not measured in this study (Figure 16, Figure 17 and Figure 18).

Figure 16 Comparison of minimum roughness for conventional and ultrasonic assisted machining (see online version for colours)

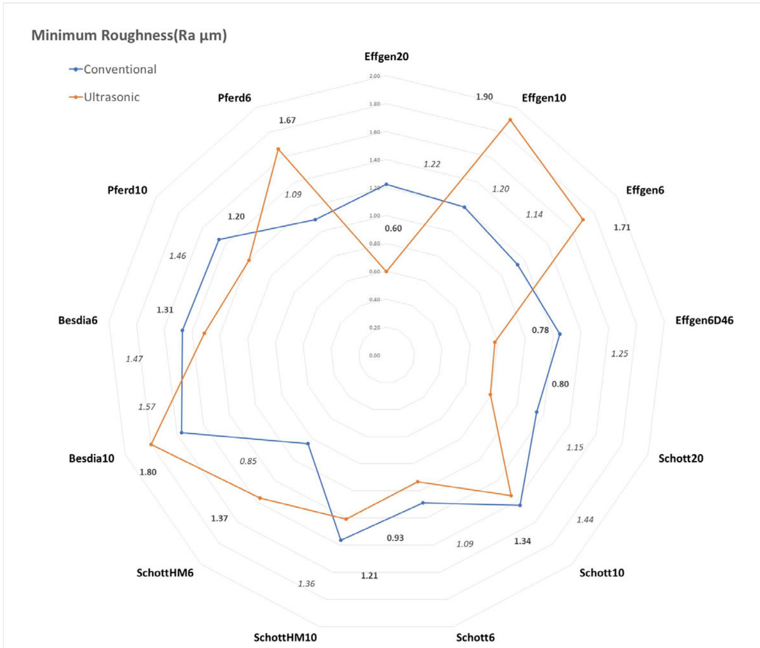


Figure 17 Comparison of maximum roughness for conventional and ultrasonic assisted machining (see online version for colours)

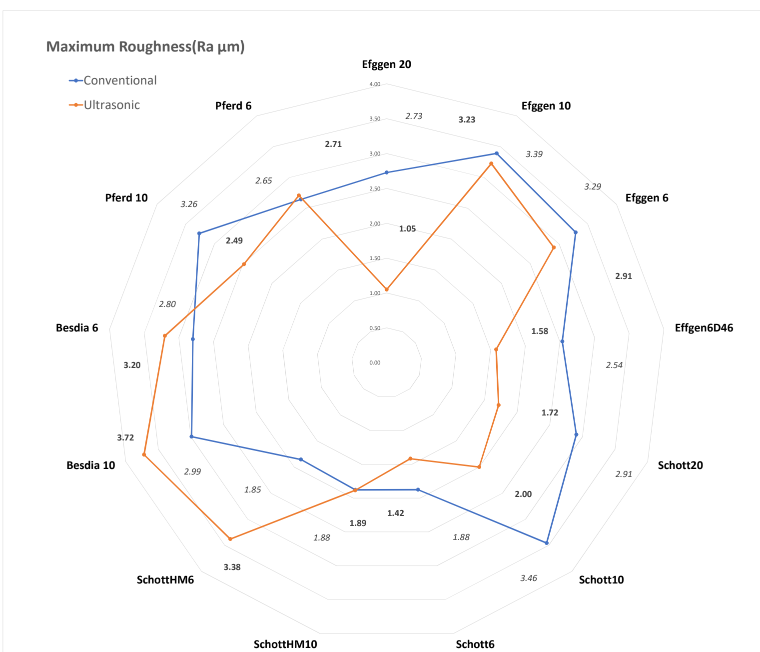


Figure 18 Comparison of minimum and maximum roughness for conventional and ultrasonic assisted machining (see online version for colours)

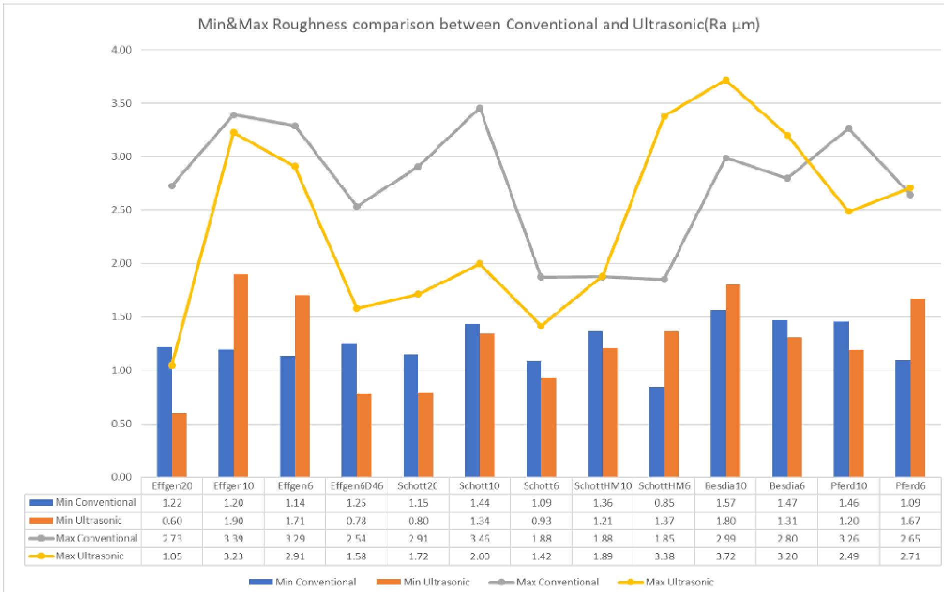
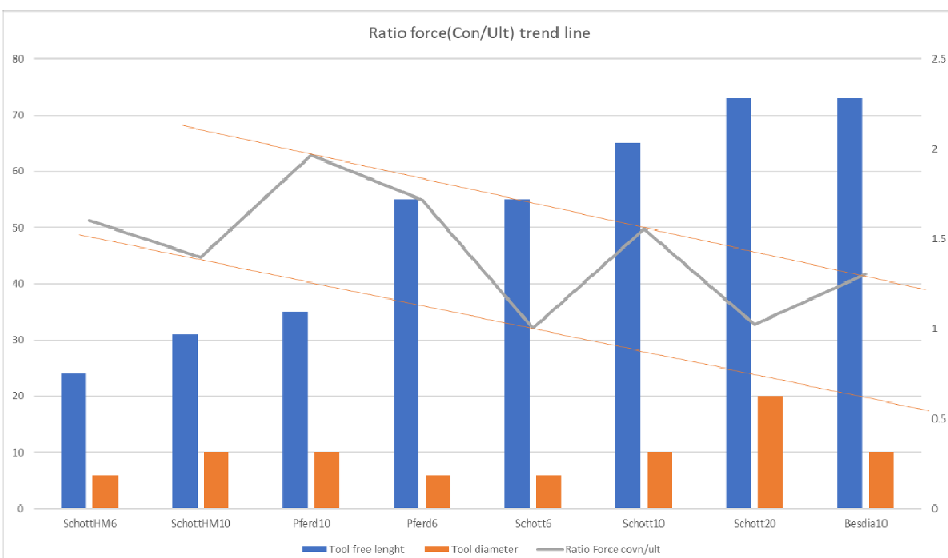


Figure 19 Trend line for ratio force of conventional over ultrasonic assisted machining (see online version for colours)



It can be considered that the results for eight of the thirteen tools (62%) have coincidence with theory. After sorting the tools according to the length, the trend lines show that with increasing the free length, tool ratio force (conventional per ultrasonic) is descending. That means the vibration and other variables are influencing the stability of the tools. It can be concluded that the force reduction achieved by the ultrasonic assisted grinding is attenuated by the tool length (Figure 19).

4.3 Conclusions and future work

In this study, our team had a great experience to work with one of the major industrial companies in Portugal that is well known for crystal glasses products. Du to the project timeline, delay for resources, limitation and time consuming of experiments and lack of some sensors to measure the vibration in real time during machining, concentration of this study had been limited to data analysis and finding the correlations between forces and roughness.

Finally, coincidence between theory and experimental for 62% of the results by a trendline between data of the tool free length, tool diameter and ratio of the forces conventional and ultrasonic had been obtained.

Vibration of the tools and effects on the crystal glass would be a great opportunity to set up a data analysis for results. Finding correlations between vibration and max and min forces and roughness would be a development in the research activity for crystal glass.

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