UNIVERSITAT POLITÈCNICA DE CATALUNYA
BARCELONATECH
Escola d'Enginyeria de Barcelona Est

MASTER'S FINAL PROJECT

Master's degree in Interdisciplinary and Innovative Engineering

STUDY OF VIBRATION ASSISTED MACHINING PROCESS

Report and Annexes

Author: Jordi-Adalbert Marqués Salvador

Director: José Antonio Travieso Rodriguez

Date: June 2021

“Without publication, science is dead”

Gerard Piel

Abstract

This project has been carried out with the aim of designing, producing and characterizing a vibration-assisted machining tool for finishing operations on a lathe. More specifically, a series of experiments has been developed in order to characterize the tool for surface finishing of C45E steel.

The tool design incorporates a sonotrode attached to the tool shank which converts it in a VAM tool, the current design developed by all the DEFAM team is under patent number ES1253134.

Once designed, manufactured and adapted to the CNC lathe, tests have been carried out manually to obtain a good starting point for the cutting conditions to be applied in the machining process. With these conditions, the experimentation phase has been carried out, making test specimens for analysis. Not only the fatigue life has been analyzed from these specimens, but the surface texture has also been measured, as well as its hardness.

The results obtained have been satisfactory, thus meeting the expectations initially set.

Resumen

Este proyecto se ha realizado con el objetivo de diseñar, producir y caracterizar una herramienta de mecanizado asistida por vibración para operaciones de acabado en torno. Más concretamente, se ha desarrollado una serie de experimentos con el fin de caracterizar la herramienta para el acabado de superficies de acero C45E.

El diseño de la herramienta incorpora un sonotrodo adherido al vástago de la herramienta que la convierte en una herramienta VAM, el diseño actual desarrollado por todo el equipo DEFAM está bajo el número de patente ES1253134.

Una vez diseñado, fabricado y adaptado al torno CNC, se han realizado pruebas de forma manual para obtener un buen punto de partida de las condiciones de corte a aplicar en el proceso de mecanizado. Con estas condiciones, se ha llevado a cabo la fase de experimentación, realizando probetas para análisis. No solo se ha analizado la vida a fatiga de estas probetas, sino que también se ha medido la textura de la superficie, así como su dureza. Los resultados obtenidos han sido satisfactorios, cumpliendo así las expectativas inicialmente planteadas.

Resum

Aquest projecte s'ha realitzat amb l'objectiu de dissenyar, produir i caracteritzar una eina de mecanitzat assistida per vibració per a operacions d'acabat en torn. Més concretament, s'ha desenvolupat una sèrie d'experiments per tal de caracteritzar l'eina per a l'acabat de superfícies d'acer C45E.

El disseny de l'eina incorpora un sonotrode adherit a la tija de l'eina que la converteix en una eina VAM, el disseny actual desenvolupat per tot l'equip DEFAM està protegit sota la patent ES1253134.

Un cop dissenyat, fabricat i adaptat a l'torn CNC, s'han realitzat proves de forma manual per obtenir un bon punt de partida de les condicions de tall a aplicar en el procés de mecanitzat. Amb aquestes condicions, s'ha dut a terme la fase d'experimentació, realitzant provetes per a anàlisi. No només s'ha analitzat la vida a fatiga d'aquestes provetes, sinó que també s'ha mesurat la textura de la superfície, així com la seva duresa. Els resultats obtinguts han estat satisfactoris, complint així les expectatives inicialment plantejades.

Agradecimientos

A Toni, Ramón y Jordi por ofrecerme esta oportunidad, sus innumerables horas dedicadas a ayudarme, aconsejarme y por todos los conocimientos que me ha aportado.

A mi madre y mi padre, por estar siempre apoyándome y dándome ánimos para llegar hasta el fin de este proyecto.

A Lu, por darme todo el apoyo necesario en este proyecto y escucharme cuando le explicaba mis ideas y lograr que sacase lo mejor de mí en todas las fases de este proyecto.

A Eric, Raúl y Jaume por toda su ayuda con la realización de los ensayos de la herramienta.

A mi abuelo, por haberme enseñado a seguir mi pasión por la innovación y la ingeniería.

A Edu, Iván y Enric, por escucharme y animarme siempre que lo he necesitado.

A Alex por sus innumerables horas dedicadas a escucharme y motivarme cuando más lo he necesitado.

Por todo esto y mucho más, Gracias a tod@s.

Glosary

CAD: acronym that refer to Computer Aided Design or computer-aided design is a computer tool through which you can make designs of parts, assemblies and plans. In the world of machining, three-dimensional CAD is usually used to visualize the part and perform the assembly and 2D CAD to create the plan that will be used to manufacture and or verify said part.

CAM: abbreviations that refer to Computer Aided Machining or Computer Aided Machining is a computer tool used to generate the machine code necessary to manufacture a part with a CNC machine. It uses a 3D CAD geometry and the tools that will be used to generate the trajectories and movements that the machine will perform.

CNC: acronyms that refer to Computer Numerical Control or computer numerical control, consists of a system that through the use of a computer allows to control the position of an element, normally used in machines with a work tool.

Machining center: machine capable of carrying out all the technological operations of chip removal, which has numerous tools with an automatic change system.

Tool holder: tool fixture, normally standardized, on which the cutting tool is mounted.

Grinding: machining technology whereby small amounts of material are removed using an abrasive wheel. It is characterized by the good surface quality that it leaves in the applied areas.

VAM: Vibration-Assisted Machining, machining process which includes a high frequency external vibration source which transmitted to the machining tool insert

NVAM: Non-Vibration-Assisted Machining also known as conventional cutting is the machining process which does not have any external vibration source.

ISO CODE / GCODE: is the most used computer numerical control (CNC) programming language.

Fatigue: weakened condition induced in metal parts of machines, vehicles, or structures by repeated stresses or loadings, ultimately resulting in fracture under a stress much weaker than that necessary to cause fracture in a single application.

Surface hardness: is a measure of the resistance to localized plastic deformation induced by either mechanical indentation or abrasion in the surface of a part.

PZT: Piezo electric transducer, actuator that uses a material with piezoelectric properties to convert electricity impulses into small scale high frequency movement.

WLI: White light interferometry is a non-contact optical method for surface height measurement, it is commonly used for obtaining surface roughness and textures of machined parts.

Índice

El siguiente índice se genera y actualiza automáticamente con la opción *"actualizar campos"* que aparece cuando se pulsa el botón derecho del ratón. Haced que el índice se inicie en una página impar.

Figure index

Table index

Introduction

Nowadays the whole machining industry is undercoming a change where other industries are demanding higher end parts but at lower prices, which implies reducing machining costs, setups and manual postprocessing of the parts. In order to continue being competitive investing in new technologies is the way to go.

1.1. Goals of the project

1.1.1. General Goal

This project has been developed with the general goal of design, manufacture and characterize an ultrasonic machining tool for a lathe which could improve the surface finish, the fatigue life and the hardness of the machined part.

1.1.2. Specific goals

- Adapt the current developed tool to the CNC lathe Pinacho SE 200
- Find the cutting parameters for the manufacturing of the specimens
- Determine the influence of Vibration Assisted Machining (VAM) in the fatigue life cycle of C45 steel
- Determine the influence of VAM in the surface texture compared with the obtained using Non-Vibration Assisted Machining (NVAM)
- Determine the influence of VAM in the surface hardness of the pieces

1.2. Scope of the project

This project seeks to obtain a functional prototype of a tool capable of turning the outside profile of a revolution part of C45 steel. This implies that the tool will have to be designed and manufactured, as well as tests need to be performed to achieve its fine-tuning.

1.3. THEORETICAL BACKGROUND

Vibration-Assisted machining is a high precession machining technique which combines the traditional machining with a small-amplitude and high frequency vibration applied in the tool to improve the fabrication process [1]. It can be applied to different manufacturing processes such as drilling, milling, burnishing, but this project will be focused in vibration-assisted turning process. The main principle of VAM is to reduce machining forces and facilitate chip separation by applying an ultrasonic vibration interaction between the tool and the part which interacts at microscopic level. [2]. This characteristic is known as Acustoplasticity which is explained by Gomez-Gras et al [3] when applying an external high frequency vibration, the yield strength of the material can change, due to the transmission of the vibration wave through the material structure enhancing mobility of dislocations, as a result, the plastic deformation or cutting forces can be reduced. Depending on the material this phenomenon can be present or not.

In order to be able to turn parts with the benefits of VAM a machine with this specific feature is required, and with the disadvantage that not all types of machines have it as an option. Furthermore, if a company has a special need for a specific operation as facing or turning complex shapes, it is very difficult to adapt and achieve optimal results with this machine.

Most of machining equipment companies manufacture these types of machines under a client request and usually they are custom made, which as always could imply a risk for the company investing in such specific machine

As it can be seen on Fig. 1, this type of machines exists, but are very specific and implies a high inversion, not only in the machine but also with the space needed to install it, operator learning and so on.

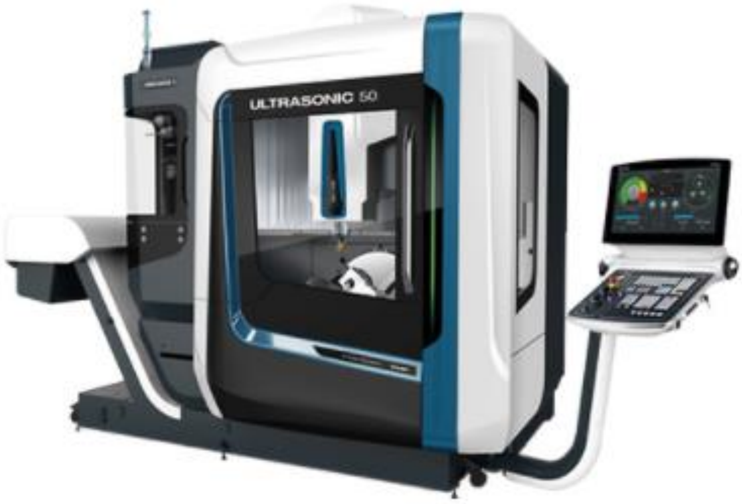

Figure 1: Ultrasonic VMC, source: DMG mori

1.4. State of the art

To carry out this research, a search and study of previous works on vibration assisted machining has been carried out. Projects of two themes have been sought: types of vibration assisted tools for machining operations and improvement of surface finish through application of vibration. Jobs have been taken as an initial reference for carrying out this project. Also, references have been used to understand better how to carry out certain experiments. As it can be seen on Figure 2, several finishing technologies are available today, each with its pros and cons.

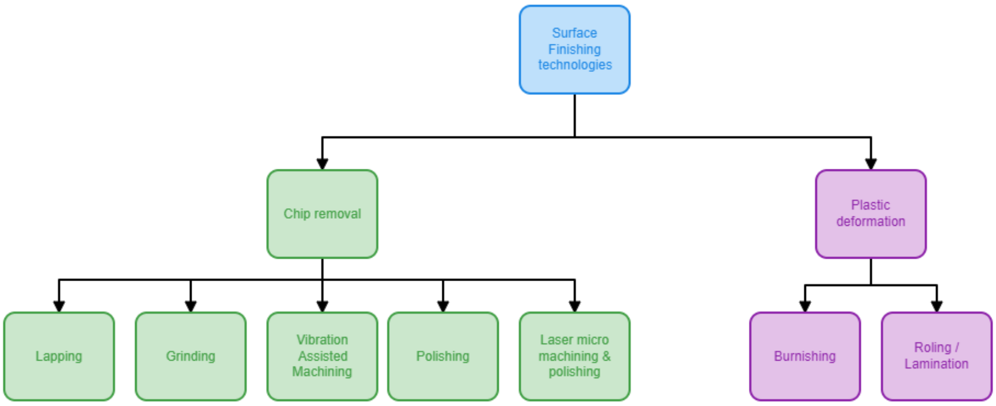

Figure 2: Surface finishing technologies

Brittle materials have the disadvantage of brittle machining, where when removing material is equivalent to producing microcracks in the surface, VAM thanks to the also mentioned Acustoplasticity phenomenon is able to transform brittle machining into ductile. As Zheng et al [4] mention it allows to increase the cutting depth and improve the machining feasibility of brittle materials, also makes it more economically viable. As it is also mentioned, another advantage of VAM is the effectiveness of the suppression of burr formation when machining, if it is compared with conventional techniques, it is possible to reduce burr formation up to an 80%. Once again, this due to the reduction in cutting forces leading to a to lower transient compressive stress and yield stress in the cutting deformation area.

An investigation about diamond turning of steel conducted by Zhang et al [5] showed that VAM is an industrially viable technique in terms of machine setup, increasing tool life without compromising the machining accuracy. The benefits of an increased cutting performance can be reflected in the reduction on the cutting force, suppression of chatter and a better surface finish. All this make possible to assure that VAM is a way to go on machining steel with diamond tool.

Furthermore, the vibration has shown great results when applied in other finishing processes. As Estevez-Urra et al [6] showed, assisting the burnishing process with an additional vibration of small amplitude and high frequency comes when the understanding of what happens with the yield strength of the material. When a material experiments plastic deformation, if an external source of vibration is applied, it enhances the mobility of the dislocations inside the crystal lattice and as a consequence the forces that need to be applied are lower that when no vibration is applied.

Gao et al [7] on its analysis of cutting stability found that the application of a continuous sinusoidal vibration during machining produced a much more stable finishing surface, also Rz and Ra values were lower in the area where VAM is applied. VAM can always increase cutting stability and no matter whether or not chatter happens, the vibration levels in VAM are much smaller than that in NVAM, which surely leads to a lower surface roughness value as it can be seen on Figure 3.

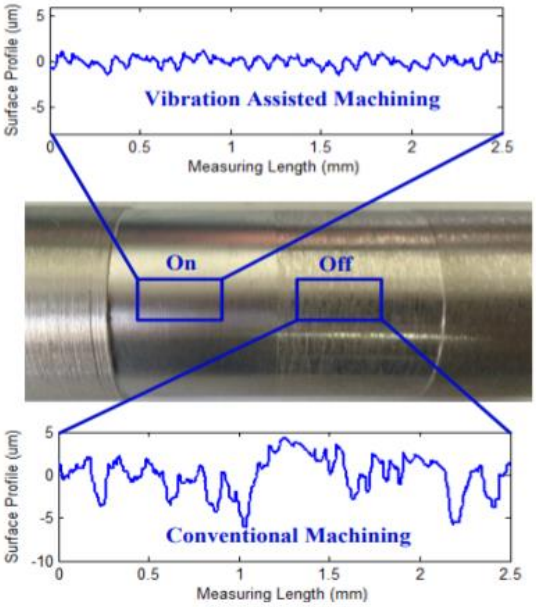

Figure 3: VAM & NVAM Surface (Gao et al [7])

2. Technical Aspects

2.1. Previous knowledge

As an initial point and with the sake of making easier to understand the project, the most important concepts are exposed hereunder.

Plastic deformation: process in which a material is permanently deformed by applying a load which exceeds its elastic limit.

Surface quality: indicator used to measure the degree of surface finish of a part, it depends on the material and the manufacturing and finishing process used.

Surface roughness: it is the measure of the micro irregularities of the surface or surfaces of a piece, which has been transformed by a manufacturing process.

Roughness meter: measuring device that by means of a probe or tip registers the profile of irregularities on the surface of a piece.

Evaluation length: is the total sampling distance.

Base length or Cut-off length: partial distance from which the roughness values are calculated, the cut-off values depend on the roughness measurement obtained and range between 0.08-2.5 mm.

Surface roughness parameters: the most five important parameters of surface texture are:

- **Sa**: (arithmetical mean height) It expresses, as an absolute value, the difference in height of each point compared to the arithmetical mean of the surface. This parameter is used generally to evaluate surface roughness.

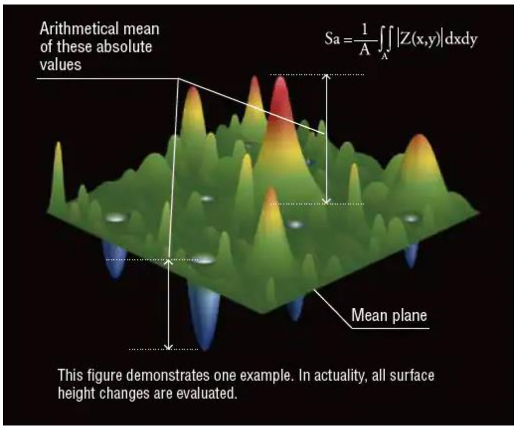

Figure 4: Sa representation (source: keyence [4])

$$Sa = \frac{1}{A} \iint Z(x, y)dxdy] \qquad \text{(Eq 2.1)}$$

- **Sz**: (Maximum height) This parameter is defined as the sum of the largest peak height value and the largest pit depth value within the definition area.

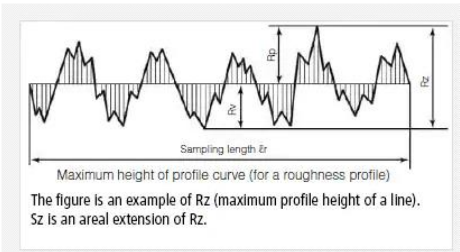

Figure 5: Sz representation (source: keyence [4])

$$Sz = Sp + Sv \qquad \text{(Eq 2.2)}$$

- **Sq**: (Root mean square height) This parameter represents the root mean square value of ordinate values within the definition area. It is equivalent to the standard deviation of heights.

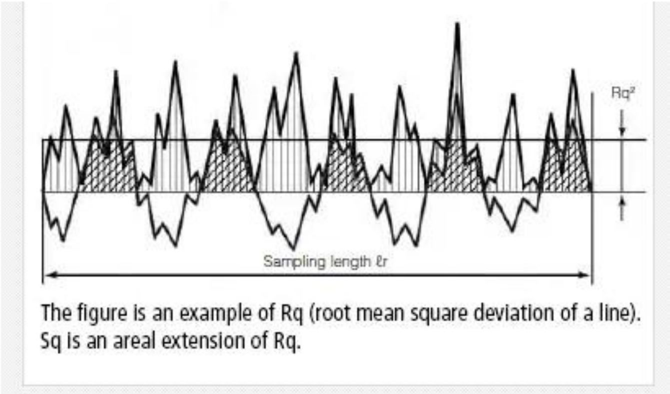

Figure 6: Sq representation (source: keyence [4])

$$Sq = \sqrt{\frac{1}{A} \iint Z^2(x,y)dxdy]} \qquad \text{(Eq 2.3)}$$

- **Ssk**: (Skewness) Ssk values represent the degree of bias of the roughness shape (asperity).
  - Ssk<0: Height distribution is biased above the mean plane.
  - Ssk=0: Height distribution (peaks and pits) is symmetrical against the mean plane.
  - Ssk>0: Height distribution is biased below the mean plane.

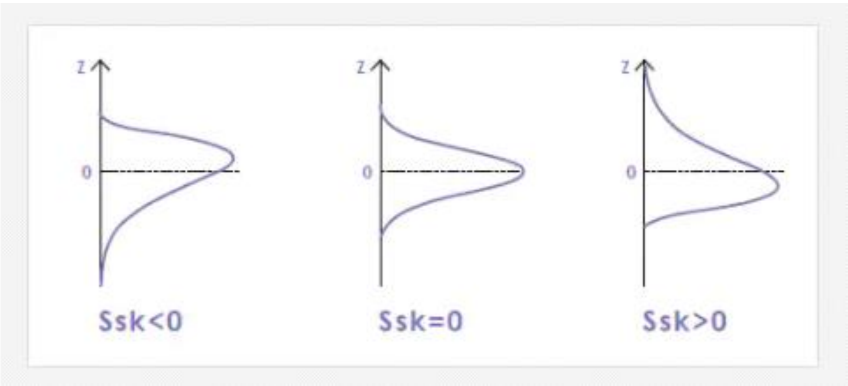

Figure 7: Skeweness representation (source: keyence [4])

$$Ssk = \frac{1}{Sq^3}\left[\frac{1}{A} \iint Z^3(x,y)dxdy]\right] \qquad \text{(Eq 2.4)}$$

- **Sku**: (Kurtosis) Sku value is a measure of the sharpness of the roughness profile.
    - Sku<3: Height distribution is biased above the mean plane.
    - Sku=3: Height distribution is normal distribution. (Sharp portions and indented portions co-exist.)
    - Sku>3: Height distribution is spiked.

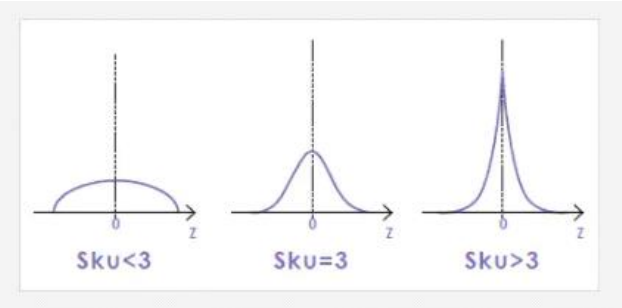

Figure 8: Kurtosis representation (source: keyence [4])

$$Ssk = \frac{1}{Sq^4}\left[\frac{1}{A}\iint Z^4(x,y)dxdy\right] \quad \text{(Eq 2.5)}$$

Machining: Machining is the set of industrial processes (cutting, marking, pressing, drilling, etc.) carried out on a piece of raw material to give it a desired final shape and size, eliminating material in a controlled way using machine tools.

2.2. Previous study for the tool design.

Before beginning with the tool design, it was necessary to make a previous search of information which was focused on the following points:

- Analyze the main machining purpose of the tool.
- Analyze existing solutions and its pros and cons.
- Study of the materials used to manufacture this type of tools.
- Analyze the machine tools where this tool could be used.

Once analyzed all these previous points the following conclusions where made with all the designing team.

- The tool will be used for turning operations, and more focused on the finishing of revolution surfaces.
- Existing solutions are a "closed package" where the tool and the CNC lathe are all integrated, but cannot be integrated in machines that haven't been conceived for this type of machining.
- These tools are usually made of tool-steel and titanium alloys.
- The tool must be able to be installed on medium to large CNC lathes, which means that the holding system of the tool must be in the range of 20-40 mm shank.

2.3. Design of the prototype V1 & V2

With all the previous assumptions the design of the tool was carried out. It is important to understand that the final design of this prototype is very similar to the design delivered to the manufacturer, but the sonotrode mass must be adapted the final. That is why the design had some adjustments made by the manufacturer and it's the design that will be explained hereunder.

2.3.1. General description

The tool is composed by seven main different parts as it can be seen on Figure 9, each with its specific purpose, most of the parts with the exception of the tool insert and the connector are custom designed and manufactured. Most of these custom parts have been manufactured through machining techniques as milling, turning and grinding.

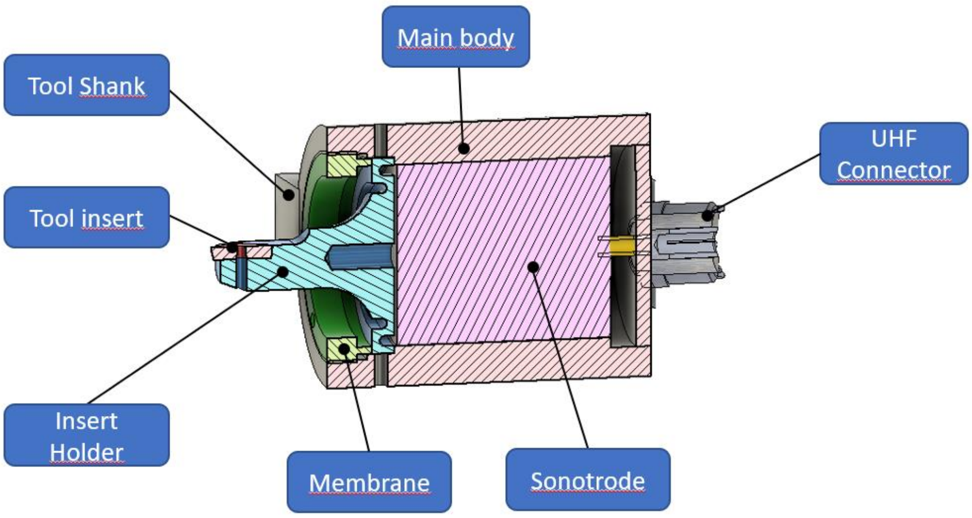

Figure 9: Tool section view

2.3.2. Main body

The main body is in charge of holding most of the components together. It is made in 1.2379 tool steel. It's been manufactured through machining turning and its main purpose is to hold all the components on it. The main body must have enough rigidity to withstand the cutting forces but an excessive size/material will make the tool less practical due to machining accessibility problems.

2.3.3. Insert

The insert geometry was chosen in the design phase and based on previous experience of machining and the availability of an insert for machining multiple materials, a well-known insert was the chosen one. A great advantage of this insert is that it is available with different coatings and chip breaking systems which allows to machine different materials by only changing the tool insert. Furthermore, most of the tool insert manufacturers, manufacture this insert as a standard, so, for future market implementation it won't be difficult for the customers to find the spare inserts. Insert shape can be seen on Figure 10.

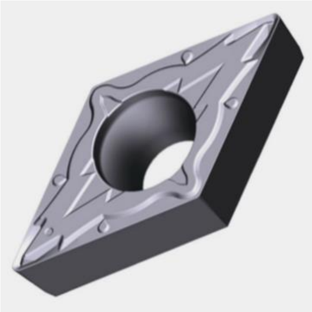

Figure 10: Insert Geometry (source: Tungaloy) DCMT070204-PSFT9215

2.3.4. Tool shank

The tool shank is where the tool gets fixed to the machine. In the first prototype and for more flexibility a straight rectangular shank was designed. This shank is made of 1.2379 tool steel and attached with 3 M6x1 DIN 7991 screws. The straight shank allows to mount the tool on any machine that accepts 20 mm or more tools but before beginning to work the height must be adjusted. Another type of shank has been designed to be compatible with the tool and it is a VDI 40 B2 type toolholder. This type of toolholders are ready to use with compatible machines, and height is adjusted by design. Both tool versions can be seen on Figure 11.

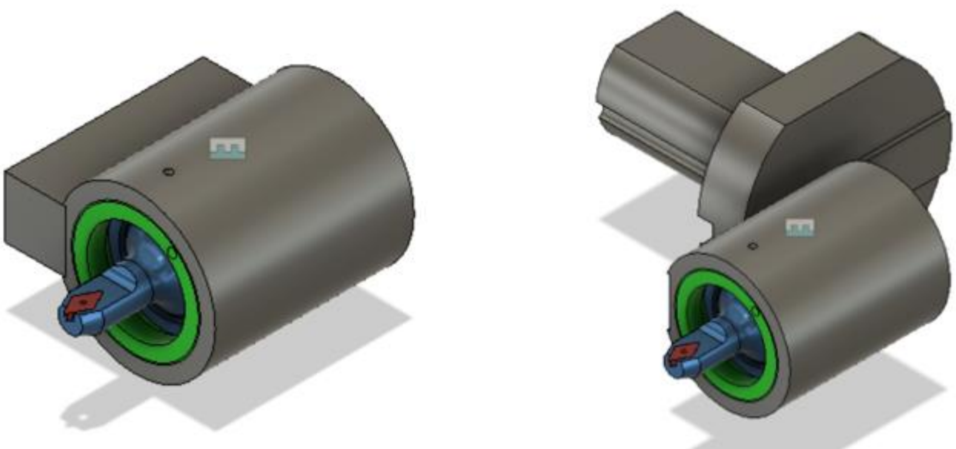

Figure 11: V1 and V2 VAM tools (left v1 , right v2 with VDI 40)

2.3.5. Sonotrode

In ultrasonic machining the sonotrode is the responsible of creating ultrasonic vibrations which will be then transmitted to the tool to cut the material. It is usually manufactured from a stack of piezoelectric transducers attached to two metal rods forming a sandwich (metal-PZT-metal) as it can be seen on Figure 12. In this particular case, the front metal will be the insert holder and the back metal the back-seal of the tool. To make the sonotrode oscillate it is necessary to apply an alternating current at ultrasonic frequency that should make the tool resonate, this frequency is specific of the tool design and this is why the manufacturer need to modify a bit the initial design. The tool resonates at a frequency of 40 kHz and the amplitude is in the range of 10 µm.

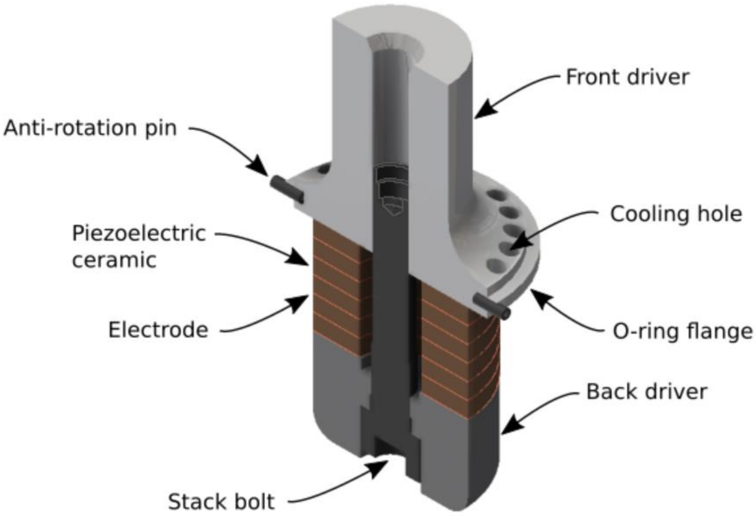

Figure 12: Sonotrode schematic (source: [14])

2.3.6. Membrane

The membrane is made from TiAl6V4. It is threaded into the main body and retains the insert holder. Although it is a solid material, due to the specific design, it acts as a retaining spring which blocks the insert holder but at the same time it allows a micrometric displacement of the same when the resonator is activated.

2.3.7. Connector

The connector is a UHF 259PL standard it is assembled onto the back of the tool by using 4 M3x0.5 screws. This connector is designed to be usable for frequencies up to 100 MHz in case that the tool must be more compact, it is possible to substitute this connector for a smaller one.

2.3.8. Differences between V1 & V2

The first version of the tool was manufactured according to all the previous requirements and thought to be as flexible as possible. This way it would be possible to adapt it to different types of machines. After using it on the Pinacho and on a HAAS lathe a second version with minor adjustments was designed.

The main problem found on the first version of the tool was that aligning the height of the tool was easy on manual lathes but not on CNC ones, which usually are designed for a specific tool shank and the insert is already leveled. This is why the second prototype will have the shank offset from center in order to achieve that mounting it on lathes from 20 mm to above will be an easy process. Another minor issue found is that depending on the lathe, it was possible.

2.4. Setup of the tool on the lathe

In order to be able to machine the specimens, the tool must be set up on the lathe. In this particular case, the CNC lathe has a six-position automatic tool change turret where it will be installed. In the set-up process there are two important things to verify:

- The tool is leveled and centered with the lathe rotation axis.
- All the tools are set in a way that when any of the machining phases is executed there is no risk of collision between tool and machine or tool and part.

As it has been previously mentioned, the first prototype was not ready to be installed and centered with the rotation axis of the lathe so an adapter had to be made. The adapter was machined in C45 steel and basically allowed to apply an offset to have the tool leveled correctly. One important thing to verify before finishing the setup of the tool is to make sure the accessibility and possible collision problems. In order to verify these possible inconveniences, the final setup of the part is simulated, setting all the tool offsets and moving the tailstock to a near final position where it would be set. After this, the CNC program is executed with Speeds and Feeds at minimum while verifying in real time that there is no risk of future collision. After this process is successfully achieved, measures of all positions and references are taken to be able to replicate this setup.

As it can be seen on the figure below, it is possible to distinguish the tool attached to an adapter which finally is attached to the lathe tool turret.

2.5. Machining process

The machining process of the produced specimens is based on a two-setup procedure. In the case of the VAM an optional stop is added to be able to turn on the vibration of the tool. If needed it is possible to interface the vibration generator to a programable output from the machine to achieve the automation of the whole process.

The machining procedure has followed the rule of 70/30 as it can be seen on Figure13 , where the seventy percent of the material is removed with roughing strategy where feedrates are higher, the 30 percent is machined with finishing strategy with lower feedrate. The finishing process is carried out by two tools, the first passes until the last one is made with a neutral tool, the last pass is made with the VAM tool, this way It is possible to increase even longer the VAM tool life.

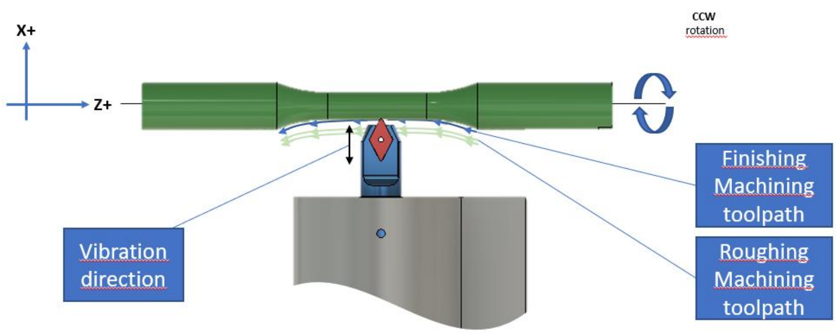

Figure 13: Machining toolpath representation

In order to machine the specimens, the first thing to do is to cut the raw material bar to length, a band saw is used for this process. These specimens are going to use in the fatigue lifespan test. To optimize the manufacturing process and reduce the scrap material, each bar will be used to manufacture two fatigue specimens. After cutting the raw stock material both extremes are ground in order to avoid any damage of the operator and machine while handling and setting it in the machine.

Once the material is ready the machining process begins. Two setups will be needed to create the specimens. The first setup is intended to create a centered spot on one of the extremes of the material. In the second setup this hole will be used with the livecenter in the tailstock. For obtaining the spot, a manual facing and after it a center drilling is performed. Setup 1 can be seen on Figure 14.

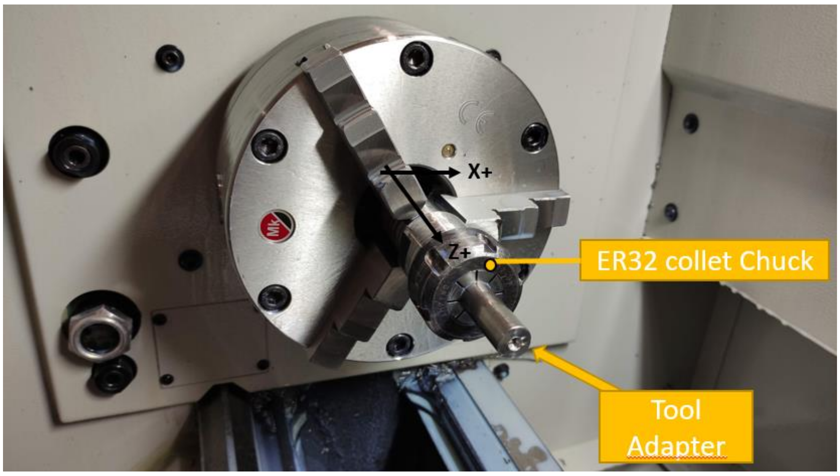

Figure 14: Setup 1 overview

The second setup is where all the specimen profile will be machined. The ISO GCODE program has been written using canned cycles and optional stops that allows the operators to have automatic pauses in the machine, to be able to verify tolerances and also to activate/deactivate the vibration-assistance when needed.

As it has been mentioned, in this setup the part length compared with the diameter of the raw stock is over 3 times the diameter. Therefore, it is compulsory to use the tailstock with a live center to reduce chatter and vibrations during the machining process. The part is also held by an ER32 collet chuck allowing repeatability and a runout below 0.001 mm. Stup 2 can be seen on Figure 15.

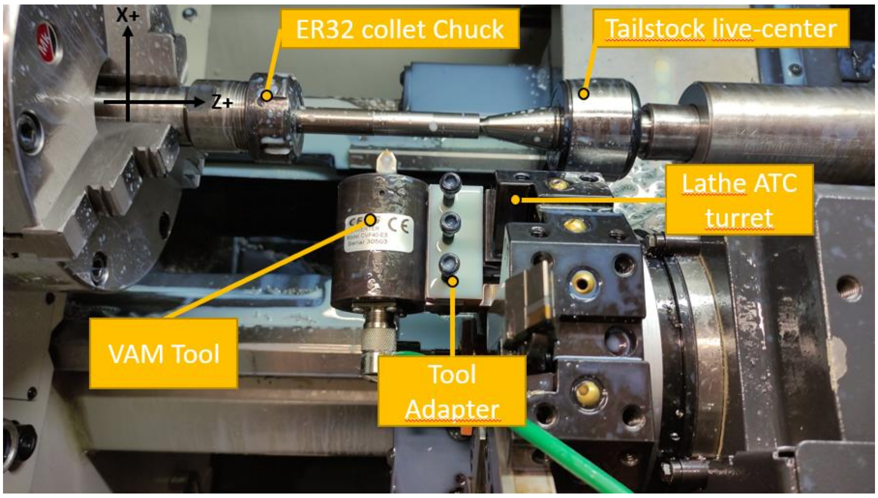

Figure 15: Setup 2 overview with VAM tool

The machining process uses three tools in 5 different type of operations. The first operation is a turning profile roughing, where a neutral tool is used to remove most of the material of the profile, the cutting parameters can be seen on the Table 1. Once the roughing is done, a pre-finishing turning profile is executed, where the same roughing tool is used but the cutting parameters will be the same as the ones used in the finishing operations. The third operations are where the VAM or NVAM process comes, an automatic tool change is executed and now the developed tool creates the finishing surface of the specimen. In this finishing pass, the operator must choose if the machining process will or will not have a VAM by activating or not the frequency generator. Once this operation has finished, the lathe pauses again automatically and a surface roughness test and dimensions are checked, if all the parameters are inside the allowed ranges, the following operations will be executed, if not an inspection of tools is made and the tool cutting inserts changed if needed. The two last machining operations consist in machining the extremes of the specimens and cutting off. In these operations the same neutral tool and a parting off tool are used.

Table 1: Machining operations

Op. Nº	Op type	S [m/min]	f [mm/rev]	Tool type
1	Profile roughing	20	0.25	Neutral
2	Profile "pre-finishing"	24	0.05	Neutral
3	Profile finshing	24	0.05	Neutral (VAM/NVAM)
4	Cylindrical turning	24	0.11	Neutral
5	Parting off	AUTO	AUTO	Band Saw

2.6. In machine inspection

After machining the specimens several experiments are carried out in order to be able to characterize the behavior of the tool in the machining process with or without vibration. A first in-machine measurement of surface roughness and diameter of the specimen is carried out to make sure that the parameters are within tolerance of the ISO-EN standards. In case that one of the measurements is not inside the range, that specimen is discarded and another one is manufactured applying the necessary corrections as it could be changing the tool insert or applying an offset to the tool.

Table 2 shows a summary of the manufactured samples is shown with the in-machine measurements done.

Table 2: In machine inspection roughness

Spec. ID	Finishing Process	Diameter	Mean Ra	Std. Dev.	Mean Rz	Rz Std Dev	Ratio [Ra/Rz]	Mean ratio	Std Deviation
1	VAM	8.03	0.860	0.008	3.507	0.062	0.245		
2	VAM	8.00	0.830	0.031	3.571	0.231	0.232		
3	VAM	8.00	1.104	0.021	4.530	0.074	0.244	0.224	0.021
5	VAM	8.02	0.660	0.046	3.410	0.109	0.193		
6	VAM	8.01	0.859	0.048	4.177	0.245	0.206		
11	NVAM	8.00	0.958	0.053	6.830	0.519	0.140		
12	NVAM	7.99	1.465	0.089	10.383	0.434	0.141		
13	NVAM	8.01	1.442	0.200	9.114	0.921	0.158	0.148	0.007328984
14	NVAM	7.99	1.341	0.190	8.645	0.975	0.155		
15	NVAM	7.98	1.261	0.074	8.634	0.692	0.146		

As it can be seen the ratio is also calculated in order to have another measure to confirm that the process is working as expected. Basically, when machining with a lathe the expected ratio must be found between 0.16 to 0.26 .

Once all samples are manufactured the following measurements has been carried out in the following order:

1. Surface Texture: to understand what is the characteristic surface that the tool has leaved with and without vibration
2. Fatigue testing: to characterize the material under fatigue cycling behavior.
3. Surface hardness: to see if the vibration leaves residual stresses or not

In the following sections the process of each of these experiments is explained and in-depth analysis of the results will be also carried out.

2.7. Tool principle and advantages

Most common applications of Ultrasonic sonotrode are found in the manufacturing industry, where they are used for applying heat to plastic surfaces and pressure at the same time in order to melt the plastic and join it. In the case of the machining tool the sonotrode is completely identical to these other ones, but the final application is completely different.

The main principle that drives the VAM tool is the sonotrode transmitting a high frequency low amplitude pulse to the horn where the tool insert is found. This transducer is driven by a high frequency generator where the resonance frequency is already set. In order to transmit the high frequency pulses from the generator to the transducer, a cable is needed, and it is important to note that this cable must have the specific length for the resonance frequency.

Once understood the principle, the main advantages and disadvantages found during the process are described in the list below.

- Advantages:
    - Compact design.
    - Tool adaptable to any range of machine.
    - Can be used for turning, profiling and facing if properly set.
    - Low maintenance cost.
    - Low cost if compared with an investment of a new machine.
- Disadvantages:
    - Long time for first setup and height regulation.
    - Many independent parts for being able to machine (tool, cable, generator).
    - At the moment only one insert available.

All this advantages and disadvantages were found during the machining process of the specimens and a new design is currently in process of being manufactured and tested.

3. Materials & methods:

3.1. Introduction

Surface roughness also known as Texture when measured in 3D is a very important quality indicator in the manufacturing process of high capacitation parts. Several theories have been probed that surface roughness level, incised on fatigue lifespan, hardness and tribology parameter of the manufacture piece. This is why a texture analysis is carried out in this project. Furthermore, if the VAM allows to obtain a constant / more constant surface finish this should be reflected on the fatigue life of specimens due to the less surface defects and cracks that can initiate the propagation and finally the fatigue failure.

Fatigue comes from de Latin word "*Fatigare*" which means "to tire". It is the progressive, localized, permanent structural change that occurs in materials subjected to fluctuating stresses and strains that may result in cracks or fractures after a sufficient number of fluctuations. The cyclic stresses are normally well below the yield strength of the material.

The main goal of fatigue cycling test is to analyze the impact of the vibration on machined specimens and to be able to determine whether it improves its endurance or not. In order to be able to create a SN curve to predict in future machined specimens the behavior it is recommended that at least 3 different loads need to be applied on the experimentation, this means to have a larger set of machined specimens than was possibly to manufacture.

For the sake of this project, the whole set of specimens has been cycled under a momentum of 10 Nm. Excess load and speed were previously tested to avoid thermal fatigue, that is an important consideration to have present in future investigations, it happened in one of the test samples.

Hardness is the resistance that a material opposes to be penetrated or cut by another one.

In the sake of the characterization of the tool it is a requirement to be able to determine how the application of the vibration can affect to this parameter. To obtain a reasonable set of measures a piece of cold rolled steel C45 has been machined with and without vibration and also one of the ends has only been cleaned with extra fine 1000 grit sandpaper. To measure the surface hardness a Vickers Hardness according to UNE-EN ISO 6507-1:2018 standard test has been done finding very promising results.

3.2. Surface Texture

To carry out the 3D surface roughness/ texture white-light interferometer has been used, which is a special type of Michelson interferometer that scans the surface height of the specimen. To achieve this, a beam splitter divides the beam coming from a white light source into two parts, the reference beam is reflected from a reference plane while the measurement being is incident on the test object when changing the distance between the sample and the interferometer. Optical interference occurs at every point of the surface where the optical path length is exactly the same for the reference and the measurement beam during the vertical scan. The interference patterns are captured by the video camera while the software computes the topography from this data.

As it has been mentioned on the theorical aspects section, the five most important parameters are: Sa, Sz, Sq, Sku and Ssk. As a brief summary the parameters that must be looked would be. It is important to note that these parameters are not directly comparable with surface roughness parameters due to the heterogeneity of the sample, which means that when measuring surface roughness depending on the direction a value is obtained, but in the case of the textures because they are statistical parameters (S) they take into count all the surface.

- Low Sa: is desired to be kept as low as possible to increase surface contact to reduce material wear over long periods of use.
- Low Sz: high value of Sz does not mean necessarily that the surface is rough, it can also mean that it has a low surface roughness in most of the area but in one concrete point it has a defect that could make It bigger, meaning a non-continuous finishing process.

- Sq: it gives us a statistical value about the standard deviation between peaks and valleys
- Ssk: The Skewness parameter is desired to be as close as 0 as possible to have as less peaks as possible, a higher Ssk will mean less contact area
- Sku: Based on the common definition of Kurtosis the main goal is to maintain it as close as 3 to have the maximum contact area.

Keeping or obtaining all of these values near the desired ones makes a part of the exactly same material and machining operations a higher performance part which will endure more under fatigue conditions and contact between moving parts

The machine used is a STIL WLI model Micromesure 2 (Figure 17) which uses a White Light Interferometer to perceive the differences in height of the surface. This equipment is a special type of Michelson interferometer that scans the surface height of the test object. To achieve this, a beam splitter divides the beam coming from a white light source into two parts the reference beam is reflected from a reference plane while the measurement being is incident on the test object when changing the distance between the sample and the interferometer optical interference occurs at every point of the surface where the optical path length is exactly the same for the reference and the measurement beam during the vertical scan the interference patterns are captured by the video camera while the software computes the topography from this data.

Figure 16: STIL WLI micromesure 2 WLI surface texture equipment

As it happens with other analysis procedures, in order to analyze the texture of the specimens, first of all the machine must be set up and prepared to hold securely the analyzed parts. To do so a pair of V blocks are used and centered and aligned with the WLI beam.

After setting the specimen the area of interest is defined in the Surface Map software, in this case, due to the low radius of the part a small patch area of 4x1 mm is defined to maintain the focus of the WLI. Subsequently the stepover between passes of the stylus must be set, in this case 0.01 is the chosen stepover to obtain high resolution surface texture. Once all this is set on the software, the stylus is focused and the measuring procedure can begin. After scanning all the patch, a graph appears in the computer screen and it must not have out of focus lines. If so, the measurement must be repeated and the stylus focused again.

The measurements have been taken using Surface Map, after the process is completed, a postprocess of the data must be performed using MOUNTAINS software, where all the parameters and signal filtering can be applied and modified if needed.

3.3. Fatigue

Once the whole set of specimens is machined, textures are inspected and all dimensions are within tolerance they are ready to be fatigue cycled, but first the fatigue machine must be set up. The machine used is the UMI Fatigue machine RFB200-500 (Figure 18), which as main futures includes an infinitely variable speed via potentiometer and a digital counter up to ten million cycles.

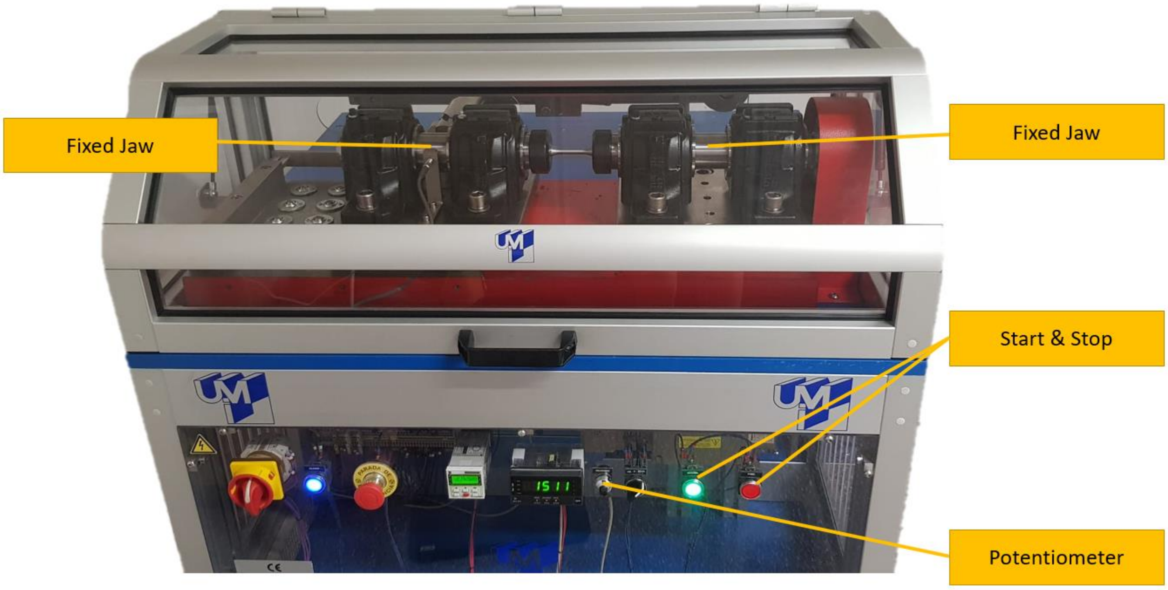

Figure 17: UMI fatigue machine

To begin with the preparation of the fatigue analysis machine some calculations need to be done following the hereunder presented equations and filling most of the unknowns with the machine parameters.

$$M = W \cdot L = 2 \cdot 0.5 = 10 \text{ [Nm]} \qquad \text{(Eq 3.1)}$$

$$\sigma_c = \frac{4 \cdot W}{\pi \cdot d^2} = \frac{4 \cdot 2}{\pi \cdot 8^2} = 0.0397 = 0.04 \text{ MPa} \qquad \text{(Eq 3.2)}$$

$$\sigma_f = 32 \cdot \frac{W \cdot L}{\pi \cdot d^3} = 32 \cdot \frac{2 \cdot 0.5}{\pi \cdot 8^3} = 0.0198 = 0.02 \text{ MPa} \qquad \text{(Eq 3.3)}$$

$$m = \frac{\sigma \cdot d^3}{49911} \qquad \text{(Eq 3.4)}$$

Procedure:

The machine is pretty simple to operate and it has three mains manipulating parts. First of all, in the front panel the main controls and the counter are found, where it is possible start, stop the machine and to read the number of cycles that the specimen has been brought under before breaking.

Then the moving and driven and drive jaws are found on the top of the machine, which basically are two axels mounted on two pillow blocks U200 each bearing mounts with a machined end of ER40 Jaws. The drive jaw is fixed to the machine bed connected to the electric motor and the driven is over a bearing bed so it has the two degrees of freedom needed. Lastly the weight is found on the back part of the machine, where several steel discs can be configured according to the experiment.

The operating procedure of the machine for the fatigue test is simple if all steps are followed correctly. First of all, the machine must not be running, so it is possible to access to the jaws area where both collet chucks have to be opened by the help of a wrench. Having the collets opened introduce each end of the fatigue specimen and tight securely, be aware that overtightening ER collets can cause runout, introducing an added cyclical vibration and ruining the test.

Figure 18: Fatigue specimens (uncycled left, cycled right)

Making sure that the specimen is correctly tightened, it is proceeded to set the rpm for the desired experiment, it is important to understand that, whether the formulas from the ISO standard for fatigue testing does not have in mind the rpm, if the load is too high or the rpm, it appears the phenomenon known as thermal fatigue, again, invalidating the test.

As mentioned, thermal fatigue avoidance: several tests have been performed before beginning with the analysis of the first set of VAM and NVAM fatigue test. These first tests were performed with the intention to obtain a first SN parameters to be able to test the specimens without incurring in thermal fatigue phenomenon, which basically can be produced by the combination of high load at high speed and produces a high variability on the results

3.4. Hardness

Hardness testing of round specimens is a technique that requires not only testing the samples as it were flat, but also some further calculations are needed to apply a correction for the round shape if the correlation between the mean diagonal and the diameter is before a threshold. Also, it is important to understand that due that the specimens are not mirror finished "polished", the results may have a slightly larger deviation as if they were super finished. All the experiments have been performed according to the UNE EN ISO 6507-1 2018

The performed analysis has used Micro-durometer STRUERS DURAMIN-5 with 50X magnification lens and a preload of 200 g. Because the material is a carbon steel, distance between indentations has been above three times the indentation size as specified on the ISO standard (UNE EN ISO 6507-1 2018).

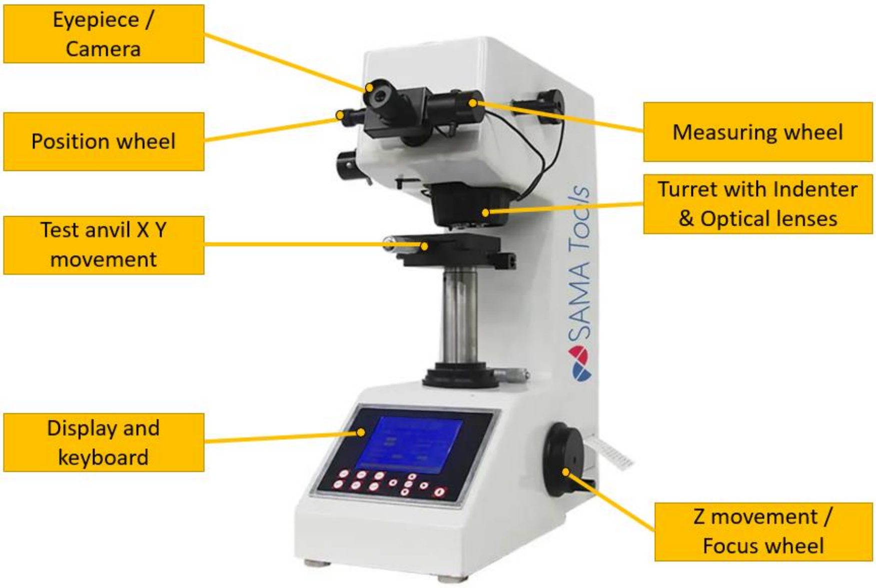

Figure 19: Vickers Hardness machine

To begin the surface hardness tests first thing to do is to set the specimen on the xy coordinate table using a V block fixture, which will allow to perform the indentations and the part will not move. Once the part is set, due it is a round part, the high spot must be found by moving the sample with the xy nonius of the test anvil and making sure the whole surface is in focus, this is the task that requires more time but is very important to do it correctly to obtain constant results. Then the indentations can be performed one after another following the hereunder steps:

1. Focus the magnification lens to be able to see the surface with clarity
2. Adjust contrast, brightness and saturation of the camera.
3. Perform the indentation
4. Set the eyepiece aligned and measure the first diagonal of the indentation stamp by using the position and measuring wheel
5. Rotate 90º and measure the second diagonal of the indentation stamp
6. Perform the Vickers Hardness Calculation

Once all the measures have been obtained, a filtering is performed using a excel spreadsheet, with it we obtain the validation of the measures taken.

To apply the compensation for the diameter the following procedure must be followed:

- Perform the mean of the diagonal measure of the indentations, it will be referred as d in the formula
- Measure the diameter of the inspected part, it will be referred as D in the formula.
- The division of $\frac{d}{D}$ will give us the number to check in the correction charts

Once the number is found for each set of surface hardness, checking the tables B.3 to B.6from the ISO STANDARD UNE EN ISO 6507-1 2018, it is found that due the correlation between d and D is so small, the correction factor will be 1, so no correction is needed to apply for these set of surface hardness experiments.

4. Results:

In this section a summary of the obtained results during the different experiments is shown. In all the results the mean and standard deviation has been calculated. In the following section an in-depth analysis is made using F of fisher statistical test.

4.1. Textures

Texture results, as it would be seen on the following sections, are the ones that have been most difficult to obtain correctly and it is assumed that due to the shape of the specimens, the obtained results are not as it would be expected. Nevertheless, the results are presented and contributed to this project as a knowledge base. Hereunder in Fig. 18, it is possible to difference the constant profile of the turned surface obtained with and without vibrations, the final results of surface texture parameters don't differ as it could have been expected.

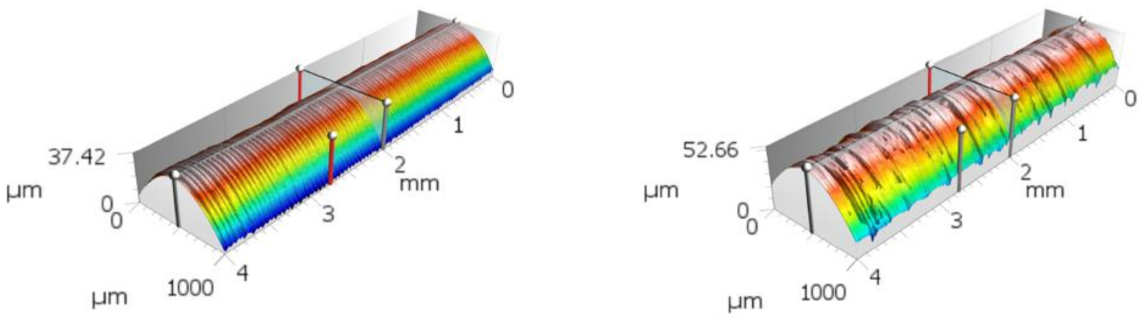

Figure 20: Surface texture output representation (left: VAM , right NVAM)

For both machining processes the mean of obtained textures and standard deviation can be seen on tables

Table 3: Textures VAM

Textures VAM Machined samples							
Specimen ID	**Specimen nº**	**VAM / NVAM**	**Sa**	**Sz**	**Sq**	**Ssk**	**Sku**
1	1	VAM	8.266	37.42	9.619	-0.6108	2.145
2	2	VAM	8.285	40.26	9.658	-0.646	2.207
3	3	VAM	8.275	52.15	9.663	0.6401	2.236
4	4	VAM	8.204	49.38	9.612	0.6519	2.278
5	5	VAM	8.333	39.39	9.765	0.6903	2.308
6	5	VAM	8.164	39.63	9.544	0.6534	2.236
Avgerage VAM			**8.2545**	**43.0383**	**9.6435**	**0.22982**	**2.235**
Standard Deviations VAM			**0.055355668**	**5.58944**	**0.06689**	**0.60713**	**0.05174**

Table 4: Textures NVAM

Textures NVAM Machined Samples							
Specimen ID	**Specimen nº**	**VAM/NVAM**	**Sa**	**Sz**	**Sq**	**Ssk**	**Sku**
11	6	NVAM	8.419	43.91	9.888	0.6513	2.295
12	7	NVAM	12.93	75.13	15.08	0.3639	2.077
13	8	NVAM	8.455	59.45	10.02	0.6718	2.498
14	9	NVAM	8.889	148.3	10.78	1.3290	10.280
15	10	NVAM	8.828	52.66	10.34	0.6389	2.300
Avgerage NVAM			**9.5042**	**75.89**	**11.2216**	**0.73098**	**3.89**
Standard Deviations NVAM			**1.72339**	**37.6202**	**1.95355**	**0.3196**	**3.19778**

Texture parameters are more constant in VAM machining than NVAM, as it can be seen standard deviations when vibration is applied are lower than in conventional cutting, making it a more reliable process.

4.2. Fatigue

Fatigue results are one of the most revealing of this whole investigation due to the large difference between VAM and NVAM machining. As it can be seen, VAM specimens have a longer fatigue life around 35 times more than NVAM specimens.

Table 5: Fatigue life results VAM and NVAM

Specimen ID	Specimen nº	VAM/NVAM	Load [N]	nº of cycles	MEAN	SD
1	1	VAM	20	10302939		
2	2	VAM	20	9956474		
3	3	VAM	20	11000384		
4	4	VAM	20	9876017		
5	5	VAM	20	10000063		
6	6	VAM	20	12500000	10605979.5	927051
11	7	NVAM	20	406020		
12	8	NVAM	20	358377		
13	9	NVAM	20	253164		
14	10	NVAM	20	162280		
15	11	NVAM	20	169206	269809.4	98344.5

4.3. Hardness

Surface hardness has been performed as the last step of the whole experimentation. Due to the previous experience with the distortion between results, a lot of measurements have been performed for each case. VAM specimens show a larger surface hardness, also larger than the raw cold rolled material, as shows Table 6.

Table 6: Surface Hardness NVAM

Surface Hardness HV NVAM			PL 200g
Sample measurement nº	**HV**	**Deviation HV**	**Deviation HV %**
1	248.90	51.06	17.02
2	322.70	22.74	7.58
3	318.00	18.04	6.02
4	286.20	13.76	4.59
5	271.70	28.26	9.42
6	307.00	7.04	2.35
7	343.70	43.74	14.58
8	278.40	21.56	7.19
9	351.20	51.24	17.08
10	282.30	17.66	5.89
11	302.80	2.84	0.95
12	295.10	4.86	1.62
13	285.40	14.56	4.85
14	306.00	6.04	2.01
Mean	299.96	21.67	7.22
Std Dev	26.8365	15.82873259	5.276998055

Table 7: Surface hardness VAM

Surface Hardness HV VAM			**PL 200g**
Sample measurement nº	**HV**	**Deviation HV**	**Deviation HV %**
1	367.90	22.34	6.46
2	358.80	13.24	3.83
3	330.50	15.06	4.36
4	316.20	29.36	8.50
5	339.60	5.96	1.73
6	362.20	16.64	4.81
7	363.30	17.74	5.13
8	386.00	40.44	11.70
9	378.00	32.44	9.39
10	315.30	30.26	8.76
11	329.50	16.06	4.65
12	332.50	13.06	3.78
13	332.50	13.06	3.78
14	325.60	19.96	5.78
Mean	345.56	20.40	5.90
Std Dev	22.346576	9.11735539	2.638396318

5. Results Analysis

In order to analyze the obtained results a F of Fisher analysis was proceed to be made. The main goal of this analysis is to determine whether the vibration has an influence in the results obtained or not. All the measurements have been analyzed with this methodology as a statistical approximation, but in some cases, results are so near that a small deviation in a measurement of a specimen could have caused a non-conclusive result. In further investigations these results will be previously filtered to try to avoid this type of conclusions.

In the F of Fisher analysis in the end two values are obtained; F1 and F2. This value will be compared following the next rule

If F1> F2, it means that there is a correlation between the data obtained in the experiment. In this way, it can be stated for the parameter that it is significant about the values. In any other case it is not sure that there exists a correlation. The confidence Interval has been chosen of a 95%.

5.1. F of Fisher test for textures

As it has been explained on the previous knowledge section, the textures are a statistical result from the measured heights of the surface of a part, these texture parameters are very useful not only to see the final value but also to visualize the surface geometry.

By applying the F of fisher, and based only on the obtained results, it can be concluded that VAM is not a conclusive parameter which enhances or decreases the texture quality of the specimens.

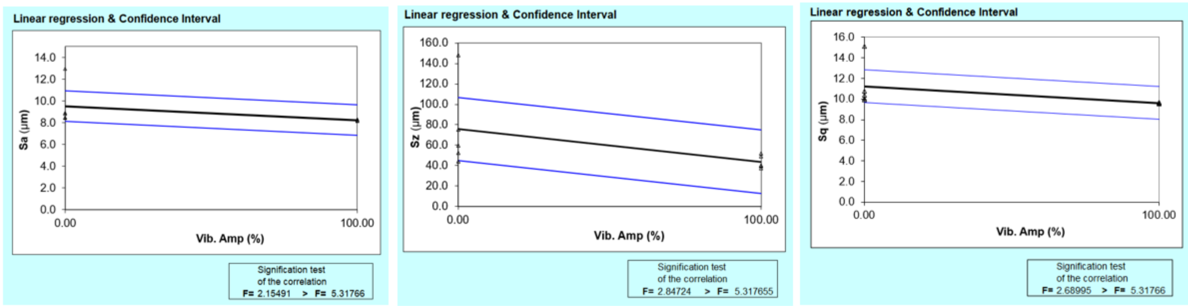

Figure 21: F of fisher (left Sa , middle Sz , right Sq)

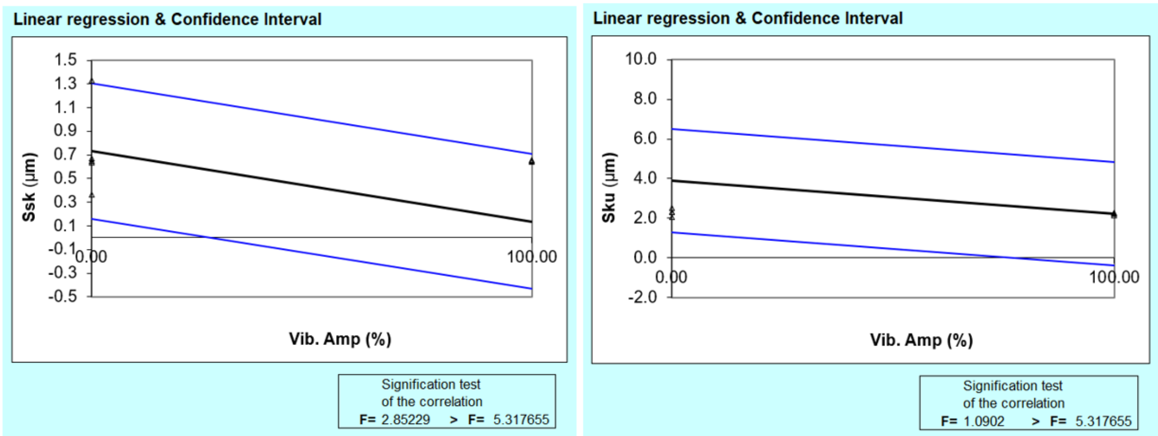

Figure 22: F of fisher (left Ssk right Sku)

Despite that the F of fisher analysis is not conclusive, it is important to mention again that in this case and as it happens in the others, VAM texture results are more constant than NVAM specimens, making it a more reliable process for high end parts or high production with high standards part. This can be seen very clearly in Figures 22 and 23 by comparing all the standard deviations from the obtained measures results. Clearly VAM has a lower standard deviation than NVAM meaning is a more constant machining process. This can be attributed to the reduction ion cutting forces generates les chatter leaving a more constant and lower roughness surface.

5.2. F of Fisher test for Fatigue experiment

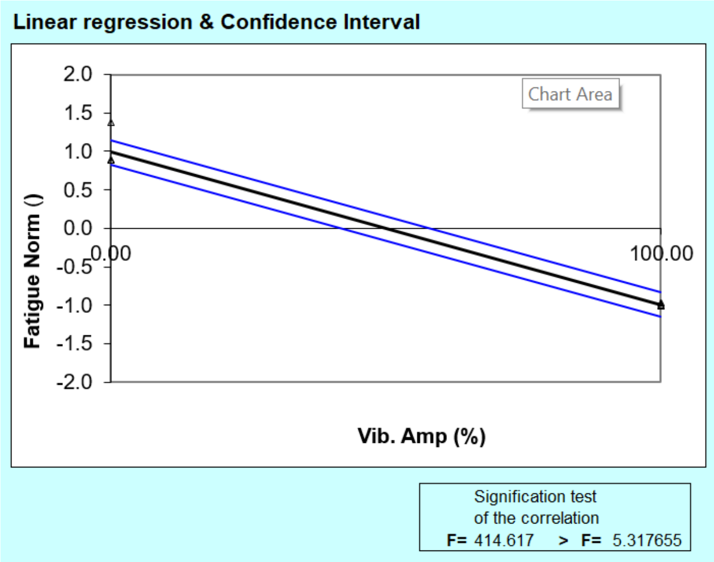

Figure 23: F of Fisher Fatigue

Fatigue testing was one of the clearest results that the VAM process is a machining technology which increases the defects of the surface, as it has been seen on Figure 24, NVAM specimens of the same material and fatigue cycling parameters broke 25 times earlier than VAM specimens in the best-case scenario, also the deviation between samples is way larger in NVAM due to the lack of constant surface and machining.

5.3. F of Fisher for Hardness test

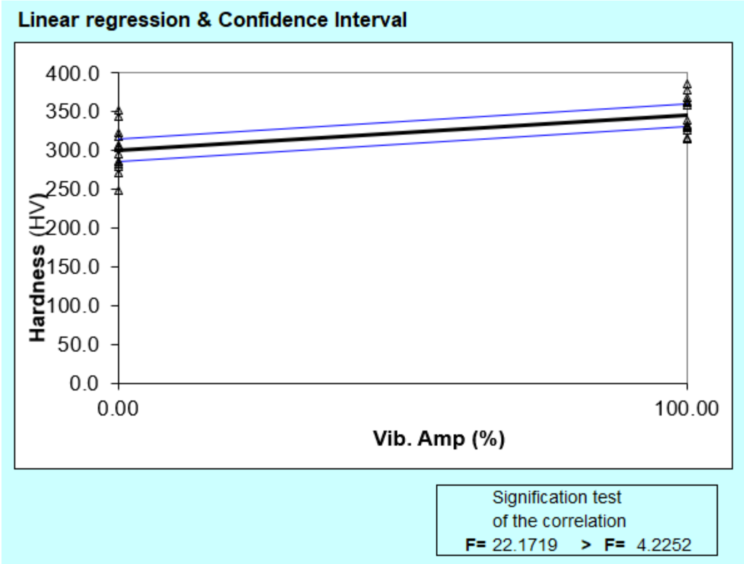

Figure 24: F of Fisher Surface hardness

Once performed the F of Fisher for hardness it is clear that VAM enhanced the Surface hardness of the specimens, as it can be seen on Figure 25, by applying F of Fisher statistical analysis it is possible to confirm again that VAM enhances the properties of the machined specimens and in this case converts it onto a harder Surface. The F1 is nearly over five times higher than F2 which confirms the initial hypothesis.

One of the main possibilities of this increase in the surface hardness is that when machining with vibration, the small amplitude high frequency applied in the insert is transmitted to the part surface. This chatter not only reduces cutting forces but it may be burnishing the surface leaving more residual stresses than if it is machined without vibration. This explanation makes sense with all the previous results found, where fatigue life is increased not only by the surface texture but also because of the increase in surface hardness.

Environmental Impact Analysis

To manufacture the tool and the various specimens, raw materials have been used, which have generated waste when machining the parts. Electric energy has also been used to be able to use the machining machines and heat treatments and test machines. In addition, having used coolant liquids during the machining operations of the parts, it must also be considered that some of these have been discharged into the environment. Regarding these aspects related to the manufacture of the tool and the specimens, it should only be added that it is recommended to optimize the manufacturing process as much as possible so that energy expenditure is as low as possible. And, on the other hand, it is recommended to correctly recycle the cutting fluid used in machine tools, when it needs to be replaced.

The finishing technology by VAM cuts the material, but as it can be seen in the conclusions, the results are better and more constant than NVAM. This makes this process cleaner and less harmful to the environment by reducing waste.

Also, it must be considered that, to operate the tool, it must be mounted on a CNC machining center, which consumes electrical energy while finishing the part. For this reason, it is also recommended, as is the case of its manufacturing process, the optimization of the process to reduce energy consumption.

The tool inserts wear out as they are used, once the insert has worn out it must be replaced with a new one, this generates a waste of material. Consideration is given to recycling them as scrap when they cannot be further grinded using certified providers as Sandvik coromant which reuses the worn carbide.

Economic analysis

This chapter breaks down the costs associated with the development of the VAM tool and all the performed tests. In this analysis, the design hours, the costs of materials associated with the manufacture of the prototype, the costs of the machine operator for the manufacture and testing of the prototype, the software costs and those of external subcontracting for the finishing of the prototypes will be considered.

Labor & Salaries				
Función	**Precio/hora (€/h)**	**Horas (h)**	**Subtotal (€)**	**Descripción**
Senior engineer	90,00	40	3600,00	Project supervision
CAD CAM CNC operator	45,00	13	585,00	CAD CAM and CNC programming
Junior engineer	30,00	300	9000,00	Project execution
Machine operator	35,00	35	1225,00	Manufacturing of parts
Lab Technician	15,00	5	75,00	Test performing and data gathering
Total Labor & Salaries			14410,00	€

Materials			
Material	**Price**	**Qtty**	**Subtotal**
C45 steel bar (3 m)	50,00	5	250,00
VAM tool	2662,00	1	2662,00
Vibration generator	2511	1	2511,00
roughing tool	85,64	5	428,20
roughing insert	10,21	4	40,84
finishing insert	12,32	5	61,60
Total Material		5953,64	€

Machine use			
Machines	**Price/h**	**hours**	**Subtotal**
Manual Lathe	25,00	2	50,00
CNC lathe	50,00	45	2250,00
Surface rougness meter	15,00	5	75,00
Vickerss	15,00	5	75,00
Fatigue	1,23	7000	8610,00
Total Machine use		11060,00	€

Software	
Software	**Cost of Licence (€)**
Fusion 360 CAD CAM	1000,00
Microsoft Office	99,00
Total software	1099,00 €

Summary	
Concept	**Subtotal €**
Labor	14410,00
Materials	5953,64
Machines	11060,00
Software	1099,00
Subcontract	700,00
Project Costs	33222,64

Conclusions

After finishing this project, it is possible to extract the following conclusions:

- The design of the VAM tool is useful but needs to continue evolving to make it more reliable in setup time.
- The found machining parameters are a good start point to continue testing the VAM tool, but it is not possible to say that they are the optimal ones. More experiments are necessary to obtain them.
- VAM is a machining technology that enhances the surface hardness of the specimens by a 15% due to the more constant surface it leaves.
- VAM increases the fatigue life by 38 times respect to NVAM specimens with the tested parameters, giving a promising future.
- VAM is a way of improving surface texture but more experiments need to be carried out.
- For future investigation more, fatigue testing needs to be made to be able to characterize the tool perfectly being able to create SN curve. Also, a DOE with the found feeds and speeds need to be made and fractography study.

Bibliography

[1] BREHL, DE and; DOW, T. A. Review of vibration-assisted machining. *Precision engineering*, 2008, vol. 32, no 3, p. 153-172.

[2] XU, Wei-Xing; ZHANG, Liang-Chi. Ultrasonic vibration-assisted machining: principle, design and application. *Advances in Manufacturing*, 2015, vol. 3, no 3, p. 173-192.

[3] GOMEZ–GRAS, Giovanni, et al. Experimental study of lateral pass width in conventional and vibrations-assisted ball burnishing. *The International Journal of Advanced Manufacturing Technology*, 2016, vol. 87, no 1, p. 363-371.

[4] ZHENG, Lu; CHEN, Wanqun; HUO, Dehong. Review of vibration devices for vibration-assisted machining. *The International Journal of Advanced Manufacturing Technology*, 2020, vol. 108, p. 1631-1651.

[5] ZHANG, XinQuan, et al. A study of the diamond tool wear suppression mechanism in vibration-assisted machining of steel. *Journal of Materials Processing Technology*, 2014, vol. 214, no 2, p. 496-506.

[6] ESTEVEZ-URRA, Aida, et al. Monitoring of Processing Conditions of an Ultrasonic Vibration-Assisted Ball-Burnishing Process. *Sensors*, 2020, vol. 20, no 9, p. 2562.

[7] GAO, Yuan; SUN, Ronglei; LEOPOLD, Jürgen. Analysis of Cutting Stability in Vibration Assisted Machining Using Ananalytical Predictive Force Model. Procedia CIRP, 2015, vol. 31, p. 515-520.

[8] «Oberflächen & Rauheitswerte - Rt, Rmax, Rz, Ra, Rp, Rmr». http://www.technisches-zeichnen.net/technisches-zeichnen/diverses/rauheitswerte.php. [consulted: 12-may-2019].

[9] ERDEMIR, Firket . How to write a materials and methods section of a scientific article? ncbi.nlm.nih.gov/ https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4548564/#:~:text=It%20is%20generally%20recommended%20that,methods%20should%20be%20described%20sequentially.
[consulted 23/04/2021]

[10] KEYENCE, 2018 Area Roughness Parameters. keyence.eu. https://www.keyence.eu/ss/products/microscope/roughness/surface/tab04_c.jsp [consulted: 02/05/2021]

[11] Rudolf J. Freund, ... Donna L. Mohr, in Statistical Methods (Third Edition), 2010

[12] NIST, 2019. 1.3.5.11. Measures of Skewness and Kurtosis. *itl.nist.gov.* https://www.itl.nist.gov/div898/handbook/eda/section3/eda35b.htm#:~:text=Skewness%20is%20a%20measure%20of,precisely%2C%20the%20lack%20of%20symmetry.&text=Kurtosis%20is%20a%20measure%20of,have%20heavy%20tails%2C%20or%20outliers. [consulted: 25 may 2021].

[13] WESTOMORELAND, 2019. What is fatigue testing. *Wmtr.com* https://www.wmtr.com/What_Is_Fatigue_Testing.html [consulted: 12 January 2020].

[14] ULTRASONICRESONATORORG 2018. Piezoelectric Design (preliminary) . ultrasonic-resonators.com http://www.ultrasonic-resonators.org/design/transducers/transducer_design.html [consulted:10 may 2021]

Annexes

All files related with measurements and machine user manuals can be found on the link below

https://drive.google.com/drive/folders/190skPFuo7Cm_-9hcfTpPtZkeY48plJ2w?usp=sharing