escola superior de tecnologia e gestão
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Project Work

Masters in Product Design Engineering

LASER MACHINING STEEL FOR MOULDS: A CASE STUDY

Ayisha Yolchuyeva

Leiria, *July*, 2016

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Ayisha Yolchuyeva

Master's project work carried out under the supervision of Doctor Carlos Alexandre Bento Capela, and Co-supervision of Doctor Henrique de Amorim Almeida and Doctor Mário António Simões Correia, Professors of the School of Technology and Management of the Polytechnic Institute of Leiria.

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Resumo

A maquinação por laser é um processo de fabrico subtrativo não tradicional. Este processo utiliza a energia térmica para remover o material metálico ou não-metálico das superfícies a maquinar. O laser é focado sobre a superfície a ser maquinada, em que a energia térmica do laser é transferida para a superfície, por aquecimento e fusão ou vaporização do material a remover da peça. A maquinação por laser é o processo mais adequado para materiais frágeis, com baixa condutividade, mas pode ser utilizado na maioria dos materiais. O laser é o sistema principal do equipamento e as suas características determinam em grande medida os parâmetros qualitativos e quantitativos do processo tecnológico.

Neste trabalho, foram selecionados os parâmetros de processamento por maquinação laser para as operações planeadas e consideradas neste trabalho. Era importante conhecer o processo de maquinação por laser bem como os parâmetros de processamento a utilizar para materiais diferentes. Como consequência da maquinação por laser, o acabamento das superfícies pode apresentar diferentes propriedades, tais como, dureza superficial, rugosidade superficial, atrito superficial e tribologia, etc. Durante este processo, foi possível adquirir conhecimentos sobre o quadro histórico e conceitual do laser, conhecer diferentes parâmetros de laser e como estes podem influenciar as propriedades superficiais das peças maquinadas por laser.

Palavras-chave: Laser Fresagem, Micron, de superfície, dureza, rugosidade

Abstract

Laser beam machining is a non-traditional subtractive manufacturing process, a form of machining, in which a laser is directed towards the work piece for machining. This process uses thermal energy to remove material from metallic or non-metallic surfaces. The laser is focused onto the surface to be worked and the thermal energy of the laser is transferred to the surface, heating and melting or vaporizing the material. Laser beam machining is best suited for brittle materials with low conductivity, but can be used on most materials. The role of the technical equipment in laser milling is to perform a controllable action of the laser radiation on the material to be treated. The laser is the main unit of the equipment and it is characteristics determine to great extent the qualitative and quantitative parameters of the technological treatments.

In this work, I had to study the laser milling process parameter selection for process planning operations from start to finish. It was important to have an understanding about laser milling and laser processing parameters for different materials. As a result from the laser milling, the surface finish will have different surface properties such as, surface hardness, surface roughness, friction and tribology etc.. During the process, I gained knowledge about the historical and conceptual framework of laser milling, the different parameters of a laser milling and how the laser milling parameters influence the surface properties of the machined parts.

Keywords: Laser Milling, Micron, Surface, Hardness, Roughness

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List of Symbols

ESTG	School of Technology and Management
Laser	Light Amplification by Stimulated Emission of Radiation
E1,E2	Excited and ground energy levels
ΔE	Energy difference
h	Planck's constant
v	Characteristic frequency
µ	Micron
m	Meter
µm	Micrometer
°C	Selsius
Pa	Pascal (pressure)
MPa	Megapascal (1.000.000 Pa)
GPa	Gigapascal (1.000.000.000 Pa)
F	Load in kf force
d	Standard diagonal size
L1,L2	Length of diagonal
λa	Average wavelength
λq	Square wavelength
MR(1,2)	Material ratio delimiting the core area
HV	Hardness Vickers
AA	Arithmetic Average

CLA	Center Line Average
Ra	Roughness average
Rz	Maximum height of the profile
Rmax	Maximum roughness height
Rk	Core roughness depth
Rzi	The single roughness depth
Rpk	Reduced peak height
Rvk	Reduced valleys depth
Steel 1.2344	Metal/ Main content: 0.39% C, 1.0% Si, 0.4% Mn, 5.3% Cr, 1.3% Mo, 0.9 % V

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Chapter I

1.1 Introduction

This document is a study about the process of laser milling and laser processing parameters. Along with Professor Carlos Alexandre Bento Capela (Doctor) and Professor Henrique Amorim Almeida, it was decided to make a project work relating to the laser milling.

The role of the technical equipment in laser micro technology is to perform a controllable action of the laser radiation on the material to be treated. In initiates a concrete technological process in areas of precisely controllable shape and size. The laser is the main unit of the equipment and it is characteristics determine to great extent the qualitative and quantitative parameters of the technological treatments.

In this work, I had to follow the laser milling process parameters selection for process planning operations from start to finish, because it was important to have an understanding about what laser machining, micromachining, laser milling and laser material interaction are, then, about laser processing of different materials (mainly steel 1.2344) and the laser processing parameters (including surface hardness, surface roughness, surface friction, surface contact angle, tribology (the study of friction) etc.). During the process, I gained knowledge about the historical and conceptual framework of laser, the different parameters of a laser milling, machining processing of different material, also about problem solving methods of the same issues related titles.

1.2 Report Structure

This work is structured as follows:

<u>Chapter 1</u>

The first part is covered by presentation and description of project structure.

Chapter 2

This section is state of the art mainly related to laser beam machining, laser technology, laser assisted machining processes and micromachining technologies by entering connected topics.

Chapter 3

3rd chapter referring to the experimental material which will be presented in this work, procedures and parameters, processes and also to the different equipments (Surface Hardness and Roughness Tester).

Chapter 4

This chapter make reference to the experimental materials and procedures. The material *Steel 1.2344* which used in this work is presented parameters and also be referred to the different equipments (Surface Roughness and Surface Hardness Tester).

Chapter 5

Research quits with Discussion of results.

Chapter 6

Final conclusion and considerations.

Chapter II

2. State of the Art

Manufacturing, in its comprehensive sense, is the process of converting raw materials into products. Manufacturing also involves activities in which the manufacturing product, itself, is used to make other products. Examples could include large processes to shape sheet metal for appliances and car bodies, machinery to make fasteners, such as bolts and nuts, and sewing machines to make clothing. A nation’s level of manufacturing activity is related directly to its economic health; generally, the higher the level of manufacturing activity in a country, the higher the standard of living of its people. *[1]*

The world manufacturing is derived from the Latin *manu factus*, meaning made by hand. The word *manufacture* first appeared in 1567, and the word “manufacturing” appeared in 1683. The word *product* means something that is produced, and the words “product” and “production” often are used interchangeably. *[1]*

Because a manufactured item typically has undergone a number of processes in which pieces of raw material have been turned into a useful product, it has a value-defined as monetary worth or marketable price. For example, as a raw material for ceramics, clay has some small value as mined. When the clay is made into the ceramic part of a spark plug, a vase, a cutting tool, or an electrical insulator, value is added the clay. *[1]*

Manufacturing is generally a complex activity involving a wide variety of resourced and activities, such as the following:

- Product design
- Machinery and tooling
- Process planning
- Materials
- Purchasing
- Manufacturing
- Production control

- Support services
- Marketing
- Sales
- Shipping
- Customer service

It is essential that manufacturing activities be responsive to several demands and trends:

1. A product must fully meet *design requirements*, *product specification*, and *standards*.
2. A product must be manufactured by the most *economical* and *environmentally friendly* methods.
3. *Quality* must be *built into the product* at each stage, from design to assembly, rather than relying on quality testing after the product is manufactured.
4. In the highly competitive environment of today, production methods must be sufficiently *flexible* to respond to changing market demands, types of products, production rates, production quantities, and to provide on-time delivery to the customer.
5. Continuous developments in *materials*, *production methods*, and *computer integration* of both technological and managerial activities in a manufacturing organization must be evaluated constantly with a view to their appropriate, timely, and economical implementation.
6. Manufacturing activities must be viewed as a large system, all parts of which are interrelated to varying degrees.
7. The manufacturer must work with the customer for timely feedback for *continuous product improvement.*
8. Manufacturing organization constantly must strive for higher level of *productivity*, defined as the optimum use of all its resources such as materials, machines, energy, capital, labor and technology; output per employee per hour in all phases must be maximized. *[1]*

An extensive and continuously expanding variety of manufacturing processes are used to produce parts and there is usually more than one method of manufacturing a part from a given material. The broad categories of the methods for materials are as follows, referenced to the relevant part in this text and illustrated with examples for each:

a) *Casting*: Expendable mould and permanent mould

b) *Forming* and *shaping*: Rolling, forging, extrusion, drawing, sheet, forming, powder metallurgy and moulding.

c) *Machining*: Turning, boring, drilling, milling, planning, shaping, broaching, and grinding, ultrasonic machining, chemical, electrical and electrochemical machining; and high-energy-beam machining. This category also including *micromachining* for producing ultraprecision parts.

d) *Joining*: Welding, brazing, soldering, diffusion bonding, adhesive bonding and mechanical joining.

e) *Finishing*: Honing, lapping, polishing, burnishing, deburring, surface treating, coating and plating.

f) *Nanofabrication*: It is the most advanced technology and is capable of producing parts with dimensions at the nano level (one billionth); it typically involves processes such as etching techniques, electron-beams and laser-beams. Present application are in the fabrication of micro electromechanical system (MEMS) and extending to nano electromechanical systems (NEMS), which operate on the same scale as biological molecules. *[1]*

Selection of particular manufacturing process or a sequence of processes depends not only on the shape to be produced but also on other factors pertaining to material properties. Brittle and hard materials cannot be shaped or formed easily, whereas they can be cast, machined or ground. Metals that are previously formed at room temperature become stronger and less ductile than they were before processing them, and thus will require higher forces and be less formable during secondary processing. *[1]*

All *machining processes* discussed up to this point were characterized by the mechanical removal of material in the form of chips, even though chip formation may have been imperfect. There are numbers of processes that remove material by melting, evaporation, or chemical and/or electrical action; collectively they are often denoted as *nonconventional* or *nontraditional* processes. Some of these processes are not really new but have gained wider industrial application primarily because of the demands set by the aerospace and electronic industries. As a group they are characterized by insensitivity to the hardness of the workpiece material, hence they are suitable parts from fully heat-treated materials, avoiding the problems of distortion and dimensional change that often accompany heat treatment. *[2]*

Machining consists of several major types of material-removal processes:

- Cutting, typically involving single-point or multipoint cutting tools, each with a clearly defined shape.
- Abrasive processes, such a grinding and related processes.
- Advance machining processes utilizing electrical, chemical, laser, thermal, and hydrodynamic methods to accomplish this task.

Machines on which these operations are performed are called *machine tools*. *[1]*. As in other manufacturing operations, it is important to view machining operations as a *system*, consisting of the

- *Workpiece*
- *Cutting tool*
- *Machine tool*
- *Production personnel*

Machining cannot be carried our efficiently or economically and also meet stringent part specifications without a thorough knowledge of the interactions among these four elements. *[1]*. The machining processes describe in above involved material removal by mechanical means, by either chip formation, abrasion or micro chipping. However, there are situations where mechanical methods are not satisfactory, economical, or even possible for the following reason:

- The workpiece material is too *brittle* to be machined without damage to the workpiece. This is typically the case with highly heat-treated alloys, glass, ceramics and powder-metallurgy parts.
- The workpiece is too flexible or too slender to withstand forces in machining or grinding or the parts are difficult to clamp in fixtures and work-holding devises.
- Special *surface finish* and *dimensional tolerance* requirements exist that cannot be obtained by other manufacturing processes or are uneconomical through alternative processes.
- *Temperature rise* during processing and *residual stresses* developed in the workpiece are not desirable or acceptable. *[1]*

Here in below Table 1 displays classification of non-traditional machining processes:

Table 1 - Classification of non-traditional removal processes

Non-traditional machining processes				
Chemical machining	*Electrochemical machining*	*Electrical discharge machining*	*High-energy beam machining*	*Other processes*
Engraving	Milling	RAM EDM	Electron beam	Plasma arc
Milling	Grinding	Wire EDM	Laser beam	Water Jet
Blanking	Shaped-tube electrolyte machining	Drilling		Abrasive waer jet
Photochemical machining		Grinding		Ultrasonic
Thermochemical deburring				

When selected and applied properly, advanced machining processes offer major technical and economic advantages over more traditional machining methods. *[1]*. Regarding to the project work which covers mainly Electrochemical and High-energy beam machining, paper continue on laser beam machining.

2.1 Laser Beam Machining

Laser beam machining (LBM) is a non-traditional subtractive manufacturing process, a form of machining, in which a laser is directed towards the work piece for machining. This process uses thermal energy to remove material from metallic or non-metallic surfaces. The laser is focused onto the surface to be worked and the thermal energy of the laser is transferred to the surface, heating and melting or vaporizing the material. Laser beam machining is best suited for brittle materials with low conductivity, but can be used on most materials.

Lasers can be used for welding, cladding, marking, surface treatment, drilling, and cutting among other manufacturing processes. It is used in the automobile, shipbuilding, aerospace, steel, electronics, and medical industries for precision machining of complex parts. Laser welding is advantageous in that it can weld at speeds of up to 100 mm/s as well as the ability to weld dissimilar metals. Laser cladding is used to coat cheap or weak parts with a harder material in order to improve the surface quality. Drilling and cutting with lasers is advantageous in that there is little to no wear on the cutting tool as there is no contact to cause damage. Milling with a laser is a three dimensional process that requires two lasers, but drastically cuts costs of machining parts. Lasers can be used to change the surface properties of a workpiece.

Laser beam machining can also be used in conjunction with traditional machining methods. By focusing the laser ahead of a cutting tool the material to be cut will be softened and made easier to remove, reducing cost of production and wear on the tool while increasing tool life.

The appliance of laser beam machining varies depending on the industry. In heavy manufacturing laser beam machining is used for cladding and drilling, spot and seam welding among others. In light manufacturing the machine is used to engrave and to drill other metals. In the electronic industry laser beam machining is used for wire stripping and skiving of circuits. In the medical industry it is used for cosmetic surgery and hair removal. *[3]*

Milling is the *machining* process of using rotary *cutters* to remove material from a workpiece by advancing (or *feeding*) in a direction at an angle with the axis of the tool. It covers a wide variety of different operations and machines, on scales from small individual parts to large, heavy-duty gang milling operations. It is one of the most commonly used processes in industry and machine shops today for machining parts to precise sizes and shapes. *[4]*

Milling can be done with a wide range of *machine tools*. The original class of machine tools for milling was the milling machine (often called a mill). After the advent of *computer numerical control (CNC)*, milling machines evolved into machining centres (milling machines with automatic tool changers, tool magazines or carousels, CNC control, coolant systems, and enclosures), generally classified as vertical machining centres (VMCs) and horizontal machining centres (HMCs). The integration of milling into *turning* environments and of turning into milling environments, begun with live tooling for lathes and the occasional use of mills for turning operations, led to a new class of machine tools, multitasking machines (MTMs), which are purpose-built to provide for a default machining strategy of using any combination of milling and turning within the same work envelope. [4]

The milling process removes material by performing many separate, small cuts. This is accomplished by using a cutter with many teeth, spinning the cutter at high speed, or advancing the material through the cutter slowly; most often it is some combination of these three approaches. The *speeds and feeds* used are varied to suit a combination of variables. The speed at which the piece advances through the cutter is called *feed rate*, or just *feed*; it is most often measured in length of material per full revolution of the cutter.

There are two major classes of milling process:

- In *face milling*, the cutting action occurs primarily at the end corners of the milling cutter. Face milling is used to cut flat surfaces (faces) into the workpiece, or to cut flat-bottomed cavities.
- In *peripheral milling*, the cutting action occurs primarily along the circumference of the cutter, so that the cross section of the milled surface ends up receiving the shape of the cutter. In this case the blades of the cutter can be seen as scooping out material from the work piece. Peripheral milling is well suited to the cutting of deep slots, threads, and gear teeth. *[4]*

A milling machine features a stationary cutting tool and a movable table to which the workpiece is secured. Manual or computer directions move the table around the rotating blade to make the desired cuts. Milling machines are capable of creating complex or symmetrical shapes across axes. The four main categories of milling machine are hand-milling, plain-milling, universal, and omniversal models. *[5]*

The laser milling is based on the generation of overlapping shallow multiple grooves by scanning a single laser beam to systematically remove the surface layer of the workpiece material. Vaporization of the material during laser scanning is a primary material removal mechanism for the formation of each groove. Overlapping of the grooves is realized by applying a continuous feed motion to the workpiece perpendicular to the laser scanning direction. The process is repeated to remove the additional layers of material by applying intermittent feed motion perpendicular to the previously machined surface to either the workpiece or the focusing lens.

The laser beam is directed along the z-axis, while, the workpiece is moved in x- and y-directions by linear translational stages. During machining, the workpiece is translated relative to the focal spot of the beam in +x- direction. The formation of continuous groove is facilitated by adjusting the workpiece translation speed and repetition rate of the laser. Figure 1 shows a schema of the laser milling process. [6]

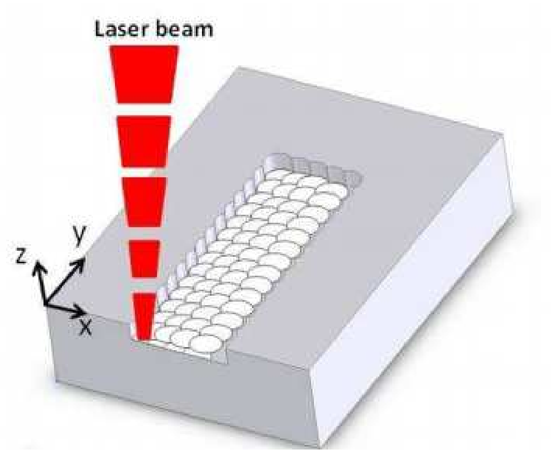

Figure 1 - Schematic illustration of the laser milling process. [6].

Laser milling is a very complex process because it is affected by the characteristics of the laser beam and the workpiece but is mainly determined by the way that both interact. Moreover, the structure and the characteristic of the material changes after each pass of the laser. Therefore, the material removal will not be the same for each laser pass. Trying to understand this complex process the authors focused the research in three levels of the process.

2.2 Background of Laser Technology

Laser signifier for lightweight amplification by excited emission of radiation, is unquestionably one in all the best innovations of 20th century. Its constant evolution has been writing new chapter within the field of science and technology. Optical maser is basically a coherent, focused and monochromatic beam of radiation with wavelength starting from immoderate 1violet to infrared.

The first theoretical foundation of Laser was established by Albert Einstein in the article Quantum Theory of Radiation in 1917. It was not until 1960 that Mainman developed a ruby laser for the first time. The laser emitted a red light in the near-invisible spectrum, with a pulse of 10 kW. Although, Maiman's work consisted in a letter of 300 words it was enough to reproduce the same experiment in other laboratories. Thus, this was followed by much basic development of lasers from 1962 to 1968. Almost all important types of lasers including semiconductor lasers, CO_2 gas lasers, dye lasers and other gas lasers. *[7]*

From the application point of view, laser material processing can be broadly divided into four major categories, namely, forming (manufacturing of near net-shape or finished products), joining (welding, brazing, etc.), machining (cutting, drilling, etc.) and surface engineering (processing confined only to the near-surface region). Figure 2 presents this classification showing some representative examples from each category of application.

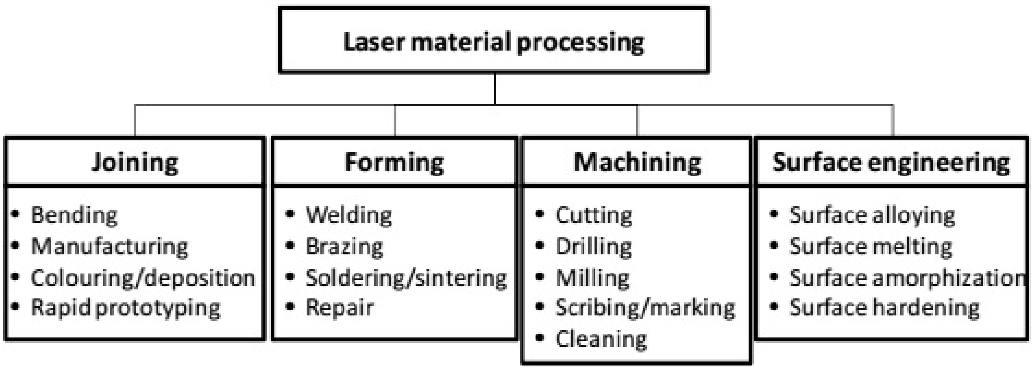

Figure 2 - Laser material processing classification from the application point of view [2].

Obviously, depending on the application the process will involve only heating (without melting/vaporizing), melting (no vaporizing) or vaporizing. Thus, the laser power density and interaction/pulse time are so selected in each process that the material concerned undergoes the desired degree of heating and phase transition. Processes like bending and surface which rely on surface heating without surface melting require low power density. On the other hand, surface melting, glazing, cladding, welding and cutting that involve melting require high power density. Similarly, cutting, drilling, milling and similar machining operations remove material as vapor; hence need delivery of a substantially high power density within a very short interaction/pulse time.

2.3 Laser Technology

Laser devices use light to store, transfer, or print images and text; they are also used in a wide range of other applications, including surgery and weaponry. The coherent radiation of the laser gives it special strength. The laser (Light Amplification by Stimulated Emission of Radiation) started life as an extension of the maser, or "Microwave Amplification by Stimulated Emission of Radiation." As its name indicates, the maser is an amplifier that was originally used for amplifying weak radio signals from space. Light waves are very much like radio waves but with a much shorter wavelength.

The laser generates light energy by converting the energy states of a material. The energy level of an atom is a function of its temperature. Its lowest energy level is called its "ground state." The application of additional heat, light, or electric field can raise its energy level. The familiar neon sign, which is glass tubing filled with neon gas, works on this principle. Two electrodes are inserted in the ends of the glass tubing and a high voltage is applied to the electrodes to raise the energy levels of the gas atoms.

A photon is an energy packet of electromagnetic waves. The energy of a photon is inversely proportional to the wavelength of the associated electromagnetic wave, so shorter wavelengths represent the higher energy photons. Small energy transitions emit photons with long wavelengths such as infrared light, while the larger energy transitions produce photons of visible light with blue light.

In the neon sign, the extra energy added is first stored in the atoms of neon gas in the tube by raising them to a higher energy state. As the neon atoms return to lower energy states, the atoms give up the excess energy as photons. *[8]*

2.3.1 How do Laser works

The basic laser consist of two mirrors which are placed parallel to each other to form an optical oscillator, that is a chamber in which light travelling down the optic axis between the mirrors would oscillate back and forth between the mirrors forever, if not prevented by some mechanism such as absorption. Between the mirrors is an active medium which is capable of amplifying the light oscillation by the mechanism of stimulated emission (the process after which the laser is named – Light Amplification by the Stimulated Emission of Radiation).

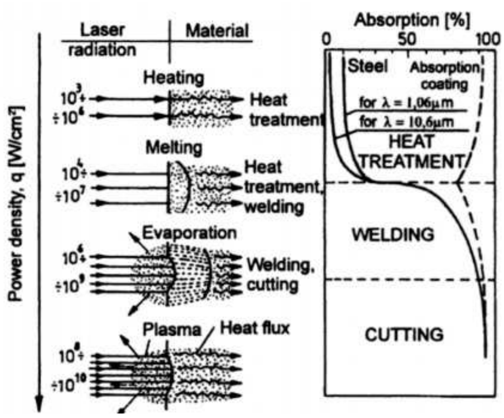

Figure 3 - Different laser-based manufacturing processes as a function of power density [4].

High powered lasers with a small spot size are generally used for machining a variety of materials and features. Laser machines have been developed for performing drilling and cutting operations in a wide range of metals. Simple three dimensional features can be manufactured using laser configurations involving two beams as shown in Figure 4. Laser based machining processes have been analysed and modelled extensively.

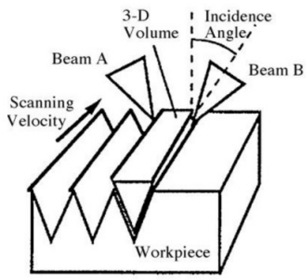

Figure 4 - Laser milling of three dimensional features using two laser beams A and B oriented at an angle to each other [4]

2.3.2 Basic Construction and Principle of Lasing

Basically, every laser system essentially has an active/gain medium, placed between a pair of optically parallel and highly reflecting mirrors with one of them partially transmitting, and an energy source to pump active medium. The gain media may be solid, liquid, or gas and have the property to amplify the amplitude of the light wave passing through it by stimulated emission, while pumping may be electrical or optical. The gain medium used to place between pair of mirrors in such a way that light oscillating between mirrors passes every time through the gain medium and after attaining considerable amplification emits through the transmitting mirror. Let us consider an active medium of atoms having only two energy levels: excited level E2 and ground level E1. If atoms in the ground state, E1, are excited to the upper state, E2, by means of any pumping mechanism (optical, electrical discharge, passing current, or electron bombardment), then just after few nanoseconds of their excitation, atoms return to the ground state emitting photons of energy hν = E2 − E1 which is show in Figure 5*[9]*.

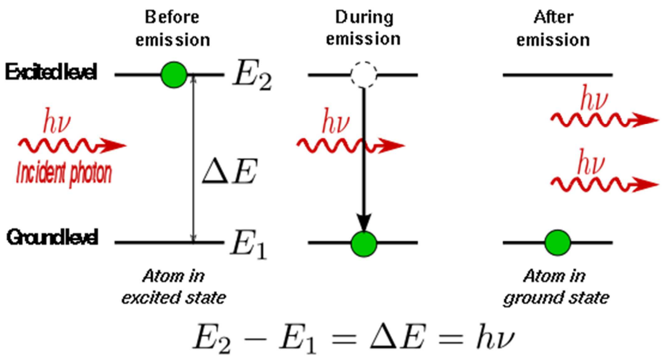

Figure 5 - Electrons are found in specific energy levels of an atom [20]

According to Einstein's 1917 theory, emission process may occur in two different ways, either it may induced by photon or it may occur spontaneously. The former case is termed as stimulated emission, while the latter is known as spontaneous emission. Photons emitted by stimulated emission have the same frequency, phase, and state of polarization as the stimulating photon; therefore they add to the wave of stimulating photon on a constructive basis, thereby increasing its amplitude to make lasing. At thermal equilibrium, the probability of stimulated emission is much lower than that of spontaneous emission (1:1033), therefore most of the conventional light sources are incoherent, and only lasing is possible in the conditions other than the thermal equilibrium. *[9]*

2.4 Process characteristics

The process of energy deposition from a pulsed/ continuous wave (CW) laser beam into the near surface region of a solid involves electronic excitation and de-excitation within an extremely short period of time. In other words, the laser–matter interaction within the near surface region achieves extreme heating and cooling rates ($10^3 - 10^{10}$ Ks^{-1}), while the total deposited energy (typically is $0 \cdot 1$–10 Jcm^{-2}) is insufficient to affect, in a significant way, the temperature of the bulk material. This allows the near surface region to be processed under extreme conditions with little effect on the bulk properties. The initial stage in all laser assisted material processing applications involves the coupling of laser radiation to electrons within the metal. Initially, photon interaction with matter occurs through the excitation of valence and conduction band electrons throughout the wavelength band from infrared (10 μm) to UV ($0 \cdot 2$ mm) regions. Absorption of wavelength between $0 \cdot 2$ and 10 μm leads to interband transition (free electrons only) in metals and interband transition (valence to conduction) in semiconductors. Conversion of the absorbed energy to heat involves: excitation of valence and/or conduction band electrons, excited electron–phonon interaction within a span of $10^{-11} - 10^{-12}$s, electron– electron or electron–plasma interaction and electron– hole recombination within $10^{-9} - 10^{-10}$s. Since free carrier absorption (by conduction band electrons) is the primary route of energy absorption in metals, beam energy is almost instantaneously transferred to the lattice by electron–phonon interaction. Similarly, transition in semiconductor or polymers having ionic/covalent bonding with energy gap between conduction and valence bands is marginally slower. *[10]*

2.4.1 Laser processing of engineering materials

Application of laser to material processing can be grouped into two major classes: applications requiring limited energy/power and causing limited microstructural changes only within a small volume/area without change of state and applications requiring substantial amount of energy to induce the change in state and phase transformation in large volume/area. The first category includes semiconductor annealing, polymer curing, scribing/marking of integrated circuit substrates, etc. The second type of application encompasses cutting, welding, surface hardening, alloying and cladding. The average power or energy input is relatively low in the first category, while that for the second category is higher as the processes involve single or multiple phase changes within a very short time. Almost all varieties of lasers can perform both types of operations in continuous wave (CW) and pulsed mode provided appropriate power/energy density and interaction time for the given wavelength are applied. *[10]*. The domain for different laser material processing techniques as a function of laser power and interaction time is illustrated in Figure 6.

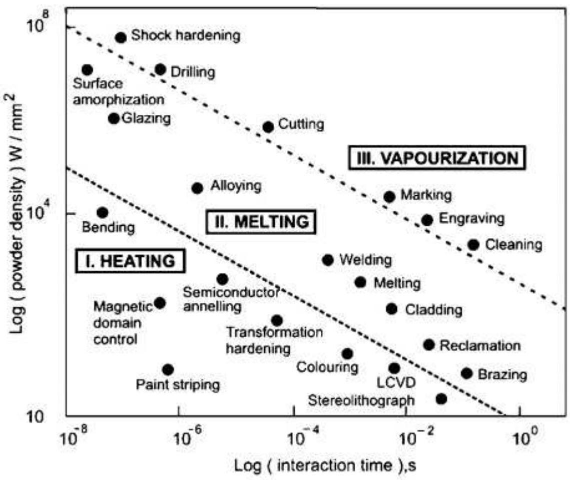

Figure 6 - Schematic process map in terms of combination of laser power density and interaction time for different types of laser material processing involving either no (only heating) or change of state (melting or vaporisation) [21]

The processes are divided into three major classes, namely, heating (without melting/vaporising), melting (no vaporizing) and vaporizing. It is evident that transformation hardening, bending and magnetic domain control which rely on surface heating without surface melting require low power density laser. On the other hand, surface melting, glazing, cladding, welding and cutting that involve melting require high power density laser. Similarly, cutting, drilling and similar machining operations remove material as vapour hence, need delivery of a substantially high power density within a very short interaction/pulse time. Since all laser material processing operations can be defined by an appropriate combination of power density and interaction time, one is tempted to combine these two into a single scalar parameter as energy density (power density multiplied by time, Jmm^{-2}) for the sake of simplification and convenience. However, the exercise is bound to prove futile and not advisable as both the quantum of energy and its temporal and spatial interaction with matter (rather than their product) are crucial to achieve the desired micro-structural/phase/state changes and properties for a given material. For instance, application of $10^{-2} J mm^{-2}$ energy density may induce either surface hardening (say, for a given material combination of 10^2 Wmm^{-2}power density and 10^{-4}interaction time) or surface melting (say, for a combination of 10^4 Wmm^{-2}power density and 10^{-6} interaction time). [10]

2.5 Micron and Micromachining Technologies

Micro machining simply means small or miniature to many of us in manufacturing. Those in academia and research define Micro in a very literal way, or 10^{-6}, in other words, as one-millionth of a meter. (A micron n: a metric unit of length equal to one millionth of a meter [syn. – micrometer. Origin - Greek m kro-, from m kros, small] quite literally as 106 (mm)],

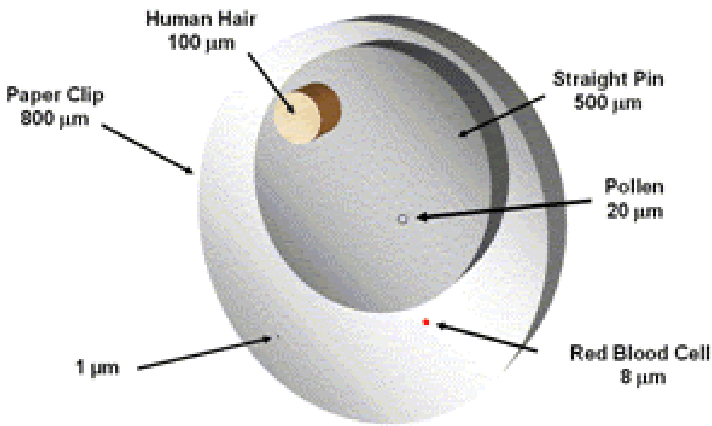

Figure 7 - What is Micron? [22]

Figure 7 illustrates the range of part and feature size machining capability. Parts with machined features below <0.004" (100 µm) fit into the middle (e.g. - meso) range of manufacturing. The chart below provides a basic reference of the micro machining range of various machining technologies.

Table 2 - Basic reference of the micro machining range [22]

Process	Principle	Minimum Feature Size		Advantages	Disadvantages
μ-Molding & Casting	Solidification	500 μm	0.019"	Mass-production	Spring-back
μ-Punching	Plastic deformation	50 μm	0.0019"	Mass-production	Need uniform clearance
μ-Milling & Grinding	Force	25 μm	0.00098"	Good geometric accuracy Good surface finish	Tool deflection/ damage due to the cutting forces
Stereo-Lithography	Lamination	12 μm	0.00047"	Complex 3D shape	Limited work materials
Eximer Laser	Ablation	10 μm	0.00039"	No heat damage on surfaces	Limited work material
μ-EDM & Laser	Melting ~ Vaporization	5 μm	0.00019"	Negligible force	Possible Surface damage and low MRR
FIB	Sputtering	0.2 μm	0.0000080"	Stress-free	Low MRR

Over the past several years there has been an increased interest in micro machining technology that has captured the imagination of every manufacturing and industry segment; from aerospace, medical appliance and the automotive world, the potential for product miniaturization continues to grow and while posing numerous technical challenges. In response to this continued miniaturization, companies are developing new technologies to meet the unique challenges posed by micro manufacturing and must develop appropriate machining systems to support this growth.

The manufacture of miniature parts is not new. Many companies have used various machining technologies such as EDM (Electrical discharge machining) and laser to produce micro details for many years. The difference today is the shears volume of products that require micro machining. The accelerated rate of change is unbelievable.

New miniature products are changing how we view the world. Many manufacturers’ are developing micro machining technologies and techniques to support this growth. Companies are looking for parts having feature sizes of less than 100 microns, or somewhat larger than a human hair.

At this scale, the slightest variation in the manufacturing process caused by material or cutting tool characteristics, thermal variations in the machine, vibration and any number of minute changes will have a direct impact on the ability to produce features of this type on a production scale.

In response to this continued miniaturization, companies are developing new products and technologies to meet the unique challenges posed by micro manufacturing.

These types of tolerances are mind boggling and would have been unthinkable just a few years ago. Talk of using end mills of 0.002" (50 µm) diameter and EDM wire diameters of 0.00078" (20 µm), or electrodes smaller than a few tenths is becoming more commonplace. The application micro-meso machining technologies are being employed in the manufacture of a wide variety of products and devices.

2.5.1 Laser Machining at the Micro-scale

Laser-assisted machining has also been successfully applied to milling. Unlike in turning, the rotating tool makes the application of laser-assisted machining more problematic. Despite that, a carefully designed beam path and focus pattern could produce very promising results. In laser-assisted micro-milling, the typical setup includes at a minimum: one or more precise (and rigid) CNC stages, a high speed spindle, a laser and miniature end mills. Generally stages with a positional accuracy of a few microns or less, spindles with speeds greater than 100 kRPM, and tools with diameters less than 500 µm are required for successful laser-assisted micro-end-milling. Unlike in macro-machining, a low power laser, typically in the range of 20-50 W, is sufficient to provide the requisite heating due to the small spot size used. Laser assisted micro-milling has been successfully implemented in a slotting configuration10, 11 and side cutting configuration.12 Improvements have been shown in terms of cutting forces, tool life, and machined surface quality for a range of materials, including aluminium, steel, stainless steel, Inconel 718, and Ti6Al4V. In micro-milling processes, cutting speeds are limited by maximum possible spindle speed and small tool diameters, leading to lower than optimum shear plane temperatures. Laser assisted micro-milling offers the ability to somewhat overcome the size-effect and often eliminates the burr formations, which are known to be a significant problem in mechanical micro-milling. *[11]*

Macro scale laser-assisted milling has also been successful in machining of ceramics and some high temperature alloys.13,14 Laser-assisted milling of silicon nitride was successfully conducted using TiAlN coated carbide tools by elevating the material removal zone temperature to 1200~1300°C. Laser assisted milling of silicon nitride yielded good surface finish, repeatable performance and acceptable tool wear.14 Laser-assisted milling of Inconel 718 also yielded a substantial improvement of machinability. LAM with the material temperature elevated to 520ºC resulted in 40-50% reduction in cutting force, over 50% reduction in tool chipping and two fold improvement in surface roughness. *[11]*

Lasers are mostly operated in continuous mode in hardening applications and in pulsed mode in machining applications. The most commonly used industrial lasers are excimer, CO2, Nd:YAG and some of the commonly used applications of these lasers are drilling of nozzles for inkjet printers, micromachining of biomedical devices and MEMS. *[12]*

Zhang et al. used Nd:YAG lasers for micromachining glass and ceramics and presented a detailed investigation of the laser induced plasma ablation process. Figure 8 shows a microfluidic device micro machined in a alumina substrate using a 190 nm UV laser while Figure 9 shows a pattern of micro holes drilled in polyimide.

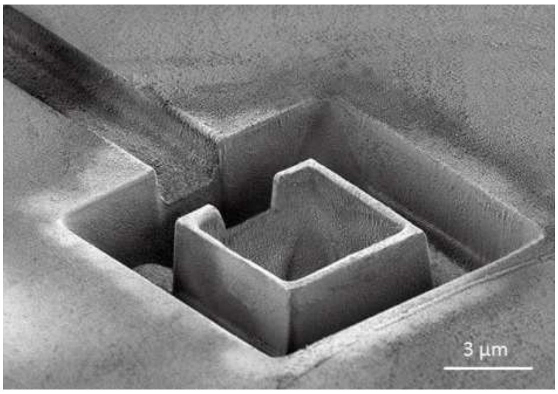

Figure 8 - Microfluidic device micro machined in a alumina substrate using a UV laser (JPSA Laser Company) [4]

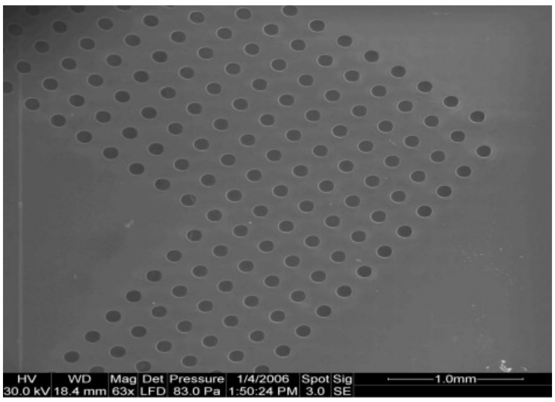

Figure 9 - Micro holes laser machined in polyimide using a UV laser (Potomac Photonics) [4]

In addition, laser micromachining of ceramics such as silicon nitride and alumina and micro-patterns on focused their studies on the use of laser micromachining for the manufacture of mould inserts in Poly Methyl Methacrylate (PMMA). The use of ultra short pulsed lasers to create micro features has drawn the attention of researchers in recent years. Because of small spot sizes, and high peak powers, they enable the creation of micro features, which can find applications in microfluidics. In addition, ultrafast lasers enable efficient ablation of materials since they induce minimum thermal damage in the surrounding work material. [12]

2.6 Advantages and Disadvantages of Laser technology

The advantages and disadvantages will be presented below:

Advantages

Since the rays of a laser beam are monochromatic and parallel it can be focused to a very small diameter and can produce energy as high as 100 MW of energy for a square millimetre of area. It is especially suited to making accurately placed holes.

Laser beam machining has the ability to engrave or cut nearly all materials, where traditional cutting methods may fall short. There are several types of lasers, and each has different uses. For instance, materials that cannot be not be cut by a gas laser may be cut by an excimer laser.

The cost of maintaining lasers is moderately low due to the low rate of wear and tear, as there is no physical contact between the tool and the workpiece.

The machining provided by laser beams is high precision, and most of these processes do not require additional finishing

Laser beams can be paired with gases to help the cutting process be more efficient, help minimize oxidization of surfaces, and/or keep the workpiece surface free from melted or vaporized material. *[3]*

Disadvantages

The initial cost of acquiring a laser beam is moderately high. There are many accessories that aid in the machining process, and as most of these accessories are as important as the laser beam itself the start-up cost of machining is raised further.

Handling and maintaining the machining requires highly trained individuals. Operating the laser beam is comparatively technical, and services from an expert may be required.

Laser beams are not designed to produce mass metal processes. For this reason production is always slow, especially when the metal processes involve a lot of cutting.

Laser beam machining consumes a lot of energy.

Deep cuts are difficult with workpieces with high melting points and usually cause a taper. *[3]*

Chapter III

3. Surface technology

Machinery and accessories have many members that slide against each other: piston and cylinders, slide ways, bearings, tools and dies for cutting and forming. Close examination reveals that some of these surfaces are smooth while other are rough, some are lubricated while others are dry, some are subjected to heavy loads while others support light loads, some are subjected to elevated temperatures (hot working dies) while others are at room temperature and some surfaces slide against each other at high relative speeds (high cutting speed) while others move slowly. *[1]*

In addition to its geometric features, a surface constitutes a thin layer on the bulk material. A surface's physical, chemical, metallurgical and mechanical properties depends not only material on the processing history but also on the environment to which the surface is exposed. The term *surface integrity* is used to describe its physical, chemical and mechanical characteristics. *[1]*

Following the outline shown in Table 3 presents surface technology and its category.

Table 3 - An outline of topics covered Chapter 3 [1].

Surface Technology		
Surface	*Tribology*	*Surface treatment*
Integrity	Friction	Burnishing
Structure	Wear	Hardening
Texture	Lubrication	Deposition
Roughness		Implantation
		Coatings
		Cleaning

Regardless of the method of production, all surfaces have their own characteristics, which collectively are referred to as *surface texture.* Although the description of surface texture as a geometrical property is complex, certain guidelines have been establish for identifying surface texture in terms of well-defined and measurable quantities. *[1]* Chapter continues mainly with two surface parameters which are follows the work.

3.1 Surface Hardness

Hardness is a measure of how resistant solid matter is to various kinds of permanent shape change when a compressive force is applied. Some materials, such as metal, are harder than others. Macroscopic hardness is generally characterized by strong intermolecular bonds, but the behaviour of solid materials under force is complex; therefore, there are different measurements of hardness: scratch hardness, indentation hardness, and rebound hardness. Hardness is dependent on ductility, elastic stiffness, plasticity, strain, strength, toughness and viscosity. *[13]*

Surface hardness is largely divided into three types, indentation hardness (including Vickers hardness, Brinell hardness, and durometer hardness), scratch hardness (including Mohs hardness and Martens' hardness), and rebound hardness (including Shore hardness), each of which is used appropriately according to the object. For the surface hardness measurement of a plastic, Rockwell hardness (indentation hardness) is often used, as the measurement can be done both simply and quickly. *[14]*

Regarding to the processes of research work in bellow examined Vickers test.

The Vickers hardness test method consists of indenting the test material with a diamond indenter, in the form of a right pyramid with a square base and an angle of 136 degrees between opposite faces subjected to a load of 1 to 100 kgf. The full load is normally applied for 10 to 15 seconds. The two diagonals of the indentation left in the surface of the material after removal of the load are measured using a microscope and their average calculated. The area of the sloping surface of the indentation is calculated. The Vickers hardness is the quotient obtained by dividing the kgf load by the square mm area of indentation. (Figure 10) *[14]*

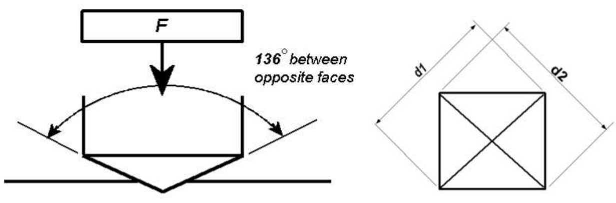

Figure 10 - Vickers hardness test method [14]

F= Load in kgf (kilo force)

d = Arithmetic mean of the two diagonals, d1 and d2 in mm (or L1, L2)

HV = Vickers hardness

$$HV=\frac{2F\sin\frac{136}{2}}{d^2} \quad HV=1.854\frac{F}{d^2} \text{approximately} \tag{3.1}$$

When the mean diagonal of the indentation has been determined the Vickers hardness may be calculated from the formula, but is more convenient to use conversion tables. The Vickers hardness should be reported like 800 HV/10, which means a Vickers hardness of 800, was obtained using a 10 kgf force. Several different loading settings give practically identical hardness numbers on uniform material, which is much better than the arbitrary changing of scale with the other hardness testing methods. The advantages of the Vickers hardness test are that extremely accurate readings can be taken, and just one type of indenter is used for all types of metals and surface treatments. Although thoroughly adaptable and very precise for testing the softest and hardest of materials, under varying loads, the Vickers machine is a floor standing unit that is more expensive than the Brinell or Rockwell machines. There is now a trend towards reporting Vickers hardness in SI units (MPa or GPa) particularly in academic papers. Unfortunately, this can cause confusion. Vickers hardness (e.g. HV/30) value should normally be expressed as a number only (without the units kgf/mm^2). Rigorous application of SI is a problem. Most Vickers hardness testing machines use forces of 1, 2, 5, 10, 30, 50 and 100 kgf and tables for calculating HV. SI would involve reporting force in newtons (compare 700 HV/30 to HV/294 N = 6.87 GPa) which is practically meaningless and messy to engineers and technicians. To convert a Vickers hardness number the force applied needs converting from kgf to newtons and the area needs converting form mm^2 to $m^2$to give results in pascals using the formula above.

To convert HV to MPa multiply by 9.807

To convert HV to GPa multiply by 0.009807 [14]

3.2 Surface Roughness

Surface roughness indicates the state of a machined surface. For example, when representing the surface of components, surface roughness can be examined by eye or rubbed with a fingertip. Expressions used to describe surface roughness include "shiny and pretty," "lustreless and rough," "like oxidized silver," or "like a mirror." Those differences are caused by the differences in the irregularities of the component surfaces. *[15]*

When a surface's level of shininess or asperity is clearly quantified, it is called surface roughness, which plays an important role in defining the character of a surface. The surface irregularities of a component or material may be intentionally created by machining, but they can also be created by a wide range of factors such as tool wobbling caused by motor vibration during machining, the quality of the tool edge, and the nature of the machined material. The form and size of irregularities vary, and are superimposed in multiple layers, so differences in those irregularities impact the quality and functions of the surface. The results of these irregularities can control the performance of the end product in aspects such as friction, durability, operating noise, energy consumption, and air tightness. If the products in question are printing paper or exterior panels, aspects of quality such as glossiness and adhesion of paint and ink can also be affected by surface roughness. *[15]*

The shape and size of irregularities on a machined surface have a major impact on the quality and performance of that surface, and on the performance of the end product. The quantification and management of fine irregularities on the surface, which is to say, measurement of surface roughness, is necessary to maintain high product performance.

Quantifying surface irregularities means assessing them by categorizing them by height, depth, and interval. They are then analysed by a predetermined method and calculated per industrial quantities standards. The form and size of surface irregularities and the way the finished product will be used determine if the surface roughness acts in a favourable or an unfavourable way. Painted surfaces should be easy for paint to stick to, while drive surfaces should rotate easily and resist wear. It is important to manage surface roughness so that it is suitable for the component in terms of quality and performance.

Many parameters have been established regarding the measurement and assessment of surface roughness. As machining technologies progress and higher-quality products are demanded, the performance of digital instruments continues to improve. The surface roughness of more diverse surfaces can now be assessed. *[15]*

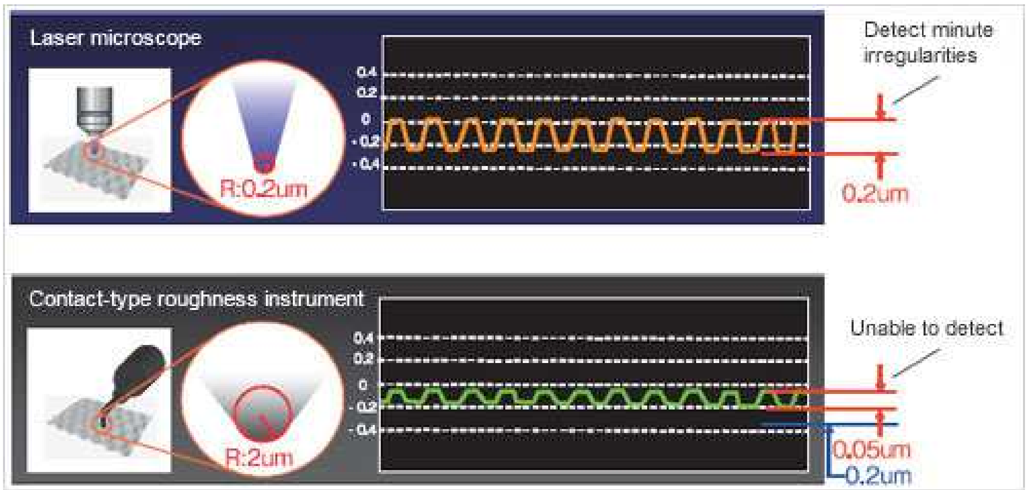

Figure 11 - The appeal of an extremely small spot diameter [8]

The tip radius of a general contact-type stylus is 2~10µm which causes the roughness data to be "filtered" by the size of the stylus. In contrast, the radius of a laser spot from a laser microscope is only 0.2µm, so it can measure surface roughness that a contact-type stylus cannot enter. (Figure 11) [15]

3.2.1 Surface Roughness parameters

Each of the roughness parameters is calculated using a formula for describing the surface. Although these parameters are generally considered to be "well known" a standard reference describing each in detail is Surfaces and their Measurement. Surface texture of mechanical components has been checked over 80 years in order to improve performances of manufactured products. The first roughness testers recorded surface heights using a stylus tip in contact with the surface and a traverse unit. The measured profile was drawn on a carbon paper and a value of roughness was given on a galvanometer. For a long time, only one parameter was known and used, under the name **Ra** (Roughness average) or CLA (Center Line Average) or even AA (Arithmetic Average). Then come RMS or Rq, Rz and Rmax, and later many more parameters. *[15][16]*

Today, *profile parameters* and *areal parameters* are defined in a handful of *international standards* that sometimes have local variations due to national or sectorial standards. Profile parameters are separated into three groups depending on the type of profile from which they are calculated: P parameters are calculated on the *primary Profile*; R parameters are calculated on the *roughness profile*; and W parameters are calculated on the *waviness profile*. *[15]*

Ra – Average roughness- The average roughness is the area between the roughness profile and its mean line, or the integral of the absolute value of the roughness profile height over the evaluation length: *[17]*

$$R_a = \frac{1}{L}\int_0^L | r(x) | \, dx \qquad \textbf{(3.2.1.1)}$$

When evaluated from digital data, the integral is normally approximated by a trapezoidal rule:

$$R_a = \frac{1}{N}\sum_{n=1}^{N} | r_n | \qquad \textbf{(3.2.1.2)}$$

Graphically, the average roughness is the area (shown below) between the roughness profiles and centre lines divided by the evaluation length (normally five sample lengths with each sample length equal to one cut-off):

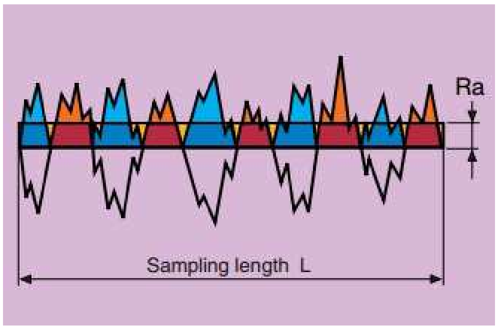

Figure 12 - Ra (Roughness average) graph [17]

Sampling length and Evaluation length

In order to overcome problems arising in the early profile-meters, such as noise or repeatability, some parameters are meant to be calculated on profile segments (*sampling lengths)* and then averaged. The sampling length is usually defined as the cut-off length (λc) of the filter used to separate roughness and waviness. For example, using a cut-off length of 0.8 mm and 5 sampling lengths Figure 12: parameters will be estimated on each segments (Ra1, Ra2, ..., Ra5) and the parameter value will be given as the mean of these estimated values.

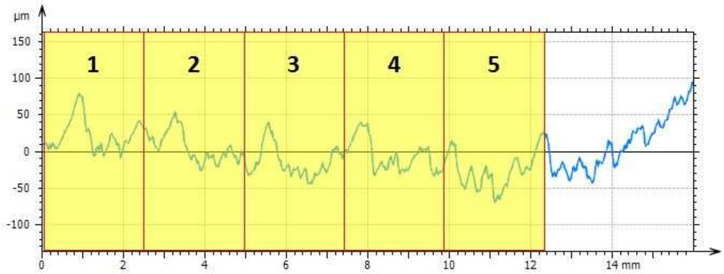

Figure 13 - Sampling and evaluation length [15]

$$R_a = \frac{1}{5}\sum_j Ra_j \qquad \textbf{(3.2.1.3)}$$

Other parameters are defined and calculated on the ***evaluation length*** which usually is the profile length after filtering. Details are given in [ISO 4288]. [15]

Rz – maximum height of the profile- is the arithmetic mean value of the single roughness depths of consecutive sampling lengths and defined on the sampling length: this parameter is frequently used to check whether the profile has protruding peaks that might affect static or sliding contact function. (Figure 14) [16]

Rzi – the Single Roughness depth – is the vertical distance between the highest peak and the deepest valley within a sampling length.

Rmax – Maximum roughness height within a sample length or maximum roughness Depth – is the largest single roughness depth within the evaluation length. (Figure 13)

The units of Rz are micrometres or micro inches.

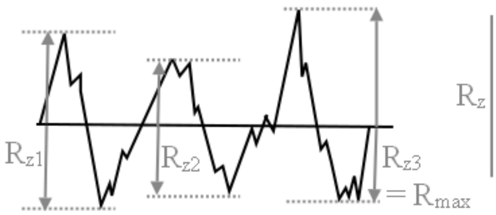

Figure 14 - Covered parameters Rz and Rmax [16]

***Rk** – is **core roughness depth** –* parameters should be calculated only if the Abbott curve has a S-shape, otherwise the graphical construction may fail and parameter values will be meaningless.

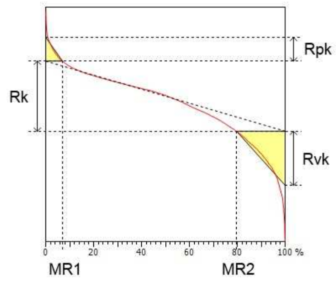

Figure 15 - Graphical construction of Rk parameters [15]

Figure also shows:

Rpk – reduced peak height – This parameter is used to characterize protruding peaks that might be eliminated during function.

Rvk – reduced valley depth – This parameters is used to characterize valleys that will retain lubricant or worn-out materials.

***MR1** and **MR2** –*is material ratio delimiting the core area. (Figure 14) *[15]*

Other "frequency" parameters are $S_m \lambda_a, \lambda_q$ S_m is the mean spacing between peaks. Just as with real mountains it is important to define a "peak". For S_m the surface must have dipped below the mean surface before rising again to a new peak. The average wavelength $\lambda_a$and the root mean square wavelength $\lambda_q$are derived fromΔ_a. When trying to understand a surface that depends on both amplitude and frequency it is not obvious which pair of metrics optimally describes the balance *[15]*, *[16]*

Chapter IV

4. Materials and experimental procedures

This Chapter cover materials and experimental procedures including two main tests and content of the Steel 1.2344.

4.1 Steel 1.2344

Hot work tool steel with high level of resistance to thermal shock and fatigue, excellent hot tensile strength properties, high hot wear resistance, good machinability and polishability, fine grain size with high level toughness, dimensional stability, extra fine structure without grain boundary carbide, nitridable, contains low P and S alloys, admits water cooling. *[18]*

Typical 1.2344 applications include die casting dies for *aluminium*, *magnesium* and *zinc*, extrusion dies for aluminium and brass, liners, mandrels, pressure pads, followers, bolsters, die cases, die holders and adaptor rings for copper and brass extrusion. Other applications include plastic moulds, shear blades for hot work and hot swaging dies. Also used to produce hot stamping and press forge dies, split hot heading dies, gripper dies, hot punching, piercing and trimming tools.*[19]*

Steel 1.2344 including: [18], [19]

Carbon	**0.35-0.42%**	**Chromium**	**4.80-5.50%**
Manganese	**0.25-0.50%**	**Molybdenum**	**1.20-1.50%**
Sulphur	**0.02% max**	**Silicon**	**0.80-1.20%**
Phosphorous	**0.03% max**	**Vanadium**	**0.85-1.15%**

Preheat slowly to 750°C then increase temperature more rapidly to 1050-1100°C. Do not forge below 850°C. It is essential to cool slowly after forging, either in a furnace or in vermiculite. Soak thoroughly at 840-860°C before furnace cooling at a maximum rate of 20°C per hour down to 600°C followed by cooling in air. To avoid scaling, box annealing in cast iron chips is preferred. [19]

When tools made from 1.2344 tool steel are heavily machined or ground, the relief of internal strains is advisable before hardening to minimize the possibility of distortion. Stress relieving of this grade of steel should be done after rough machining. To stress relieve, heat the component carefully to 700°C, allow a good soaking period (two hours per 25mm of section). Cool in the furnace or in air. Tools may then be finish machined before hardening. *[19]*

Preheat to 780-820°C. Soak thoroughly then increase rapidly to the hardening temperature of 1000-1030°C. When it has attained this temperature, soak for 20 to 30 minutes.

Cool in air. Large sections may be quenched in oil. To reduce scaling or decarburisation, we recommend isothermal molten salt bath treatment. Preheat in salt at 780-820°C then transfer to salt bath standing at 1000-1030°C. Soak and quench into salt standing at 500-550°C. Allow to equalise, withdraw and cool in air. Alternatively, 1.2344 tool steel may be vacuum hardened or pack hardened. Tools should be tempered as soon as they become hand-warm. *[19]* Heat uniformly to the required temperature allowing a soaking time of two hours per 25mm of ruling section. Withdraw from the furnace and allow cool in air. A second tempering is strongly advised, the tool being allowed to cool to room temperature between tempers. The usual tempering range is 530-650°C depending on the hardness requirements and the operating temperature of the tool. *[19]*

Temperature [°C]	**400**	**500**	**550**	**600**	**650**
Hardness [HRc]	**54**	**56**	**54**	**49**	**47**

Heat treatment temperatures, including rate of heating, cooling and soaking times will vary due to factors such as the shape and size of each component. Other considerations during the heat treatment process include the type of furnace, quenching medium and work piece transfer facilities. Please consult your heat treatment provider for full guidance on heat treatment of tool steels.

1.2344 tool steel is supplied in accordance with *ISO 9001:2008* registration.

4.2 Parameters of laser machining processes

Steel is by far the most important, multi-functional and most adaptable of materials. The development of mankind would have been impossible but for steel. The backbone of developed economies was laid on the strength and inherent uses of steel.

One of the most important factors in getting good parts is the application of appropriate technologies to cut materials to erode.

The various uses of steel which in turn is a measure of adaptability of steel can be judged from the following characteristics of steel:

- ✓ Hot and cold formable
- ✓ Hard, tough and wear resistant
- ✓ Corrosion resistant
- ✓ Heat resistant and resistance to deformation at high temperatures

To obtain these values it was necessary small squares erode (Figure 17) in order to find the best technology, altering some of the laser process variables, such as: cutting intensity (%) Frequency is (kHz) and speed (mm/s).

Here in below displayed (Figure 16, 17) the samples which are ready perform the tests.

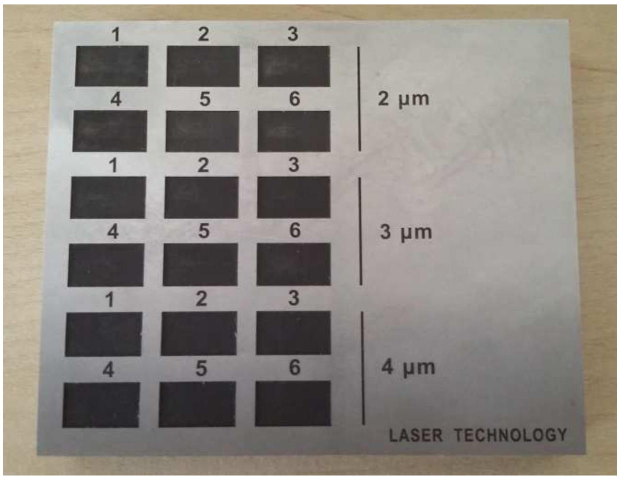

Figure 16 - Laser machining 2, 3, 4 µm with 0.2 mm depth

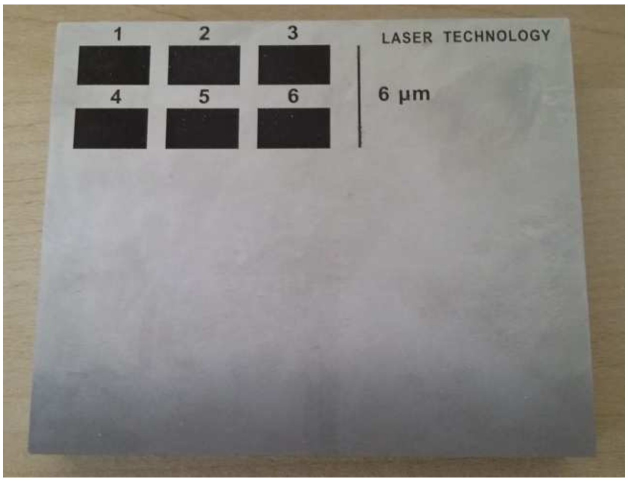

Figure 17 - Laser machining 6 µm with 0.2 mm depth

There are results of the values of current intensity to the steel 1.2344 in above Table 4.

Table 4 - Values of current intensity to the steel 1.2344

Material Steel 1.2344 Tests and Results with Nd:YAG laser [1][2]				
Tests	***Technics***	***Depth mm***	***Intensity %***	***Time hour/min***
1	*2µm_ht10_60Khz_200mm/s*	*0.2*	*18.7*	*1:20*
2	*2µm_ht10_60Khz_400mm/s*	*0.2*	*24.7*	*0:44*
3	*2µm_ht10_60Khz_600mm/s*	*0.2*	*31*	*0:32*
4	*2µm_ht10_80Khz_200mm/s*	*0.2*	*22.5*	*1:20*
5	*2µm_ht10_80Khz_400mm/s*	*0.2*	*27*	*0:44*
6	*2µm_ht10_80Khz_600mm/s*	*0.2*	*33*	*0:33*
1	*3µm_ht10_60Khz_200mm/s*	*0.2*	*22.4*	*0:53*
2	*3µm_ht10_60Khz_400mm/s*	*0.2*	*29.9*	*0:29*
3	*3µm_ht10_60Khz_600mm/s*	*0.2*	*38*	*0:23*
4	*3µm_ht10_80Khz_200mm/s*	*0.2*	*25.8*	*0:53*
5	*3µm_ht10_80Khz_400mm/s*	*0.2*	*31.8*	*0:30*
6	*3µm_ht10_80Khz_600mm/s*	*0.2*	*38.7*	*0:23*
1	*4µm_ht10_60Khz_200mm/s*	*0.2*	*25.8*	*0:40*
2	*4µm_ht10_60Khz_400mm/s*	*0.2*	*35*	*0:22*
3	*4µm_ht10_60Khz_600mm/s*	*0.2*	*42.1*	*0:16*
4	*4µm_ht10_80Khz_200mm/s*	*0.2*	*29.7*	*0:39*
5	*4µm_ht10_80Khz_400mm/s*	*0.2*	*37*	*0:22*
6	*4µm_ht10_80Khz_600mm/s*	*0.2*	*43.2*	*0:16*
1	*6µm_ht10_60Khz_200mm/s*	*0.2*	*29.5*	*0:27*
2	*6µm_ht10_60Khz_400mm/s*	*0.2*	*39.5*	*0:15*
3	*6µm_ht10_60Khz_600mm/s*	*0.2*	*51.5*	*0:11*
4	*6µm_ht10_80Khz_200mm/s*	*0.2*	*33.2*	*0:27*
5	*6µm_ht10_80Khz_400mm/s*	*0.2*	*41.2*	*0:15*
6	*6µm_ht10_80Khz_600mm/s*	*0.2*	*51.3*	*0:11*

Nd:YAG (neodymium-doped yttrium aluminium garnet; Nd:Y3Al5O12) is a crystal that is used as a lasing medium for solid-state lasers. The dopant, triply ionized neodymium, Nd(III), typically replaces a small fraction (1%) of the yttrium ions in the host crystal structure of the yttrium aluminium garnet (YAG), since the two ions are of similar size. It is the neodymium ion which provides the lasing activity in the crystal, in the same fashion as red chromium ion in ruby lasers. *[1]*

Laser operation of Nd:YAG was first demonstrated by J. E. Geusic et al. at Bell Laboratories in 1964. *[2]*

4.3 Surface Hardness Test

Hardness is the property of a material that enables it to resist plastic deformation, usually by penetration. However, the term hardness may also refer to resistance to bending, scratching, abrasion or cutting.

The micro hardness tester is a piece of equipment that is indispensable to metallographic research, product quality control, and the creation of product certification materials. For this type of work, it is important to be able to measure the hardness of small parts and metallic structures used in precision equipment, processed surface layers, metal plating layers, etc. This type of measurement must be performed on a limited small area with small damage to the area being measured, and must yield extremely reliable results. The HMV Series hardness testers have been designed to meet these demanding conditions, providing outstanding performance with ease of use and user friendly design. Display functions of this micro-hardness tester include statistical calculation data editing, conversion, graph display, and an acceptable/not acceptable decision function.

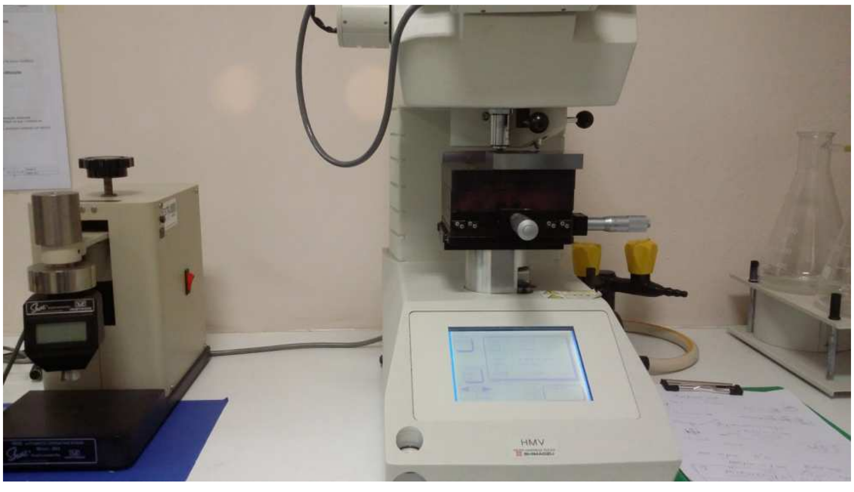

Figure 18 - Hardness Vickers Tester (SHIMADZU HMV)

Below in Figure 19 shows Vickers tester working process on Steel 1.2344

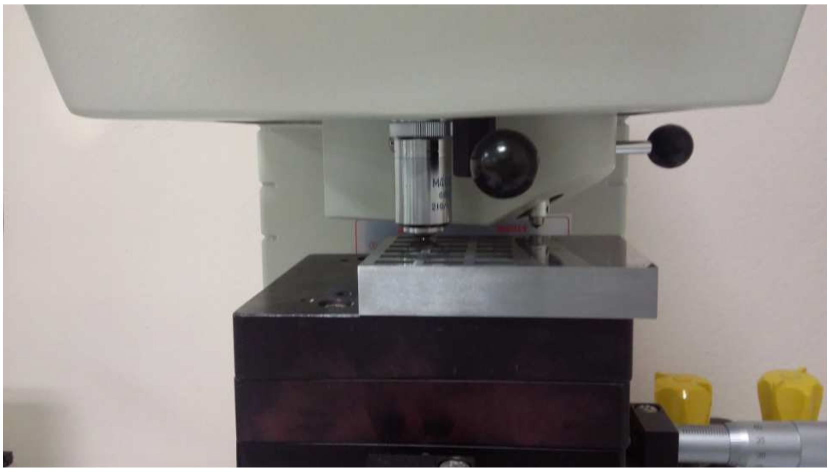

Figure 19 - Hardness Vickers Tester (SHIMADZU HMV/during the test process)

Figure 20 is displaying how the Tester leaves a trace in over Steel 1.2344 after the process.

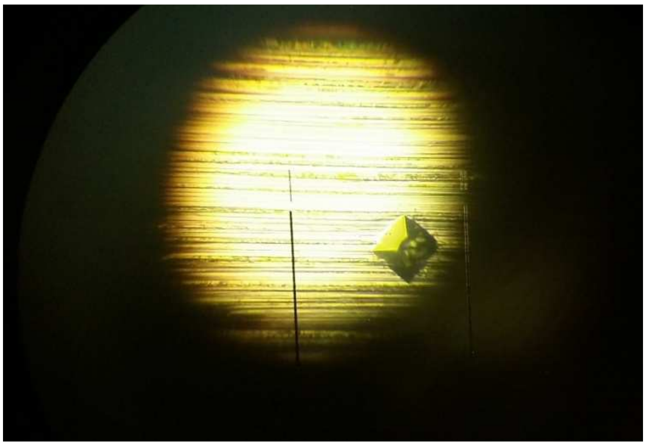

Figure 20 - Vickers Impression on top of Steel 1.2344

4.4 Surface Roughness test

After completion of machining processes 4 measuring were observed by “Perthometer” (Figure 21)

Figure 21 - PerthometerMahr M2

The result of the measurement, obtaining several important indicators, such as Average roughness – [Ra], Maximum average height of the profile– [Rz], Maximum roughness height within a sample length or maximum roughness depth (peaks and valleys) – [Rmax] and Core roughness depth or statistical roughness – [Rk]

Figure 22 - Tests with Perthometer Mahr (during the test measuring Ra. Rz, Rmax, Rk roughness parameters)

Chapter V

5. Discussion and Results

5.1 Surface Hardness tests results

This chapter presents the results of analysis of machined surfaces by laser, as well as the results of the mechanical behaviour of the machined material.

Data result display of Hardness Vickers (HV) Tester including: Data number, Length of diagonal (L1,L2), Hardness, Averages, Standard Deviation, Coefficient of Variation, Maximum Value, Minimum Value, Acceptable/Not Acceptable Decision, Data Editing (Table 5, 6, 7, 8).

Table 5 - Hardness Test data parameters for 2 μm

Spot No	HV	L1 [μm]	L2 [μm]	
1	1259	26.72	27.54	**2 μm**
2	1073	29.7	29.06	
3	898	31.13	33.13	
4	703	35.1	37.53	
5	734	34.67	36.39	
6	657	36.07	39.08	

In Figure 23, the hardness is higher on the 1^{st} spot of sample in 2 μm. In Table 5 and Figure 23 from surfaces 1 to 3 it is evaluated the influence of the laser speed from 200, 400 and 600 mm/s, respectively. The decrease of hardness is observed for the same conditions of spot (2 μm) and frequency (60 khz). The same observation should be done for the cases of surfaces 4, 5 and 6 in cases of 80 khz frequency.

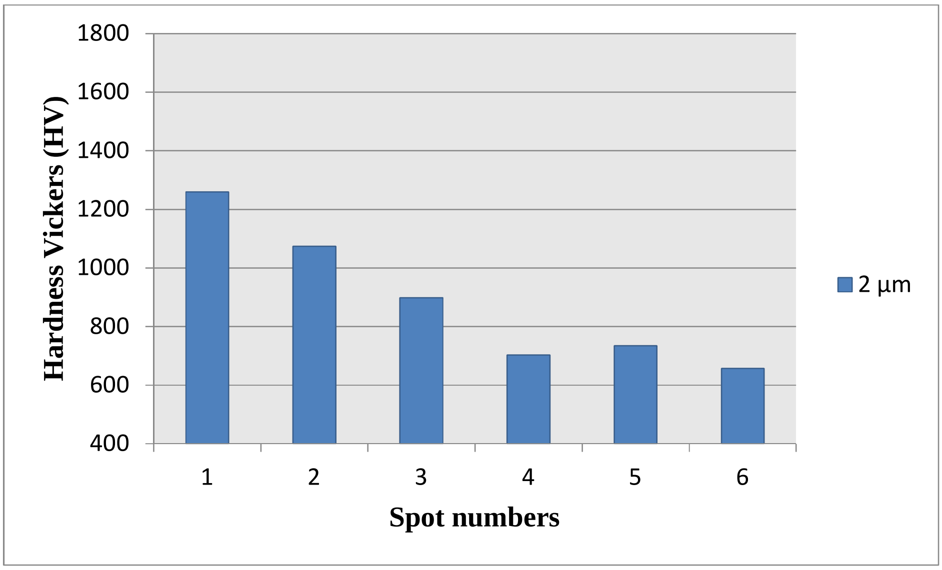

Figure 23 - Hardness Vickers Test results for 2 µm in separate (1-6) spots

Table 6 - Hardness Test data parameters for 3 µm

Spot No	HV	L1 [µm]	L2 [µm]	
1	1325	27.25	25.65	**3 µm**
2	1140	29.86	27.17	
3	931	29.93	33.17	
4	818	33.58	33.75	
5	751	35.21	34.96	
6	641	36.85	39.29	

In Figure 24, the hardness is higher on the 1st spot of sample in 3 µm. Similar observation for the decrease of hardness values must be done in the cases of Table 6 and Figure 24 (3 µm), Table 7 and Figure 25 (4 µm), Table 8 and Figure 26 (6 µm).

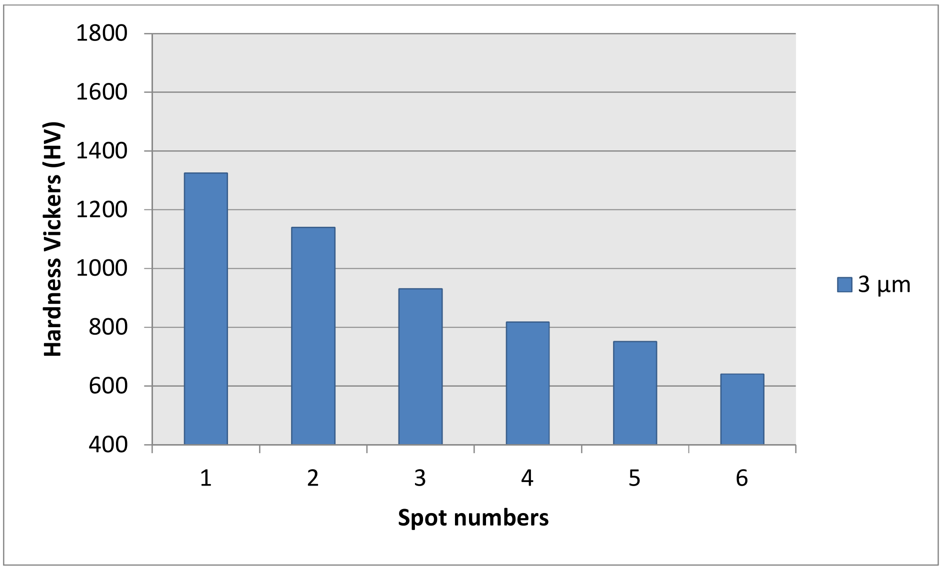

Figure 24 - Hardness Vickers Test results for 3 µm in separate (1-6) spots

Table 7 - Hardness Test data parameters for 4 µm

Spot No	HV	L1 [µm]	L2 [µm]	
1	1558	25.59	23.18	
2	1191	28.27	27.61	
3	963	31.39	30.67	**4 µm**
4	827	33.65	33.29	
5	795	37.37	30.9	
6	568	38.59	42.19	

In Figure 25, the hardness is higher on the 1st spot of sample in 4 µm.

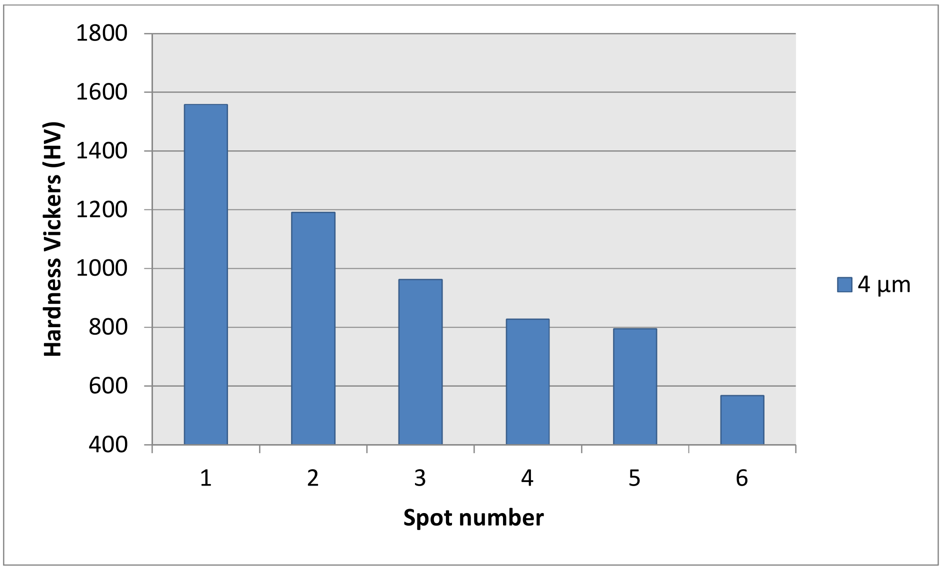

Figure 25 - Hardness Vickers Test results for 4 µm in separate (1-6) spots

Table 8 - Hardness Test data parameters for 6 µm

Spot No	HV	L1 [µm]	L2 [µm]	
1	1666	23.97	23.2	**6 µm**
2	1388	24.33	27.34	
3	1036	28.9	30.91	
4	839	33.03	33.47	
5	824	33.45	33.64	
6	497	40.7	45.65	

In Figure 26, the hardness is higher on the 1st spot of sample in 6 µm.

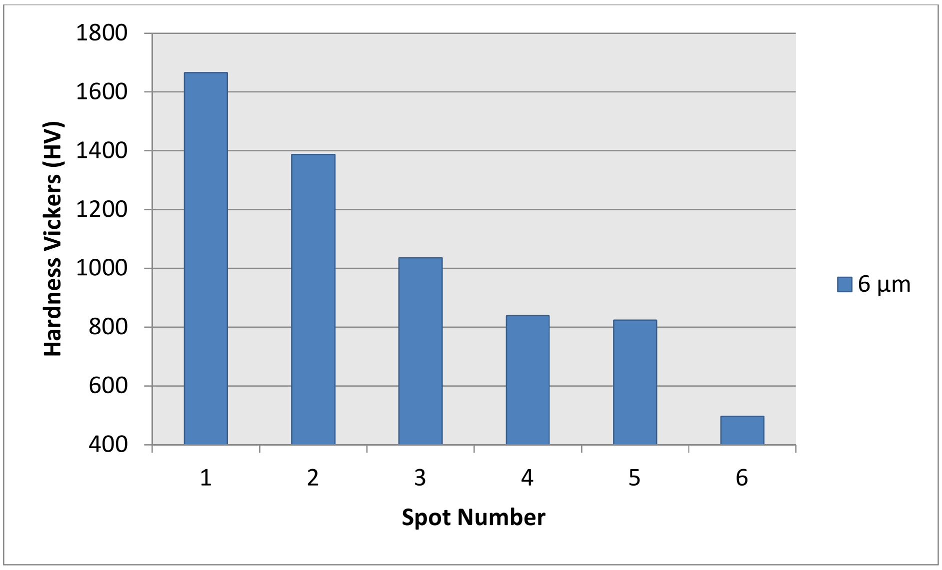

Figure 26 - Hardness Vickers Test results for 6 µm in separate (1-6) spots.

Table 9 - Hardness Test data parameters for spots and microns

Micron [µm]	HV in 1^{st} spot	HV in 2^{nd} spot	HV in 3^{rd} spot	HV in 4^{th} spot	HV in 5^{th} spot	HV in 6^{th} spot
2	1259	1073	898	703	734	657
3	1325	1140	931	818	751	641
4	1558	1191	963	827	795	568
6	1666	1388	1036	839	824	497

In Figure 27, the hardness is higher in 6 µm on the all 1^{st} spots of sample. In Table 9 the results for each surface is showed. In Figure 27 for surfaces #1 the influence of spot diameter laser in the hardness is observed. There is an increase of hardness with the diameter of the laser spot diameter. The same observation should be done to the other cases, Figure 28 for surfaces #2, Figure 29 for surfaces #3, Figure 30 for surfaces #4 and Figure 31 for surfaces #5.

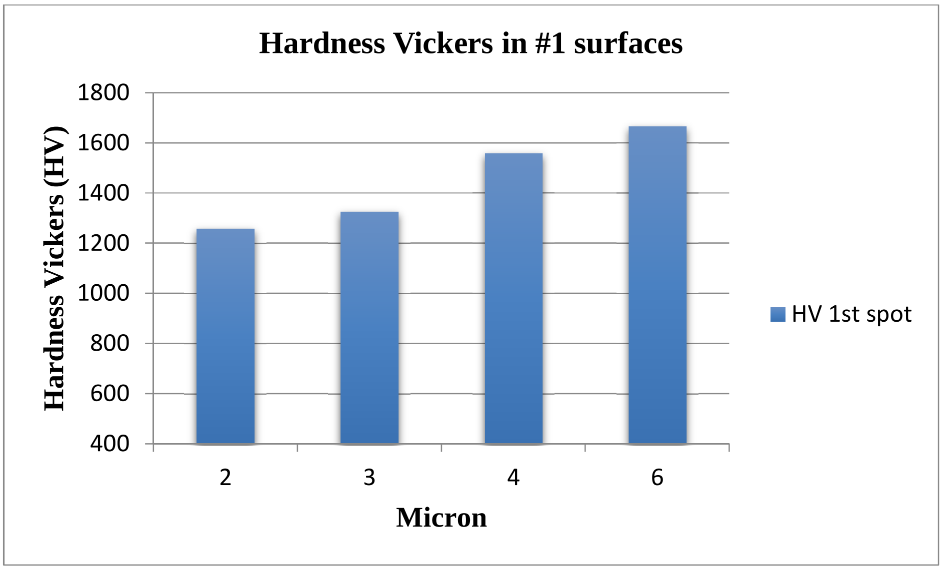

Figure 27 - Hardness Vickers test results in #1 surfaces for different spots laser (2 µm, 3 µm, 4µm, 6 µm).

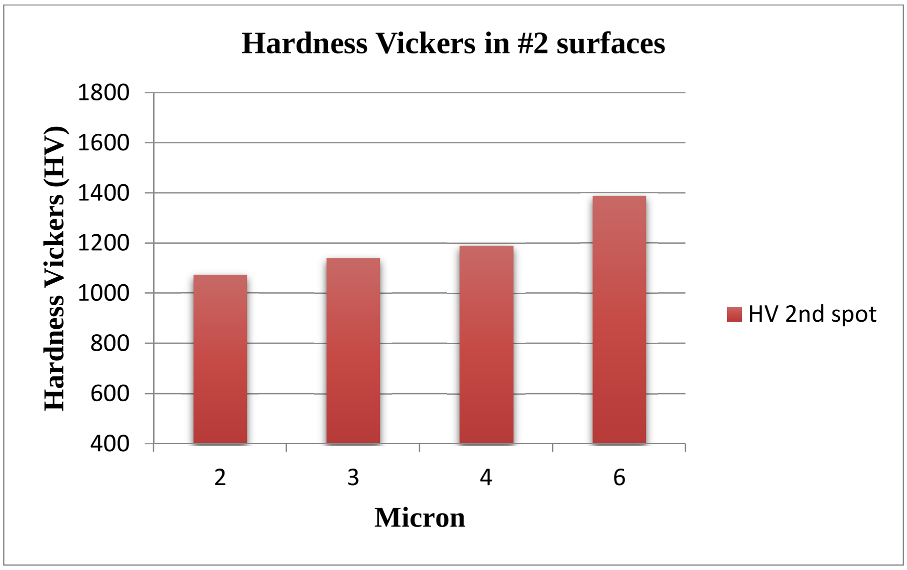

Figure 28 - Hardness Vickers test results in #2 surfaces for different spots laser (2 μm, 3 μm, 4μm, 6 μm).

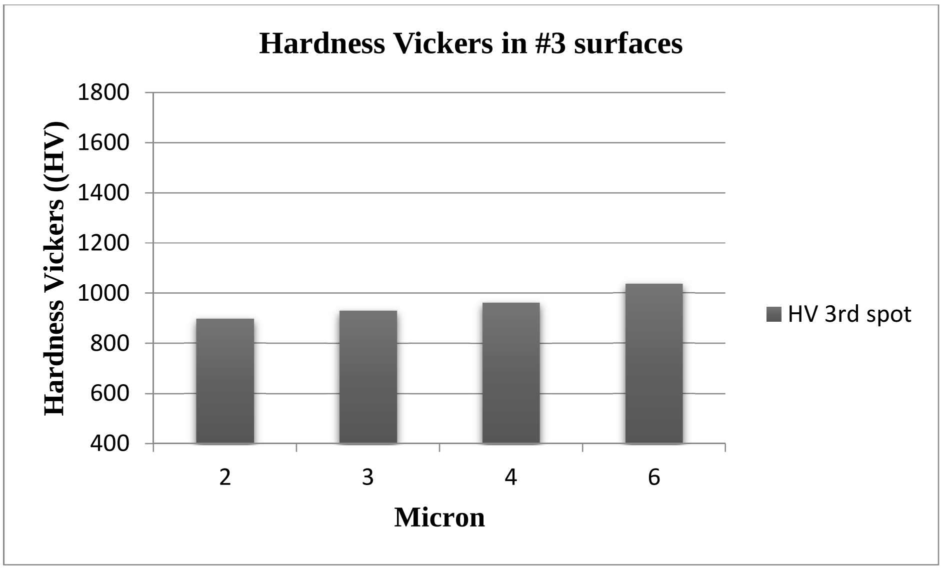

Figure 29 - Hardness Vickers test results in #3 surfaces for different spots laser (2 μm, 3 μm, 4μm, 6 μm).

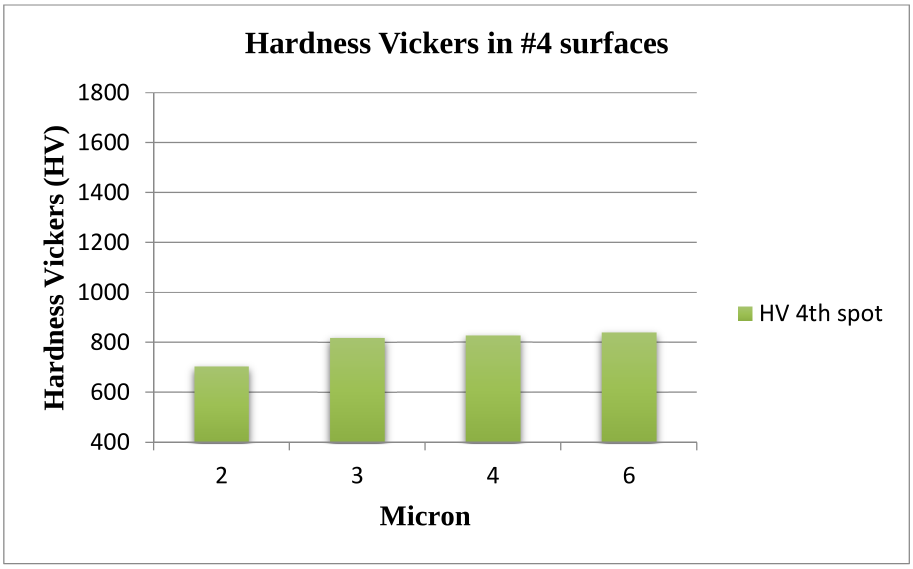

Figure 30 - Hardness Vickers test results in #4 surfaces for different spots laser (2 µm, 3 µm, 4µm, 6 µm).

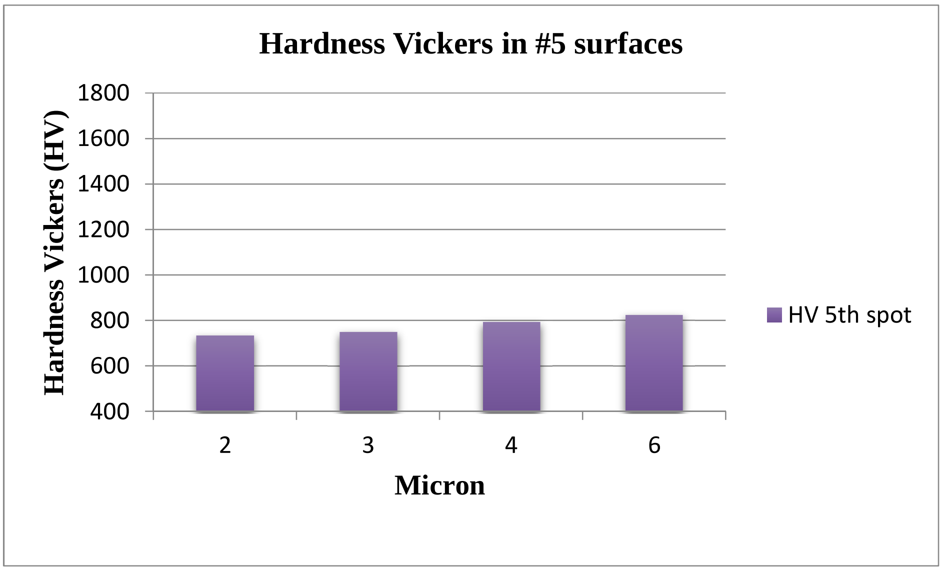

Figure 31 - Hardness Vickers test results in #5 surfaces for different spots laser (2 µm, 3 µm, 4µm, 6 µm).

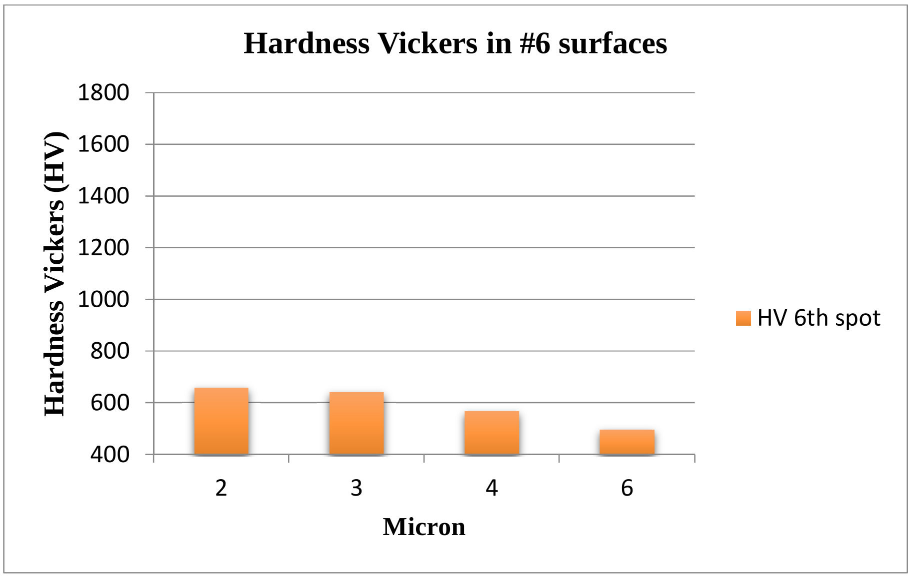

Figure 32 - Hardness Vickers test results in #6 surfaces for different spots laser (2 µm, 3 µm, 4µm, 6 µm).

In Figure 32 for surfaces #6 different behaviour occurs. More tests should be addressed to these cases on which there is a faster laser movement and the time in each place is lower. The combination of these two effects leads to a lower laser time action in each specified area. Thus, possibly, increased hardness due to thermal treatment associated with the laser passage does not occur, and in fact decreases the hardness with the increase of the affected area by laser.

5.2 Surface Roughness tests results

In bellow (Table 10, 11, 12, 13) the data result of roughness parameters measurement working on *Perthometer Mahr M2*.

Table 10 - Roughness Test data parameters with the speed for 2 µm.

Frequency [kHz]	Laser Speed [mm/s]	Ra[µm]	Rz [µm]	Rmax [µm]	Rk [µm]	
60	200	1.589	8.24	10.6	5.71	**2 µm**
	400	1.140	5.37	7.39	4.04	
	600	1.101	5.51	6.98	4.03	
80	200	1.569	7.37	7.9	5.02	
	400	1.484	8.16	8.82	4.5	
	600	1.232	6.55	7.58	3.91	

In Figure 33 for 2 μm and Ra, all values of roughness parameters decreases with the growing of the laser displacement speed. The laser speed increment results in the tendency of smother surfaces with low values of roughness appears.

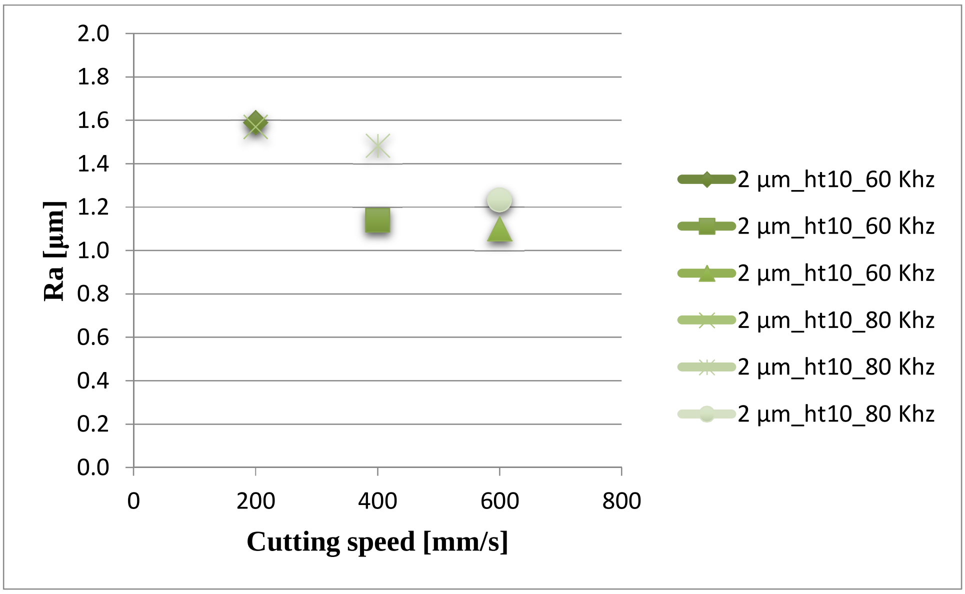

Figure 33 - Ra [μm] function during the demonstrating speed [mm/s] for 2 μm.

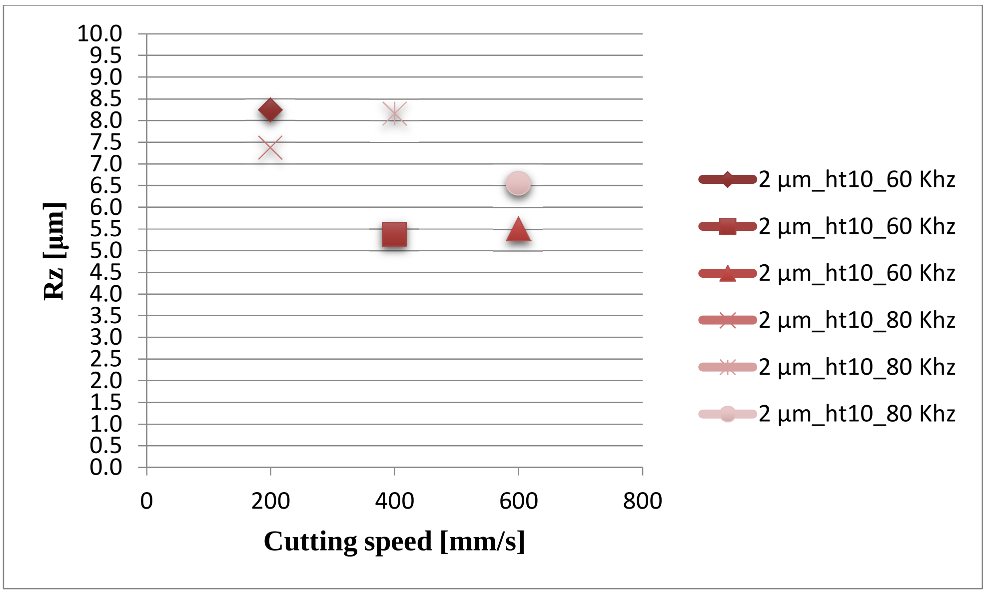

Figure 34 - Rz [μm] function during the demonstrating speed [mm/s] for 2 μm.

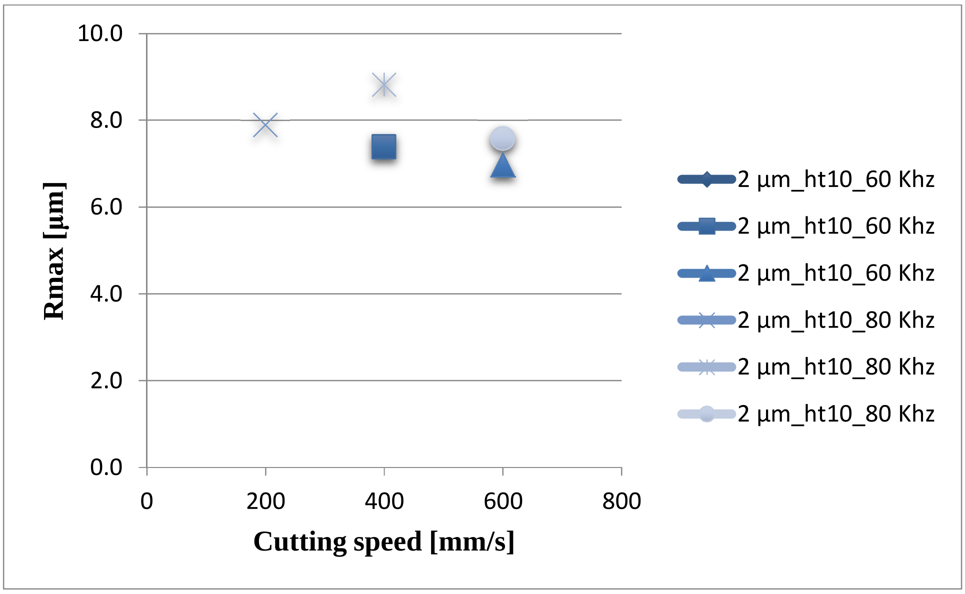

Figure 35 - Rmax [µm] function during the demonstrating speed [mm/s] for 2µm.

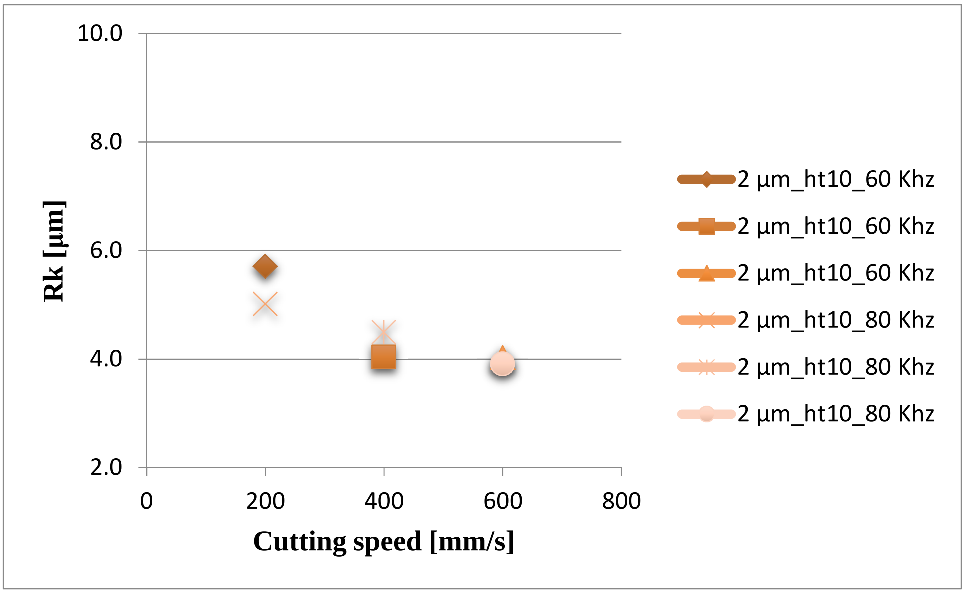

Figure 36 - Rk [µm] function during the demonstrating speed [mm/s] for 2µm.

Figure 34, Figure 35 and Figure 36 shows the variation of the others roughness parameters, Rz, Rmax and Rk respectably.

Table 11 - Roughness Test data parameters with the speed for 3 µm

Frequency [kHz]	Laser Speed [mm/s]	Ra [µm]	Rz [µm]	Rmax [µm]	Rk [µm]	
60	200	1.604	7.69	8.91	5.53	3 µm
	400	1.355	6.77	8.03	4.41	
	600	1.325	7.42	11.9	2.23	
80	200	1.524	8.46	10.2	5.13	
	400	1.770	8.71	9.34	5.59	
	600	1.645	8.66	12	5.49	

In Figure 37 for 3 µm and for higher values of frequency the roughness parameters are higher and this results in worst surfaces. The increment of the laser speed for the 3 µm spot results, in general, in the decrease of roughness values. But in some cases this behaviour it is not the tendency.

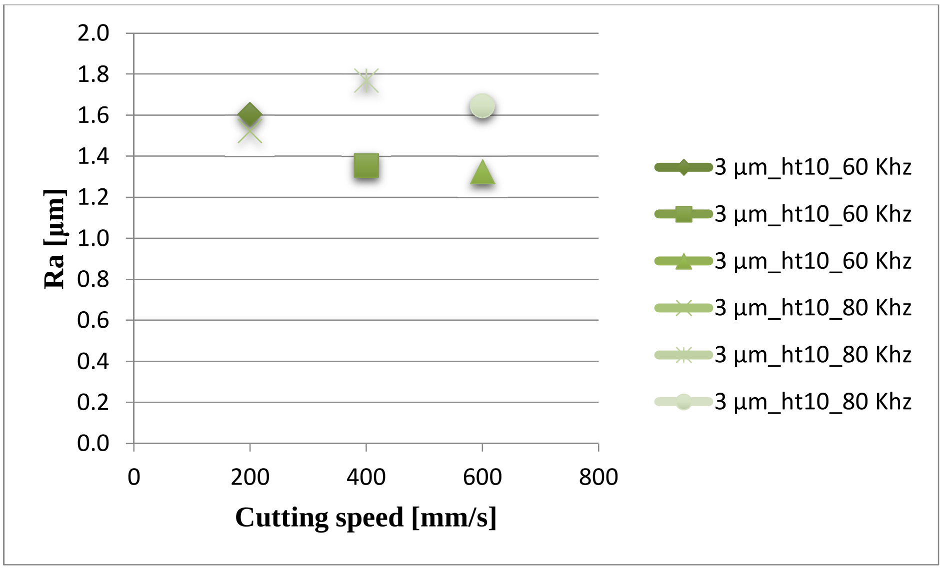

Figure 37 - Ra [µm] function during the demonstrating speed [mm/s] for 3µm.

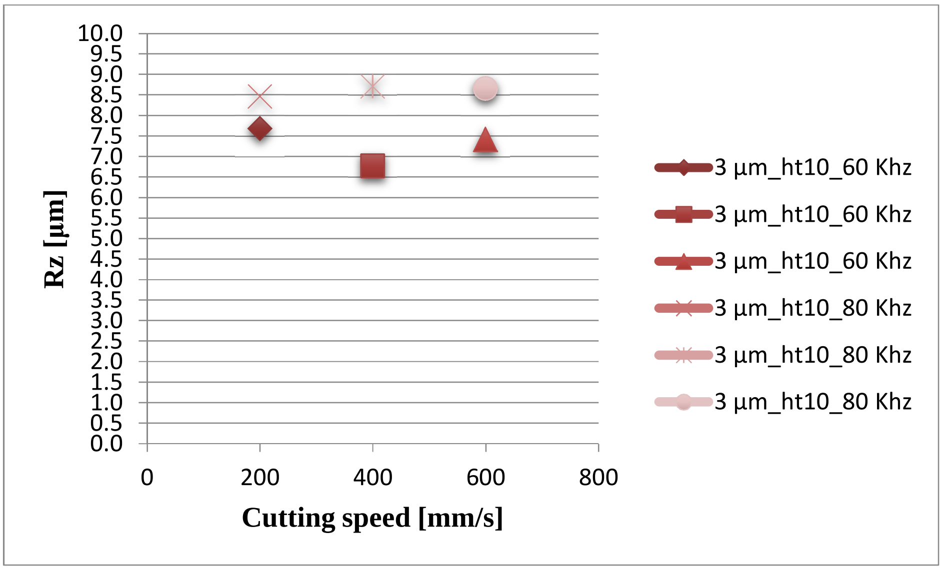

Figure 38 - Rz [µm] function during the demonstrating speed [mm/s] for 3µm.

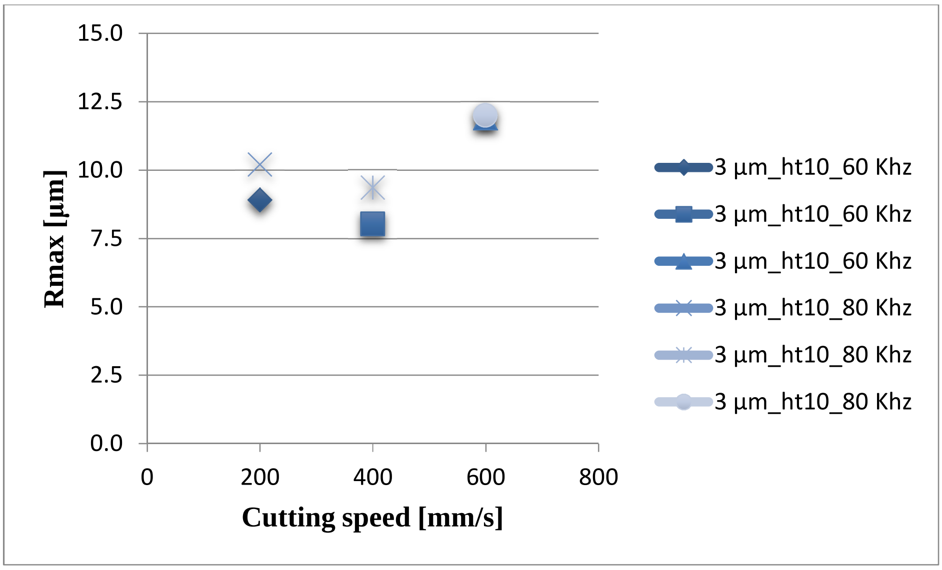

Figure 39 - Rmax [µm] function during the demonstrating speed [mm/s] for 3µm.

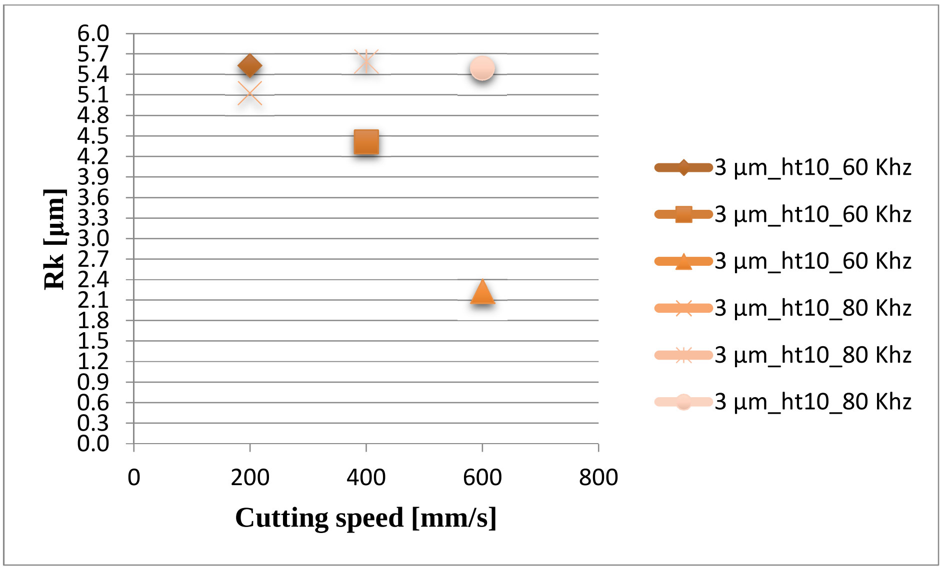

Figure 40 - Rk [µm] function during the demonstrating speed [mm/s] for 3µm.

In Figure 38, Figure 39 and Figure 40 the results for the others roughness parameters are showed.

Table 12 - Roughness Test data parameters with the speed for 4 µm.

Frequency [kHz]	Laser Speed [mm/s]	Ra [µm]	Rz [µm]	Rmax [µm]	Rk [µm]	
60	200	2.347	12.5	16.8	7.66	**4 µm**
	400	2.556	13.3	15.3	8.56	
	600	3.428	16.19	21.9	9.45	
80	200	2.631	12.9	17.4	8.72	
	400	2.249	12	13.5	8.31	
	600	2.660	14.1	15.5	8.54	

The table 12 resumes the results for 4 µm for all roughness parameters. In Figure 41, Figure 42, Figure 43 and Figure 44 the plot of values are showed. With the increment of frequency the roughness decreases with one exception that is for the laser speed of 200 mm/s.

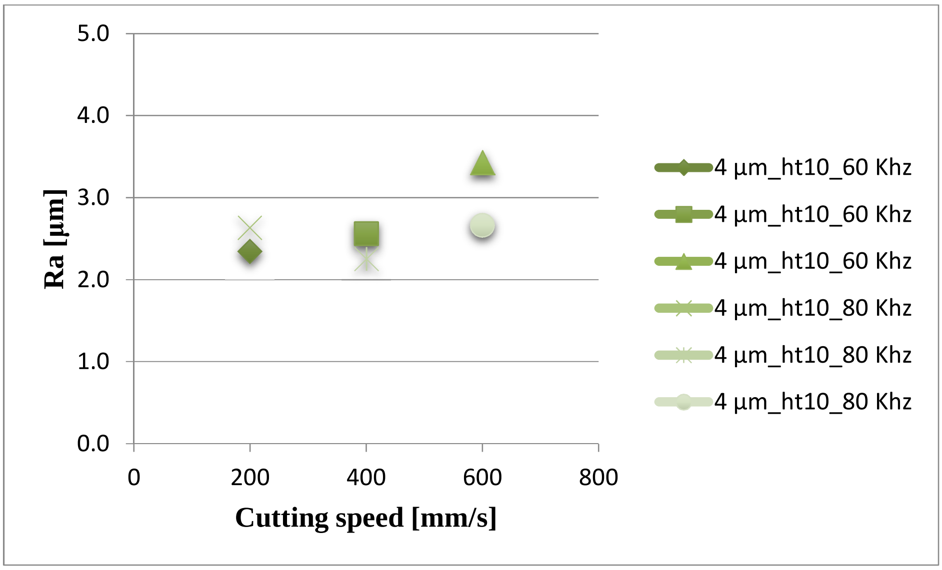

Figure 41 - Ra [µm] function during the demonstrating speed [mm/s] for 4µm.

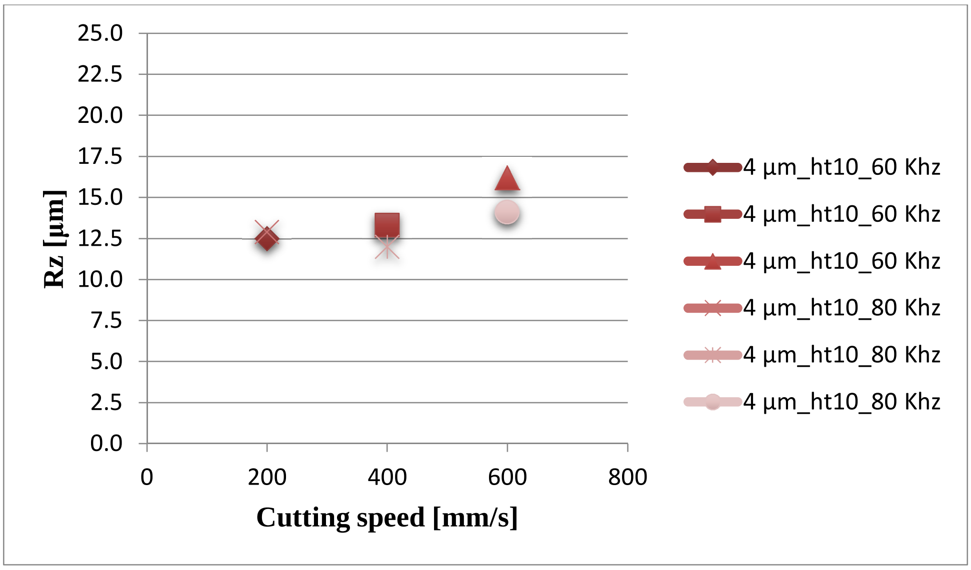

Figure 42 - Rz [µm] function during the demonstrating speed [mm/s] for 4µm.

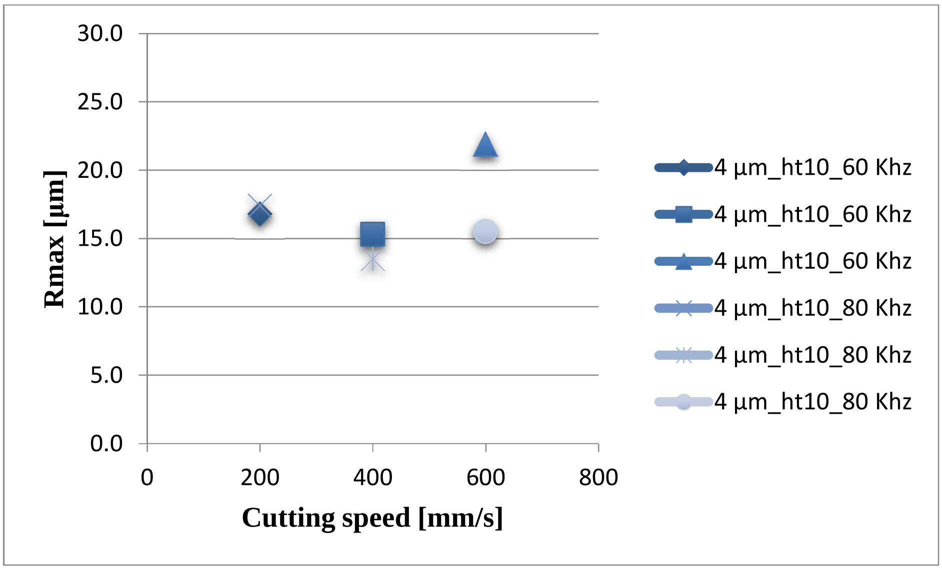

Figure 43 - Rmax [µm] function during the demonstrating speed [mm/s] for 4µm.

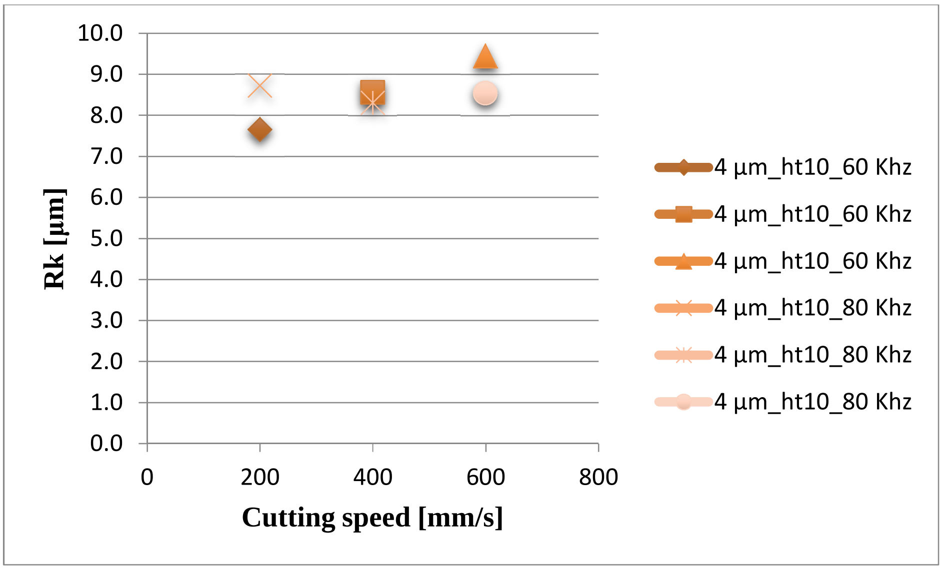

Figure 44 - Rk [µm] function during the demonstrating speed [mm/s] for 4µm

Table 13 resumes the results for 6 µm for all roughness parameters. In Figure 45, Figure 46, Figure 47 and Figure 49 the plot of values are showed. With the increment of frequency and laser speed the surfaces will appear with worst surface finishing.

Table 13 - Roughness Test data parameters with the speed for 6 µm

Frequency [kHz]	Laser Speed [mm/s]	Ra [µm]	Rz [µm]	Rmax [µm]	Rk [µm]	
60	200	2.813	13.3	15.3	9.9	6 µm
	400	3.909	19.3	22.9	13	
	600	4.527	23.2	27.3	13.1	
80	200	3.820	19.2	29.3	12.1	
	400	3.878	18.9	23.6	13	
	600	4.536	21.7	25.9	16.7	

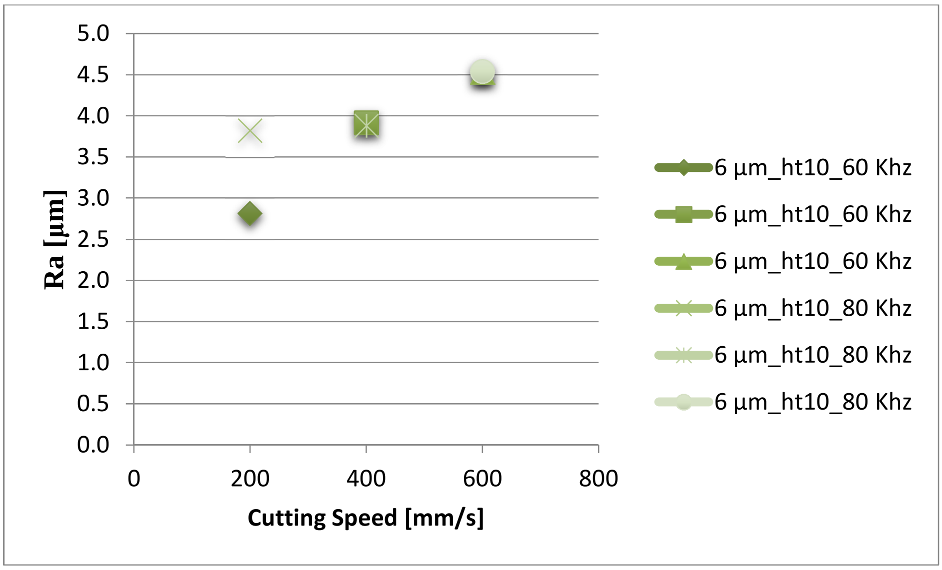

Figure 45 - Ra [µm] function during the demonstrating speed [mm/s] for 6 µm.

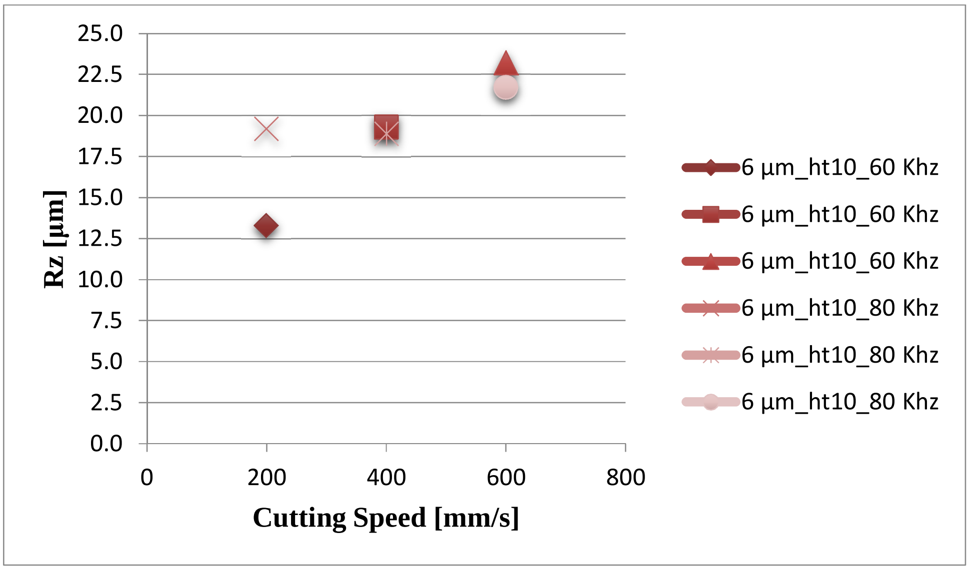

Figure 46 - Rz [μm] function during the demonstrating speed [mm/s] for 6μm.

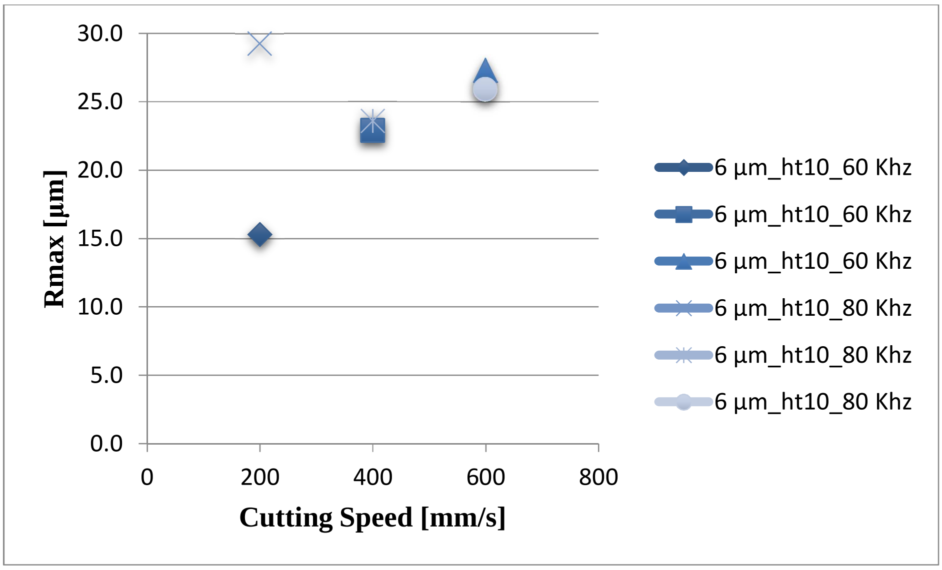

Figure 47 - Rmax [μm] function during the demonstrating speed [mm/s] for 6μm.

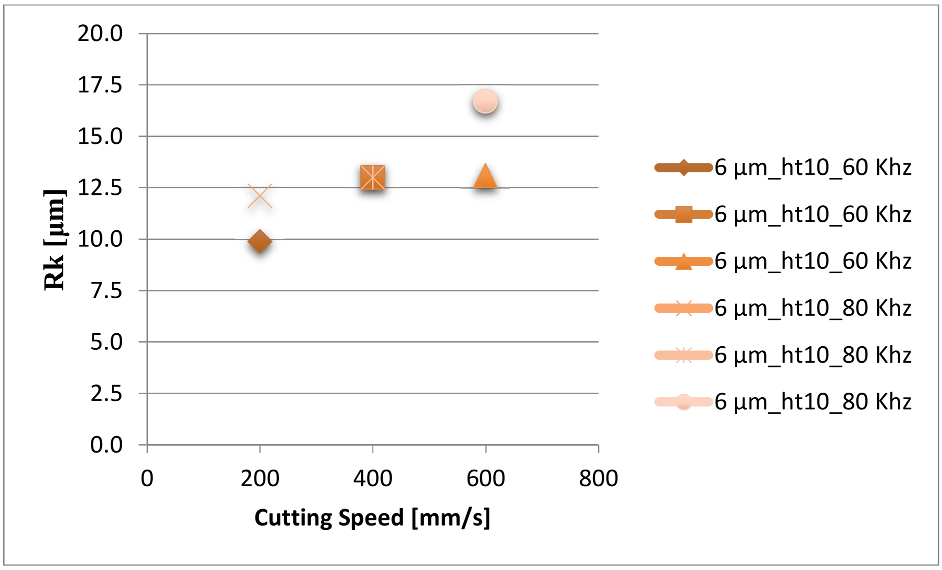

Figure 48 - Rk [µm] function during the demonstrating speed [mm/s] for 6µm.

The results of roughness were accessed for all experimental cases in order to understand the contribution of the laser milling parameters on the roughness values and surface structure.

Chapter VI

6. Conclusions

Laser beam machining is a non-traditional subtractive manufacturing process, a form of machining, in which a laser is directed towards the work piece for machining. This process uses thermal energy to remove material from metallic or non-metallic surfaces. The laser is focused onto the surface to be worked and the thermal energy of the laser is transferred to the surface, heating and melting or vaporizing the material. Laser beam machining is best suited for brittle materials with low conductivity, but can be used on most materials. The role of the technical equipment in laser milling is to perform a controllable action of the laser radiation on the material to be treated.

In this work, I had to follow the laser milling process parameter selection for process planning operations from start to finish. It was important to have an understanding about laser milling and laser processing parameters for different materials. As a result from the laser milling, the surface finish will have different surface properties such as, surface hardness, surface roughness, friction and tribology etc.. The two parameters that was analysed in this research work was surface hardness and surface roughness.

Based on the surface hardness, the following conclusions were obtained:

- The hardness is always higher for lower laser frequencies and lower laser speed on the spot.
- The hardness increases hardness with the diameter of the laser spot diameter.

Based on the surface roughness, the following conclusions were obtained:

- The Roughness values decreases with higher values of laser displacement speeds.
- For higher values of laser frequency, the roughness parameters are higher and this results in surfaces with poorer quality.

During the process, I gained knowledge about the historical and conceptual framework of laser milling, the different parameters of a laser milling and how the laser milling parameters influence the surface properties of the machined parts.

Bibliography

[1] Serope Kalpakjian, Steven R. Schmid Manufacturing Engineering and Technology ISBN 0-13-148-965-8 fifth edition.

[2] John. A. Schey Introduction to manufacturing processes ISBN 0-07-031136-6 third edition.

[3] Laser beam. Retrieved from: https://en.wikipedia.org/wiki/Laser_beam_machining.

[4] Laser Milling. Retrieved from: https://en.wikipedia.org/wiki/Milling_(machining).

[5] Laser Milling. Retrieved from: http://www.thomasnet.com/articles/custom-manufacturing-fabricating/mechanical-vs-laser-cutting.

[6] Contribution to laser milling process parameters Retrieved from: http://www.tesisenred.net/bitstream/handle/10803/124506/tdte.pdf?sequence=6

[7] William M. Steen. (2005). Laser Material Processing Third edition.

[8] Laser Technology Computer Sciences 2002 Helfrick, Albert D. 2002 The Gale Group Inc.

[9] Lasers: Fundamentals, types and operations. Retrieved from: http://www.wiley-vch.de/books/sample/3527327150_c01.pdf

[10] Laser Material Processing. Retrieved from: https://www.researchgate.net/publication/233502119_Laser_material_processing

[11] Study of the Influences of Laser Parameters on Laser Assisted Machining Processes. Retrieved from: http://www.industrial-lasers.com/articles/print/volume-26/issue-1/features/laser-assisted-machining.html

[12] Mukund Kumar. (2011) Laser Assisted Micro Milling of Hard Materials. Retrieved from: https://smartech.gatech.edu/bitstream/handle/1853/41213/kumar_mukund_201108_phd.pdf

[13] Hardness. Retrieved from: https://en.wikipedia.org/wiki/Hardness

[14] Surface hardness. Retrieved from: http://www.toray.jp/plastics/en/torelina/technical/tec_012.html

[15] Surface roughness. Retrieved from: http://www.olympus-ims.com/en/knowledge/metrology/roughness

[16] Surface roughness parameters. Retrieved from: http://www.digitalsurf.fr/en/guideprofileparameters.html

[17] Simple Roughness Amplitude Parameters. Retrieved from: http://db.materialoptions.com/ASETSDefense/SEDB/EHC_Alts/Tech_Matls_Info/Surface%20Metrology%20Guide%20-%20Profile%20Parameters.pdf

[18] Steel 1.2344. Retrieved from: http://ozct.com.tr/en/pdf/1.2344%20X40CrMoV5-1.pdf

[19] 1.2344 Tool Steel. Retrieved from: http://www.westyorkssteel.com/steel-specifications/werkstoff-standards/tool-steel-w-nr/1-2344

[20] Laser. Retrieved from: https://en.wikipedia.org/wiki/Laser

[21] Laser Material Processing. Retrieved from: https://www.researchgate.net/publication/233502119_Laser_material_processing

[22] Micromachining technology. Retrieved from: https://www.makino.com/about/news/Trends-in-Micro-Machining-Technologies/315