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VYSOKÉ UČENÍ TECHNICKÉ V BRNĚ

FACULTY OF MECHANICAL ENGINEERING
FAKULTA STROJNÍHO INŽENÝRSTVÍ

INSTITUTE OF MANUFACTURING TECHNOLOGY
ÚSTAV STROJÍRENSKÉ TECHNOLOGIE

INFLUENCE OF SURFACE ROUGHNESS ON OPTICAL PROPERTIES OF MACHINED MATERIALS

VLIV DRSNOSTI POVRCHU NA OPTICKÉ VLASTNOSTI OBRÁBĚNÝCH MATERIÁLŮ

BACHELOR'S THESIS
BAKALÁŘSKÁ PRÁCE

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Assignment Bachelor's Thesis

Institut:	Institute of Manufacturing Technology
Student:	**Ghaith Ashqar**
Degree programm:	Engineering
Branch:	Fundamentals of Mechanical Engineering
Supervisor:	**Ing. Radim Kupčák**
Academic year:	2020/21

As provided for by the Act No. 111/98 Coll. on higher education institutions and the BUT Study and Examination Regulations, the director of the Institute hereby assigns the following topic of Bachelor's Thesis:

Influence of surface roughness on optical properties of machined materials

Brief Description:

Mechanical components of optical devices are designed so that they suppress a stray light. A stray light in general has negative effects on optical performance of optical devices. It can be partially eliminated using baffle systems or coatings with highly absorptive properties. An alternative solution can be a careful choice of cutting parameters, therefore achieving specific surface roughness. The author will design a set of samples for future optical measurments.

Bachelor's Thesis goals:

Research of surface roughness.
Design of samples.
Manufacturing technology of samples.
Evaluation of samples.

Recommended bibliography:

BUMBÁLEK, B., ODVODY, V. a OŠŤÁDAL, B. Drsnost povrchu. Praha, SNTL, 1989. 04-252-89.

WHITEHOUSE, D. J. Handbook of Surface Metrology. Bristol, Institute of Physics Publishing Ltd. 1994. ISBN 0-7503-0039-6.

DE CHIFFRE, L., et al. Quantitative characterisation of surface texture. CIRP Annals - Manufacturing Technology, 2000, vol. 49, no. 2, p. 635-652. ISSN 0007-8506.

JIANG, X. and WHITEHOUSE, D. J. Technological shifts in surface metrology. CIRP Annals - Manufacturing Technology, 61 (2). pp. 815-836. 2012. ISSN 0007-8506.

Deadline for submission Bachelor's Thesis is given by the Schedule of the Academic year 2020/21

In Brno,

L. S.

doc. Ing. Petr Blecha, Ph.D. Director of the Institute	doc. Ing. Jaroslav Katolický, Ph.D. FME dean

ABSTRAKT

První, teoretická, část této bakalářské práce se věnuje problematikám souvisejícím s výrobou mechanických položek pro optické přístroje. Poskytuje úvod k parazitnímu světlu a přehled způsobů jeho eliminace. Následuje obecná část zabývající se soustružení a sekce věnovaná měření drsnosti povrchu. V praktické části jsou tyto poznatky zúročeny v podobě návrhu a následné výroby prototypového vzorku který bude sloužit k vyhodnocení vlivu drsnosti povrchu na množství parazitního světla v optickém přístroji. Drsnost povrchu jednotlivých vzorků byla změřena a porovnána s teoretickou hodnotou získanou výpočtem. Prototyp byl vyvinut v úzké spolupráci s R&D oddělením přerovské firmy Meopta – optika, s.r.o. Na základě budoucích zkoušek a měření bude vyhodnoceno, zda je autorem navrhovaná inovace aplikovatelná v oblasti přesné mechaniky a optiky.

Klíčová slova

drsnost povrchu, soustružení, parazitní světlo, optika

ABSTRACT

The first half of this bachelor’s thesis devotes itself to topics relating to the manufacturing of mechanical components for optical devices. It introduces stray light and brings an overview of methods of its elimination. A general section, that deals with turning and surface roughness measurements, follows. The major objective of the second part of this thesis is the design and manufacturing of prototype samples. These samples will be used for the evaluation of surface roughness, and the influence of surface roughness on stray light will be studied in the future. The surface roughness of each sample was measured and compared with the theoretical value. The prototype was developed in close cooperation with the R&D department of Meopta - optika, s.r.o. Future tests and measurements would indicate if the innovation proposed by the author will have application in precise mechanics and optics.

Keywords

surface roughness, turning, stray light, optics

BIBLIOGRAPHIC CITATION

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AFFIRMATION

I declare that this bachelor thesis is my work, led by my supervisor and all used references are listed in the bibliography.

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Date Ghaith Ashqar

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I would like to thank my supervisor Ing. Radim Kupčák and Meopta - optika, s.r.o., for their cooperation during this bachelor work. Big thanks to my family and my friends for their support and help during all my studies.

CONTENTS

INTRODUCTION

Optical devices are complex structures, that require careful design and precise manufacturing of both mechanical and optical components for them to work according to required specifications. One phenomenon, that can deteriorate the quality of such an optical device can be stray light. Stray light is unwanted light in the system, which does not carry any information about the displayed subject.

There are many ways of eliminating stray light, one of them is creating optical grooving on inner parts of mechanical components of the optical device. This established method is used by many optics manufacturers. One of these manufacturers is Meopta – optika,s.r.o., a Czech manufacturer of sport and industrial optics with long history and tradition. This thesis, which has been worked out in cooperation with Meopta is part of a bigger objective of making optical grooving more economical.

The goal of this thesis is the preparation of prototype samples, which will be used to evaluate a new method of manufacturing optical grooving. Instead of careful manufacturing of specific shape of the grooves, rough surface is generated by linear turning, but with specific cutting conditions (generally higher feed rate than is usual). This generates a surface similar to optical grooving, but with much shorter machining time and using basic turning inserts.

The behaviour of light reflecting off the rough surface is complicated and impossible to predict using recently available ray-tracing software. Because of that, many types of surface finishes, using different cutting conditions, need to be prepared, measured, and optically tested in the future. Theoretical and real surface roughness of different samples was compared and evaluated. Based on the future results of the optical measurements, it can be evaluated, if similar results to optical grooving can be achieved this way.

1 THEORETICAL PART

1.1 Theory of light and its properties

Light or visible light is electromagnetic radiation within the portion of a range of frequencies (spectrum) that can be perceived by the human eye. The wavelength of the visible light is in the range of 400-700 nm, and it locates between infrared radiation (IR) and ultraviolet radiation (UV) [1;2;3].

Old Greek studied light and its properties. Light travels in straight lines and it can reflect or refract. In the following centuries, scientists developed theories about light properties, and it can be described as a wave and particle [4].

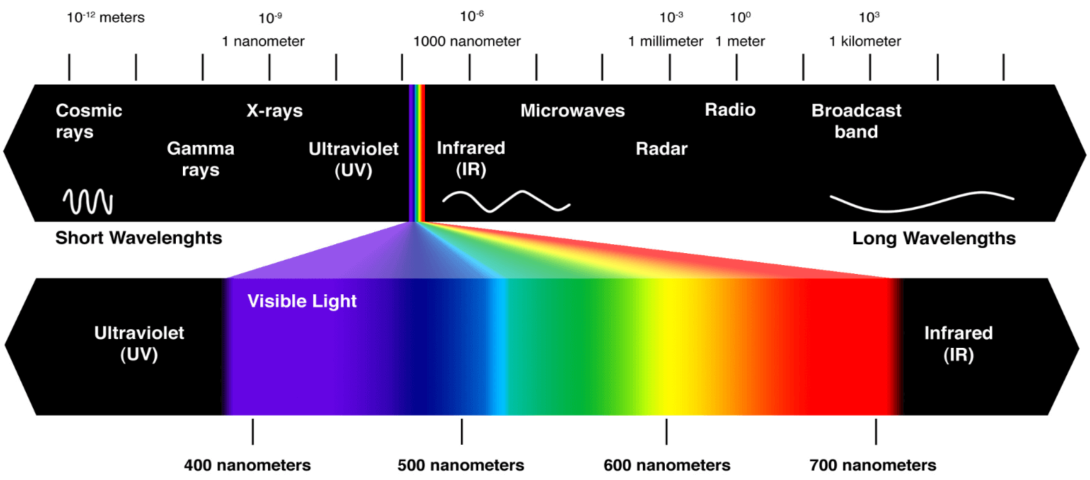


Fig. 1 The visible light spectrum range [5].

The arrangement of wavelengths (see Fig. 1) starts from ultraviolet (UV) on the left and continues to infrared (IR) on the right. Longer wavelengths have lower frequencies. The red color has longer wavelengths than the blue in the visible light spectrum, which is so tiny compared to the whole range. There are colors outside the visible range of wavelengths, it is the colors that the human eye cannot see [6]. However, the main interest in this bachelor's work is the visible spectrum of light.

When light hits pigment molecules, the energy of this light vibrates the electrons more strongly. And the energy of light is absorbed by the pigment molecule, so the light disappears, and other colors are reflected giving the color we see. The exact structure of each pigment molecule affects the reflected light representation. A small change in the pigment chemistry can make a big change in color. As shown in Fig. 2 the properties of light may be divided into 7 basic properties: reflection, refraction, diffraction, interference, polarization, dispersion, and scattering. Light behaves differently when it falls on different objects. When light falls on the surface of a non-luminous object, it can behave in three ways [6; 7]:

1. If light falls on a rough surface, it changes as a form of heat energy and it will be mostly absorbed, for this reason, a black surface can be used to absorb most of the light.
2. If light falls on a smooth surface it bounces off in one direction. This light bounces off in one direction and in this case, it is called reflection of light.
3. Light might be transmitted to the other side when it falls on transparent objects.

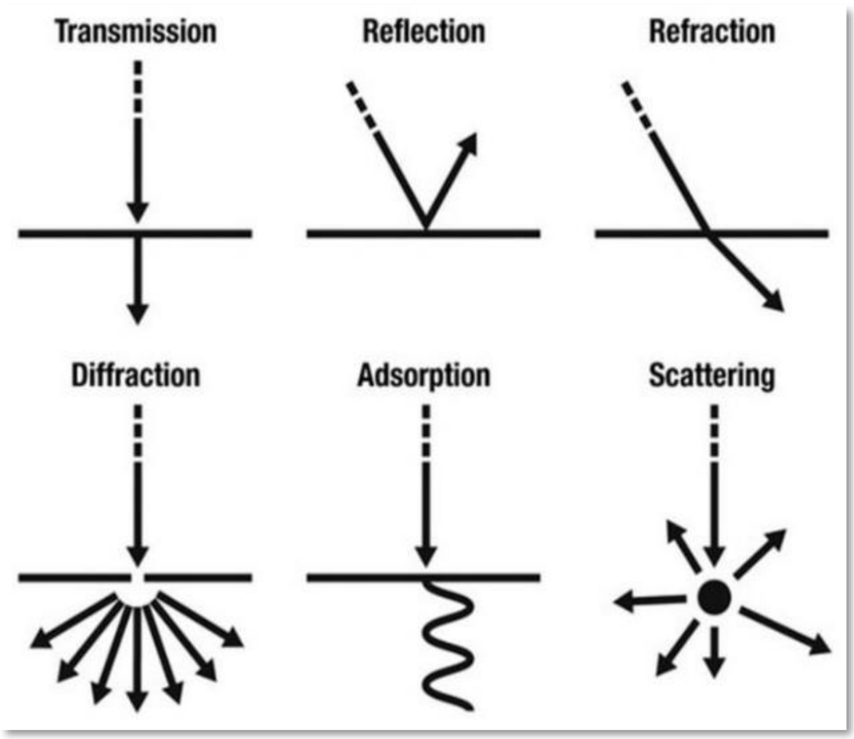


Fig. 2 Light wave behaviour [8].

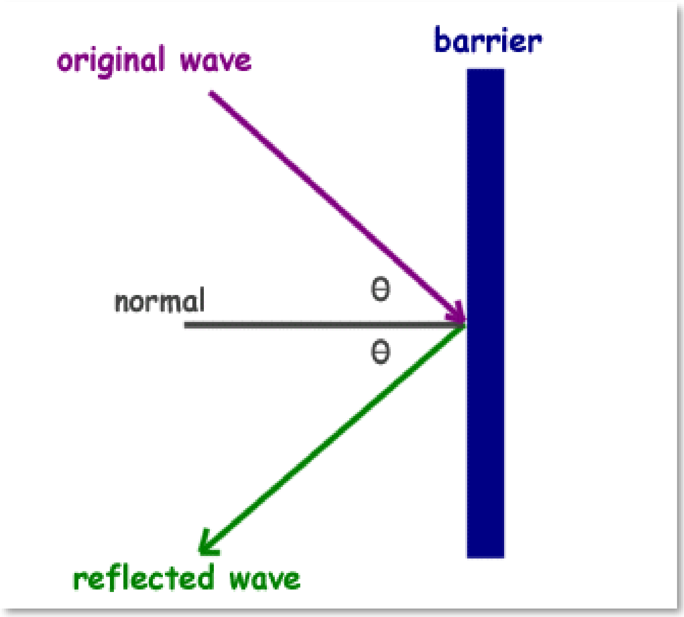


Fig. 3 Light wave reflected by angle θ [9].

Light travels in straight lines in a homogeneous isotropic medium, this is referred to as rectilinear propagation of light. When a beam of white light enters a prism, all the colors of white light refract at different angles. It causes the white light to split into its component colors. Sunlight is often called white light, although it is a combination of different colors. These colors exist in a rainbow. A rainbow forms when sunlight is refracted and reflected by tiny water droplets [7].

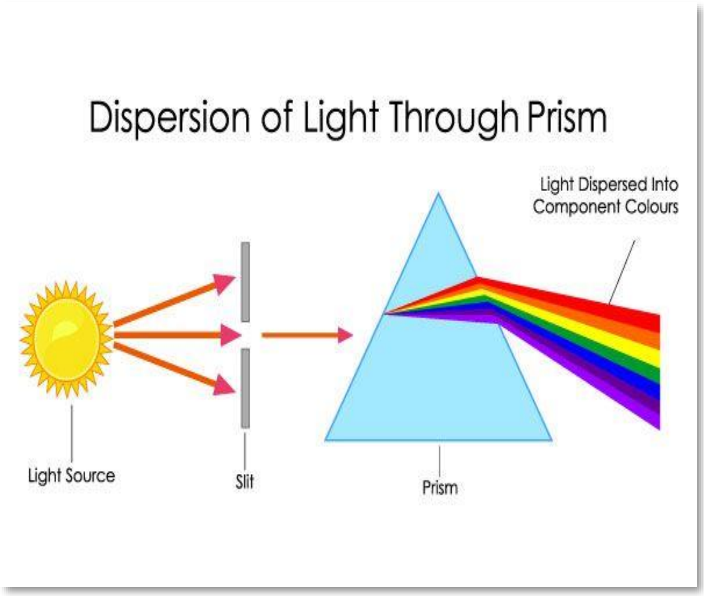


Fig. 4 Dispersion of light through prism [10].

1.2 Stray light in optical systems

Stray light is light in the optical system, which is not intended and may be initiated from the intended source, but it follows different paths than intended. Stray light has different colors (wavelength) than intended in the design. This light often sets a working limit on signal-to-noise ratio and dynamic range, which affects the photometric accuracy and precision. For the binocular optical device, the main issue is that the stray light causes a loss in contrast and unwanted glaring. Stray light may have different causes, its existence may be caused by different design and manufacturing factors, the level of the stray light inside the optical device depends on the design of the instrument. for example, Interior finish. Part of this unwanted light may be called re-entrant spectra, because of the diffracted light onto the entrance [11].

The Newtonian telescope is an example of an optical system, which consists of a concave primary mirror and a flat diagonal secondary mirror. It was invented by Sir Isaac Newton (1642–1727). Newton built his reflecting telescope because he thought that it proves his theory that white light is composed of a spectrum of colors [12; 13].

Fig. 5 The national geographic telescope [14].

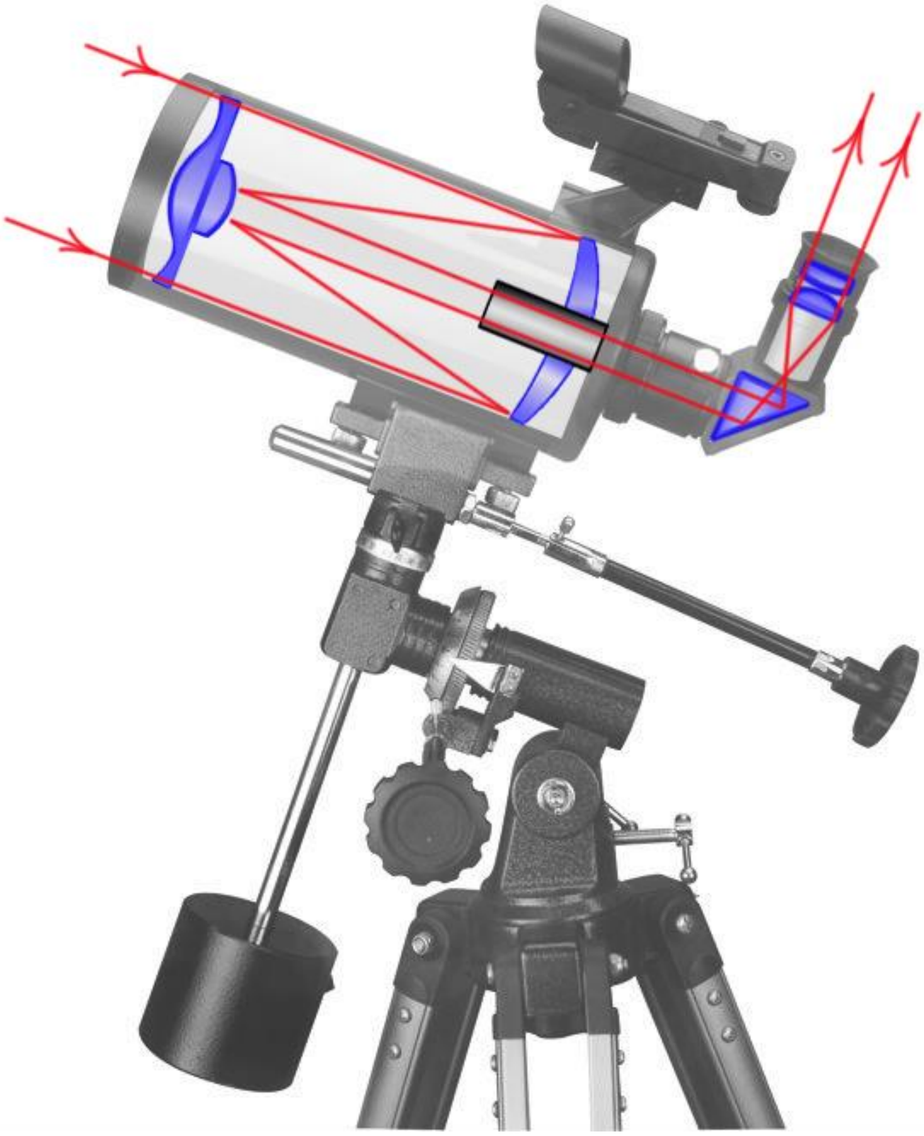


Fig. 6 Reflecting telescope scheme [15].

Fig. 6 shows the simplified instruments of the telescope and the path of the light, which enters the telescope in parallel paths, and it reflects into the surface of a parabolic mirror, then it reaches a plane mirror to find its way out to the eyepiece.

Stray light problem is common in optical devices, and it is necessary to control it due to its negative effect on the performance of the optical device so that the Newtonian telescope is a good example where the stray light problem appears.

Mainly, there are two kinds of stray light: direct and indirect. All direct stray light should be eliminated, as much indirect stray light as practicable should be eliminated and direct stray light can be eliminated by careful design. Light from a small field of view will be brought to a focal surface and rendered as an image. The focal length of the instrument controls the scale of this image, so for this situation, a focuser baffle might be added to the telescope, which is known as a powerful tool in blocking stray light [16].

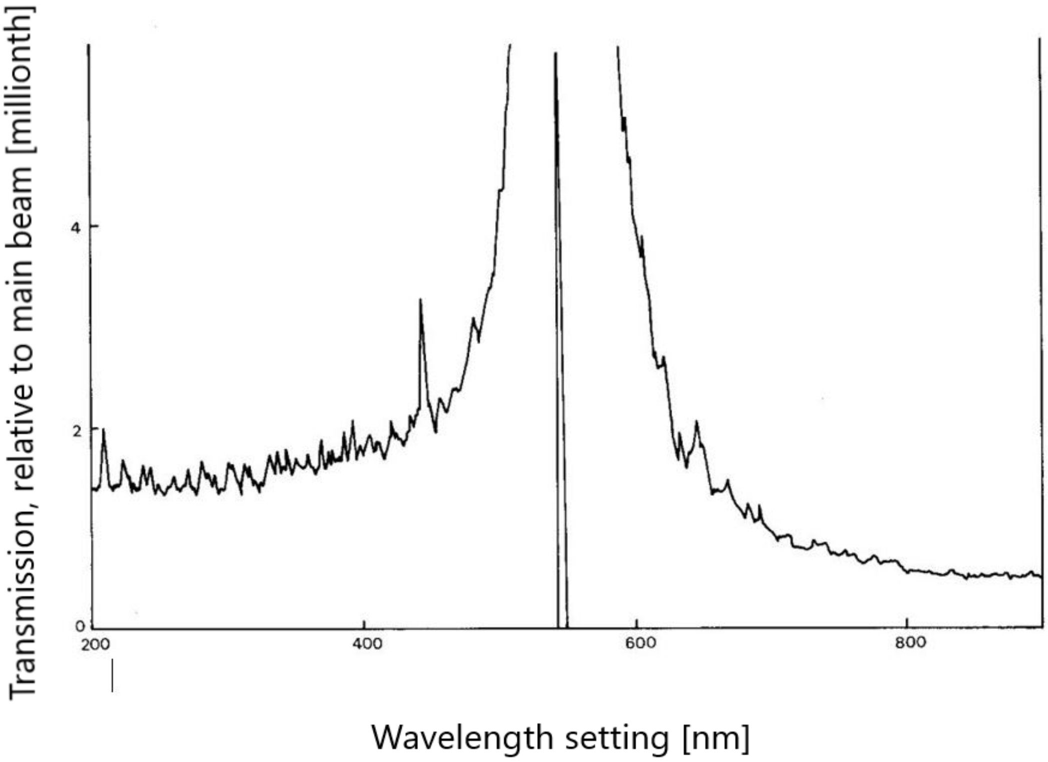


Fig. 7 Typical stray light profile obtained with an ‘Optica’ monochromator [17].

In spectrophotometers, the term (stray light) is used to refer to the minute amount of unwanted light having wavelengths outside the narrow band isolated by the optical system. The effect of stray light is to reduce the accuracy of the instrument and in some cases to restrict the wavelength range over which the instrument may be used [17].

1.2.1 Methods of stray light elimination

In this section, stray light elimination will be described, and the methods which will be used as a solution to eliminate stray light, for example, baffle system, coatings, a material with highly absorptive properties and surface roughness, or even by creating carefull design considering a minimum output of stray light.

Baffle system

A baffle system (see Fig. 8) is a mechanical system, whose function is to shield the light coming from sources outside the field of view of the camera. The light outside the angular view of the system must execute multiple numbers of reflections on its surfaces, minimizing the intensity of the light that effectively reaches the optical system.

It consists basically of a tube, which has vanes in internal walls. These vanes are used to reduce the intensity of light that is reflected on the walls. At least two reflections from blackened surfaces are required between the stray light source and the optical element.

The light from inside the baffle is required to execute a maximum number of surface reflections from blackened surfaces before entering the optical system. A minimum number of edges directly exposed to the sun is used. Surfaces, which are not optical components in the field of view, are covered with a black material [18; 19].

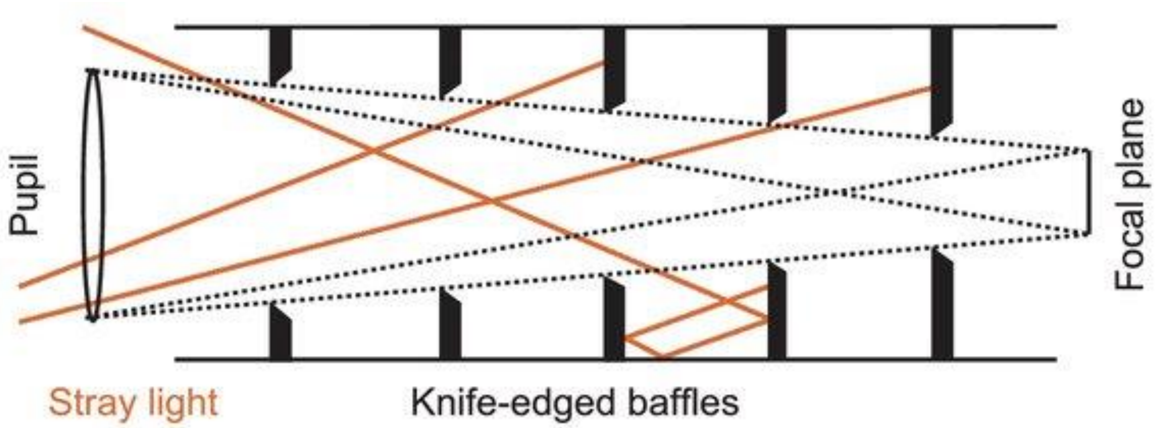


Fig. 8 Stray light in Knife-edged baffles system [20].

Coating

A black coating to a pipe or tube can provide a benefit because it influences stray light. A simple cylinder baffle can have a stray light reduction of about 5 orders of magnitude or 10^5 attenuations. Two-stage baffles or more complicated baffle designs can reduce the stray light by a factor of 10^8 or more.

This is of course dependent on black coatings on the inside of the baffle. The main purpose of black coating for optical systems is to maximize the absorption of light and reduces the reflections. This is done, in the case of black coatings, through absorption. Absorption is usually most effective at angles close to the surface normal. Rays of light through glancing angles have less likelihood of being absorbed. This is where surface roughness helps but usually does not eliminate glancing angle reflections. To reduce the glancing angle reflections from getting through, baffle geometry must be employed to deal with this in the best way possible for each system [21].

1.3 Turning technology

Methods of machining are divided depending on different aspects, for example, the character of work as the manual work. Machining methods can be divided into [22]:

- Machining methods using tools with defined geometry (turning, milling, drilling, reaming, boring, etc.),
- Machining methods with undefined geometry (finishing methods, grinding, lapping, superfinishing),
- Unconventional machining methods (chemical machining, ultrasonic machining, etc.),
- Modification of machined surfaces (rolling, smoothing, polishing, etc..).

Turning is a technological machining process used to produce parts of rotary shapes (see Fig. 9), usually, it uses a single edge tool of various designs. Turning can be used to machine external and internal cylindrical or conical-shaped surfaces.

The main movement is rotary, it is performed by the workpiece and the feed movement is rectilinear, it is performed by the tool. The cutting movement performs a helical shape when turning a cylindrical surface. It is used to produce rotational, typically axisymmetric, parts that have many features, such as holes, grooves, threads, tapers, various diameter steps, and even contoured surfaces [22].

The values of the cutting speeds and feed rates are calculated using the following formulas [22]:

$$v_c = \frac{\pi \cdot D \cdot n}{1000} \tag{1}$$

$$v_f = f \cdot n \tag{2}$$

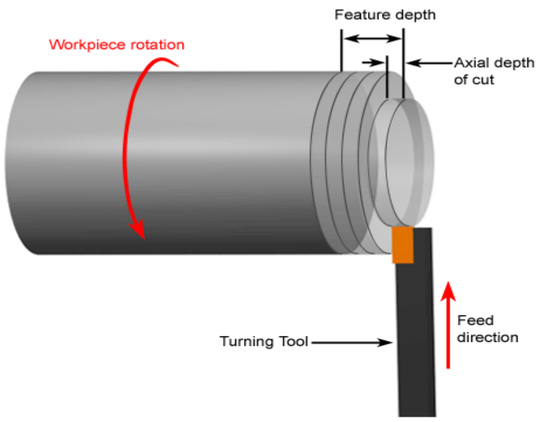


Fig. 9 Turning process [23].

A single-point turning tool moves axially, along the side of the workpiece, removing material to form different features, including steps, tapers, chamfers, and contours (see Fig. 10). These features are typically machined at a small radial depth of cut and multiple passes are made until the end diameter is reached [23].

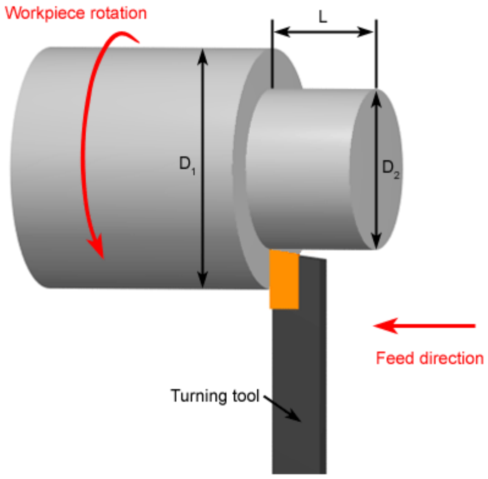


Fig. 10 Single-point turning tool [23].

Turning operations may be performed to the workpiece to achieve the desired part shape. These operations are classified as external or internal operations. External operations modify the outer diameter of the workpiece, while internal operations modify the inner diameter of the workpiece (see Fig. 11) [23].

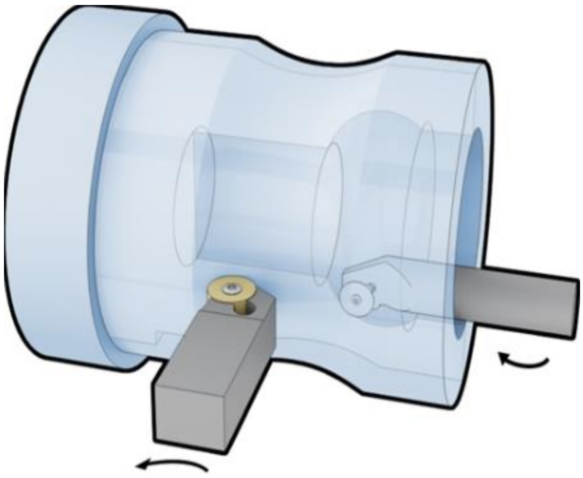


Fig. 11 Internal and external turning [24].

As shown in Fig. 12 a descripton of the manual lathe parts, which uses a manual control for machining process , and it follows with Fig. 13 which describes a single-point cutting tool and the cutting edges.

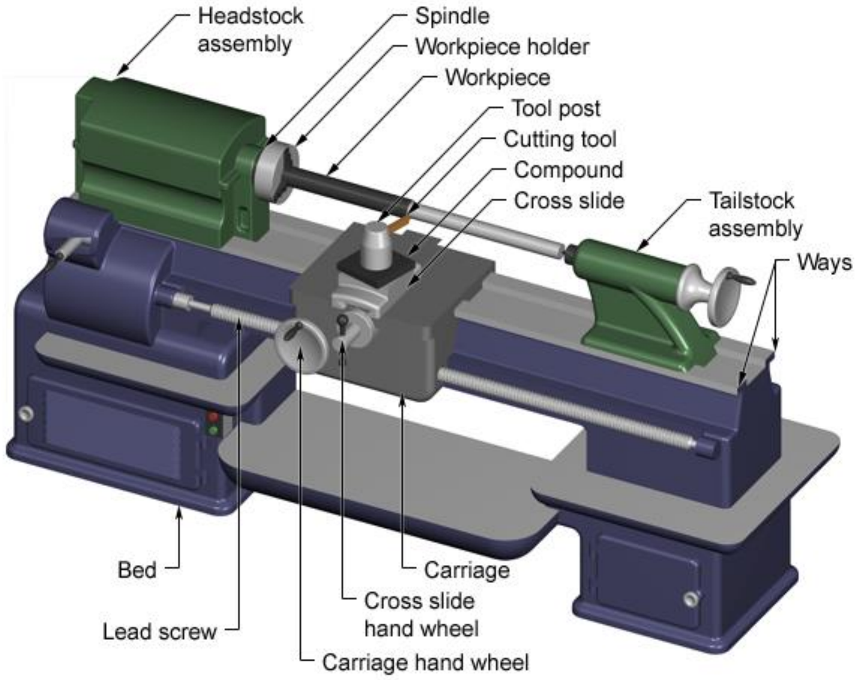


Fig. 12 Manual lathe [23].

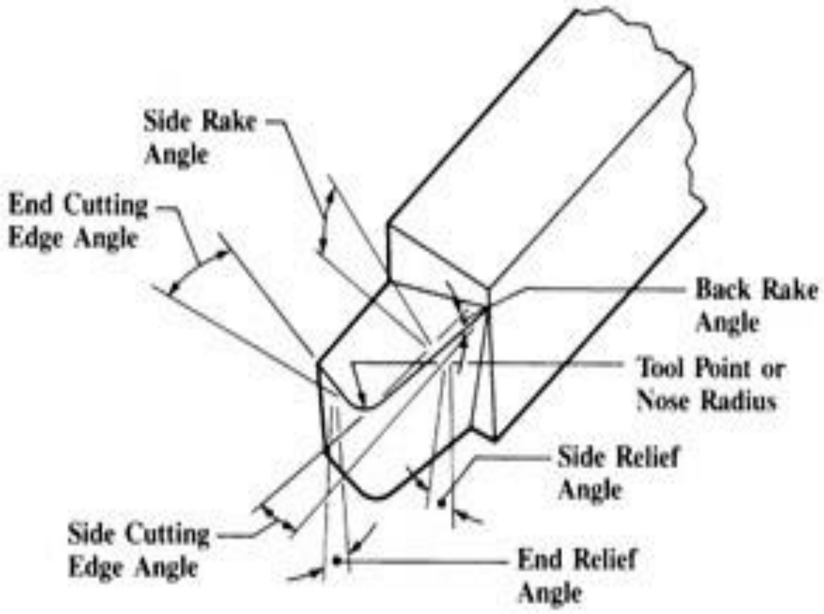


Fig. 13 Terms applied to single-point turning tool [25].

1.3.1 Aluminum alloys

Aluminum alloys are defined as a chemical composition where other elements are added to pure Aluminum to improve aluminum element properties, primarily to increase its strength. Alloys are assigned a four-digit number, in which the first digit identifies a general class, or series, characterized by its main alloying elements.

Aluminum alloys can be made stronger through heat treatment or cold working. Some alloys are strengthened by solution heat-treating and then quenching, or rapid cooling. Using heat treatment for the solid and the alloying element heat them at a specific point. The alloy elements, called the solute, are homogeneously distributed with the aluminum putting them in a solid solution.

The solute atoms consequently combine into a finely distributed precipitate. This occurs at room temperature which is called natural aging or in a low-temperature furnace operation which is called artificial aging. These alloys are mentioned as heat-treatable alloys. There are also non-heat treated alloys, which are strengthened through cold-working.

Cold working is the action of working the metal to make it stronger and it occurs during forging or rolling methods. Cold working builds up dislocations and vacancies in the structure, which prevents the movement of atoms relevant to each other so that as a result this increases the strength of the metal. The 6xxx series are heat treatable, highly formable, weldable, and have high strength with good corrosion resistance. Alloy 6061 is the most widely used alloy in this series and is often used in truck and marine frames.

Zinc is the primary alloying agent for7xxx series, and when magnesium is added in a smaller amount, the result is a heat-treatable, very high strength alloy. Other elements such as copper and chromium may also be added in small quantities. The most known alloys are 7050 and 7075, which are widely used in the aircraft industry [26].

1.3.2 Aluminum anodizing

As shown in Fig. 14, Anodizing is an electrolytic process used to increase the oxide layer on the surface of Aluminum, it uses an electrical current to generate an electrolysis reaction, which includes anodic oxidation and cathodic reduction, considering that Aluminum anode is covered almost entirely, by an alumina film, and it is used to create a layer with better hardness and high resistance to abrasion [27].

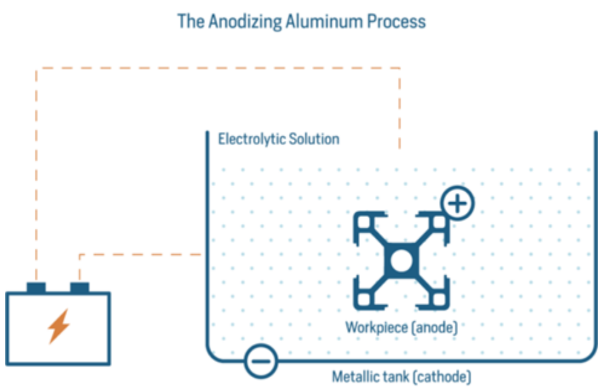


Fig. 14 Aluminium anodizing process [27].

In Fig. 15 an aluminum piece is lowered into an electrolytic bath and the current passes through an electrolytic solution. Aluminum here functions as the anode electrode of an electrical circuit, hence the name anodizing. The electrolytic bath forms an oxide film, which, is combined into the aluminum instead of being on the surface of the metal [27].

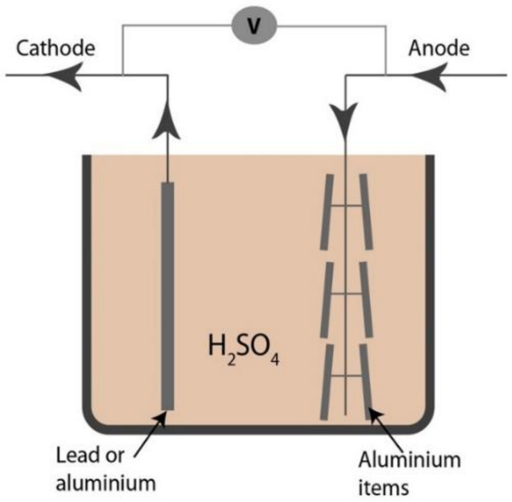


Fig. 15 Aluminium anodizing process [28].

At the anode [29]:

$$2H2O\ (l) \rightarrow O2\ (g) + 4H+\ (aq) + 4e–$$

The oxygen produced reacts with the anode to form the protective layer:

$$3O2\ (g) + 4Al\ (s) \rightarrow 2Al2O3\ (s)$$

These chemical reactions are presented in Fig. 16.

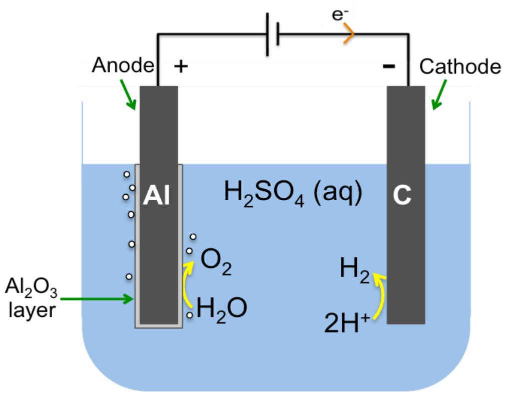


Fig. 16 Forming oxide layer on Aluminium surface by anodizing[29].

1.4 Surface texture

Surface finish, also known as a surface texture or surface topography, is the nature of the surface as defined by the characteristics such as lay, surface, roughness, and waviness. Surface texture is one of the important factors that control friction during sliding. However, in some cases, it's essential to have a much rougher surface. For example, in the case of mating parts, which are not to be moved and there is no sliding between two mating parts such as parts in an interference fit, so in such cases to prevent the relative motion between two parts, it's necessary to have a slightly rough surface.

In some other cases that require a very fine surface to improve the look of the component. Surface roughness is important from the point of view of fundamental problems such as friction and wear, surface contact, lubrication, fatigue strength, and tightness of joints. It affects conduction of heat and electrical current, cleanliness, reflectivity of the surface, sealing action.

It also affects the positional accuracy of mating parts, load-carrying capacity, resistance to corrosion, and adhesion of paint and coatings. The accuracy and surface-finish requirements for machine parts in modern industry are becoming more rigid [30].

Surface texture can be analyzed according to [31]:

I. Lay: is defined as the direction of the predominant surface pattern,

II. Roughness height: is a measure of the height of the irregularities compared to a reference line,

III. Roughness width: is the distance between the two successive peaks or ridges of the predominant surface pattern, which is measured in a direction parallel to the surface,

IV. Surface waviness: can be distinguished from roughness based on spacing and surface irregularities, this waviness is affected by heat treatment, vibrations, residual stresses.

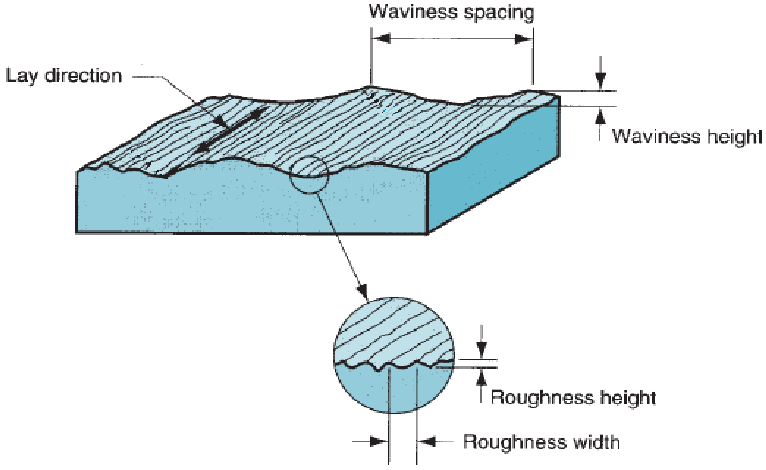


Fig. 17 Surface texture [31].

1.4.1 Basic parameters of surface roughness

Surface roughness is defined as the shorter frequency of real surfaces relative to the troughs. A product's exterior cover, a vehicle's dashboard, a machined panel---the differences in appearance, specifically whether something is shiny and smooth or rough and matte, are due to the difference in surface roughness. Surface roughness not only affects the object's appearance but also produces texture or tactile differences [32].

Definitions and indications for surface roughness parameters -for industrial products- are specified. They are divided into amplitude parameters (peak and valley), amplitude average parameters, spacing parameters, etc...[33].

1. Amplitude average parameters [33]:

Arithmetic mean deviation (R_a): It represents the arithmetic mean of the absolute ordinate Z(x) within the sampling length. One of the most widely used parameters is the mean of the average height difference for the average surface. It provides stable results as the parameter is not significantly influenced by scratches, contamination, and measurement noise.

$$R_a = \frac{1}{l}\int_0^l |Z(x)|dx \tag{3}$$

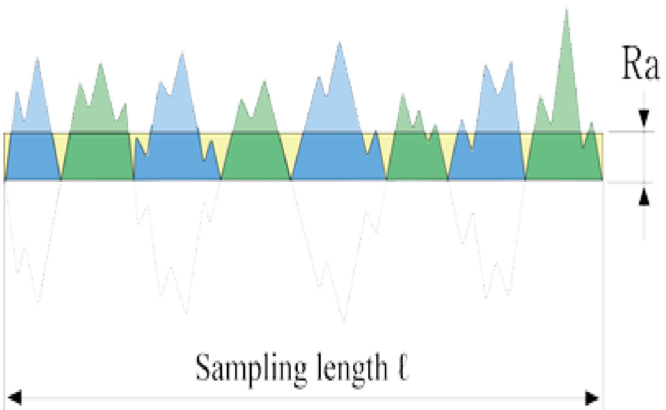


Fig. 18 Arithmetic mean deviation (R_a) [33].

Root mean square deviation (R_q): It represents the root mean square for Z(x) within the sampling length. This is one of the most widely used parameters and is also referred to as the RMS value. The parameter Rq corresponds to the standard deviation of the height distribution. The parameter provides for easy statistical handling and enables stable results as the parameter is not significantly influenced by scratches, contamination, and measurement noise.

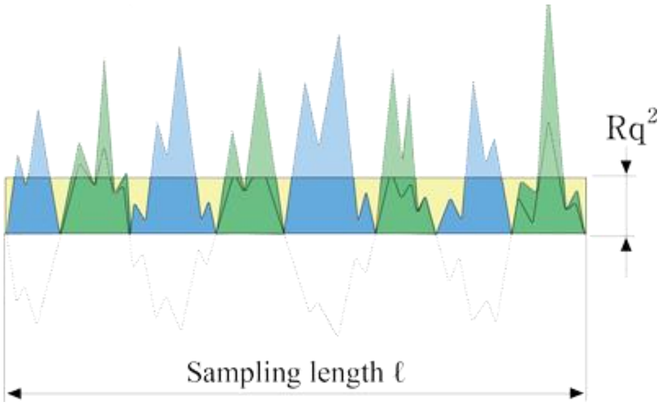


Fig. 19 Root mean square deviation (R_q) [33].

There are other parameters considered with the amplitude average parameters such as skewness (R_{sk}) and kurtosis (R_{ku}).

2. Amplitude parameters (peak and valley) [33]:

Maximum height (R_z): is the arithmetic mean value of the single roughness depths of consecutive sampling lengths. Z is the sum of the height of the highest peaks and the lowest valley depth within a sampling length. Rz has two characteristics due to DIN and ISO and it can be defined as the mean peak-to-valley height found by measuring the peak-to-valley height in 5 adjoining samples and taking the average of the 5. Maximum height is significantly influenced by scratches, contamination, and measurement noise due to its reliance on peak values.

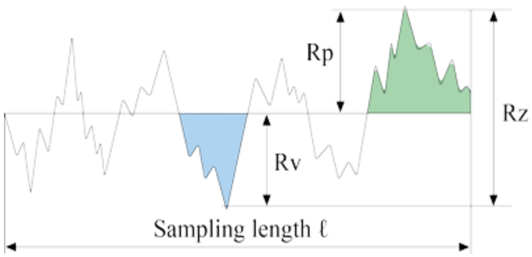


Fig. 20 Maximum height (R_z) [33].

$$R_z = R_p + R_v \tag{4}$$

Ten-point mean roughness (R_{zjis})**:** It Represents the sum of the mean value for the height of the five tallest peaks and the mean of the depth of the five deepest valleys of a profile within the sampling length.

Other amplitude (peak and valley) parameters: Mean height (R_c), total height (R_t).

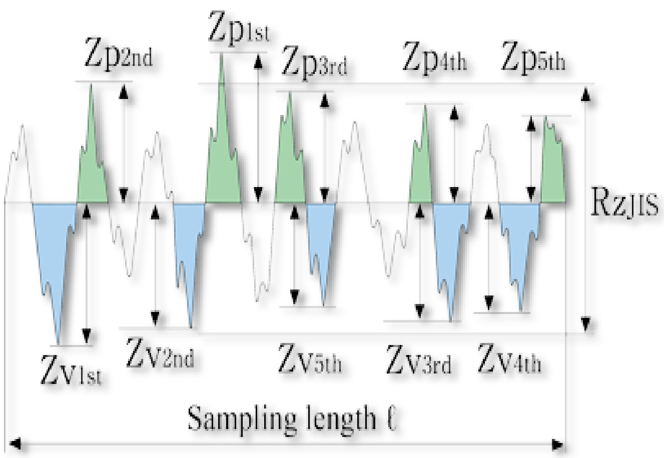


Fig. 21 Ten-point mean roughness (R_{zjis}) [33].

$$R_{zjis} = \frac{1}{5}\sum_{j=1}^{5}(Z_{pj} + Z_{vj}) \quad (5)$$

There are other parameters considered with the amplitude parameters (peak and valley) such as mean height (R_c) and total height (R_t).

3. Spacing parameters [33]:

Mean width (R_{Sm}): It represents the mean for the length of profile elements within the sampling length. This parameter is used to evaluate the horizontal size of parallel grooves and grains instead of the height parameters.

There are other parameters are considered when measuring the surface roughness for example hybrid parameters, material ratio curves, motif parameters, and parameters of a surface with stratified functional properties.

1.4.2 Surface roughness measurements

Surface roughness is a measurement of the structure of the surface. It is calculated as a vertical deviation of the actual surface from its ideal shape, caused by the machining or by chemical or physical processing in production. If these deviations are high, the surface is rough. If the value is low, the surface is smooth. Various measurement instruments are capable of measuring surface roughness, and they can be categorized into contact and noncontact-based instruments [34,35].

Contact type measurement, this type of measurement uses mainly a stylus roughness instrument to evaluate the value of surface roughness, on the other hand, the non-contact method of measurement, which doesn't use a stylus and uses coherence scanning interferometers or laser microscope [34].

Each method of measuring has advantages and some limitations for its use. However, in this bachelor work, the measurements were initiated based on contact type of measurements which is common and has a lower cost compared to the non-contact type of measurement, and it's explained briefly in the following tables [34].

Tab. 1 Contact type of measurements [30].

Description/Method	Contact-based measurement
Advantages	• Enables reliable measurement as the sample surface is physically traced with a stylus. • Has been used for a long time.
Limitations	• Limited to measuring a single section with a reduced quantity of measurement information. • Incapable of measuring adhesive surfaces and soft samples. • Difficult to precise position the probe. • Incapable of measuring details smaller than the stylus probe tip diameter

Contact type measurement uses mainly a stylus as shown in Fig. 22, which depicts the stylus movement over some length on a metal surface and it measures the value of the roughness parameter R_t.

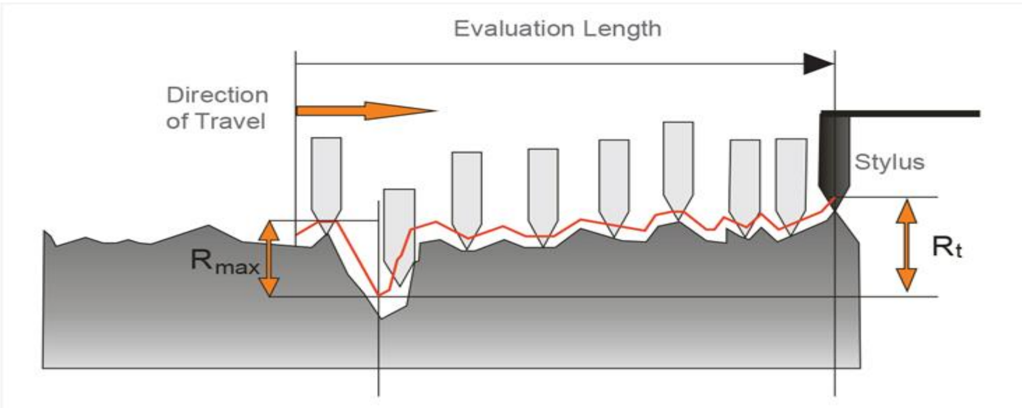


Fig. 22 Stylus movement on metal surface and related roughness parameters [35].

So as follows in Fig. 23 the limitation and inaccuracy of measuring a sample surface at a small scale measurement, so for such a case it’s more accurate to use a non-contact type of measurements.

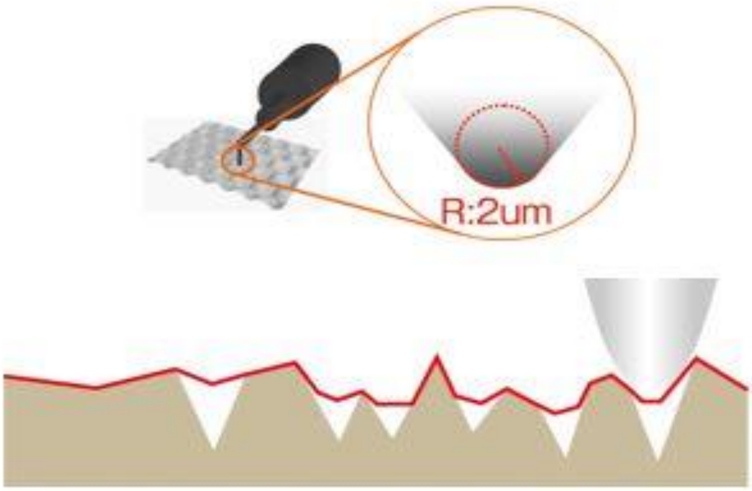


Fig. 23 Stylus limitations at small scale measurement [34].

As shown in Tab.2 and Tab. 3, they describe the advantages and limitations of the noncontact type of measurements, which is more accurate than the stylus method, but it's more expensive.

Tab. 2 Non Contact type of measurements (laser microscope) [34].

Description/Method	Non-contact-based measurement (laser microscope)
Advantages	• High angle detection sensitivity, enabling analysis of steeply inclined slopes. • High XY resolution, providing for clear, high-contrast images.
Limitations	• Incapable of conducting sub-nanometer measurements. • Inferior height discrimination capabilities at lower magnification rates.

Tab. 3 Non Contact type of measurements (coherence scanning interferometers) [34].

Description/Method	Non-contact-based measurement (coherence scanning interferometers)
Advantages	• Quick measurements • Enables sub-nanometer measurement of smooth surfaces at low magnification.
Limitations	• Has trouble measuring rough surfaces. • Has trouble measuring samples with significant differences in brightness. • Low contrast makes it difficult to locate the areas subject to measurement. • Low XY resolution

Other examples of non-contact-based measurement such as digital microscope and scanning probe microscope (SPM).

As shown in Fig. 24 a Wyko Vision 32 analysis software provides accurate, non-contact surface metrology based on white-light interferometry to achieve a high resolution of 3D surface roughness measurements at the nanometer scale. Coherence scanning interferometers has some limitations and troubles measuring rough surfaces and samples with significant differences in brightness [36].

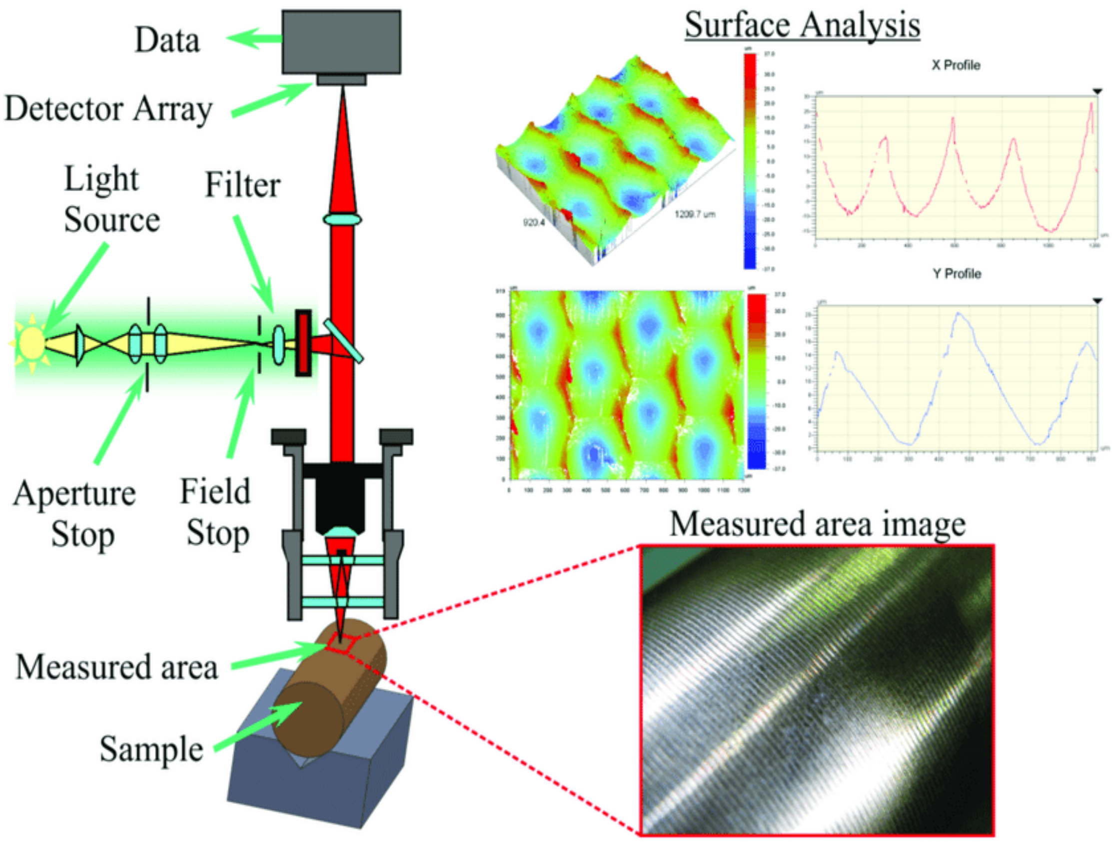


Fig. 24 3D white-light interferometry for surface-roughness measurement [36].

In this thesis, Surface roughness is evaluated by using the Optacom VC-10 series machine, which is used in the company Meopta for roughness and contour measurements. Optacom machine was developed in Germany in 1999 and it uses instruments that can measure actual profiles and surface roughness using stylus probes and direct contact [37].

Fig. 25 An example model of Optacom series LC-10 [37].

Fig. 26 Optacom surface roughness measurement machine [37].

There are different types of normal Stylus tips such as gear, angle, track, etc... all these tips can be coated as desired, some of these Stylus tips are described (see Tab. 4).

Tab. 4 Stylus tips types and uses [37].

Optacom stylus tip	Stylus tips use
Angle	This stylus tip is well suited to measure threads and parts with a pitch
Thread	This stylus tip is well suited to measure threads, ball screws, and parts with a pitch
Track	This stylus tip is well suited to measure parts with symmetric contour For example - ball screws
Roughness	This stylus tip is well suited to measure roughness
Top/down external	This stylus tip is best used for top/down measurement
Top/down internal	This stylus tip is best used for top/down measurements within drill holes.

1.4.3 The effect of stylus radius on surface roughness measurement

Surface roughness measurements are normally made using tracing stylus instruments. Theoretically, to provide a true reproduction of the surface irregularities, the stylus tip radius should be zero and the cone angle of the stylus as small as possible.

The usual cone angles used for styli are 90 ° and 60 ° and the stylus shape may be conical, pyramidal, or chisel-edged. In all cases, the tip will have a certain radius. Variations in the tip radius of the stylus affect the shape of the traced profile considerably. As the stylus radius increases, contact is made with fewer points on the surface and hence the profile gets modified. There are practical difficulties in evaluating the effect of stylus radius on the roughness values by measuring the same profile with different styli. An easier and accurate method would be to simulate the tracing of a profile with different stylus radii. For this, a digitized surface profile traced by a fine stylus is required [38].

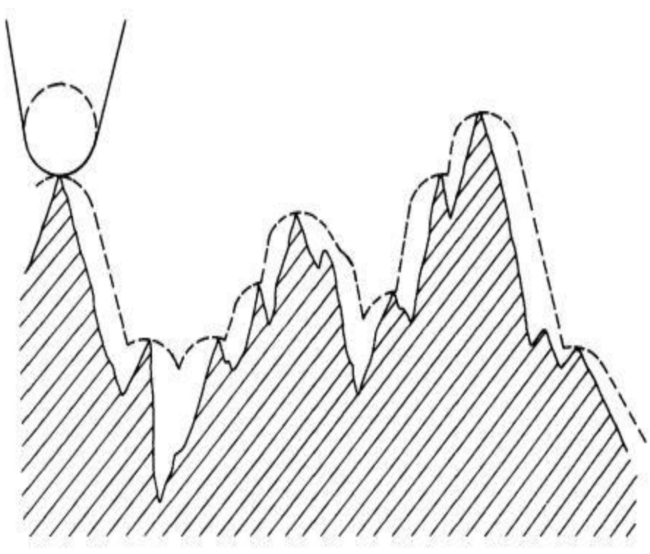


Fig. 27 Profile modification due to stylus radius [38].

As shown in Fig. 28 and Fig. 29 the value of normalized roughness value decreases with increasing stylus tip radius, when some technological process is applied such as turning, milling, etc...

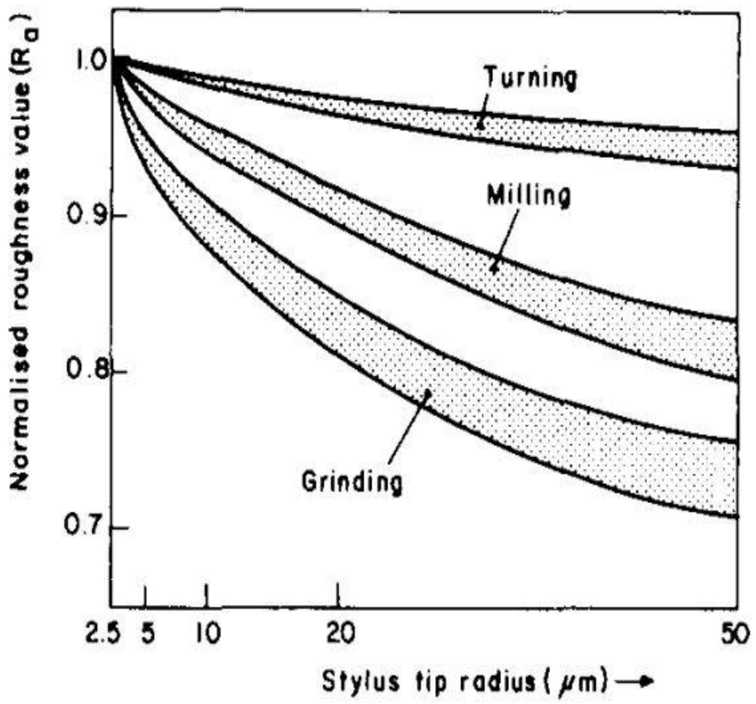


Fig. 28 Relationship between normalised roughness value R_a and stylus tip radius [38].

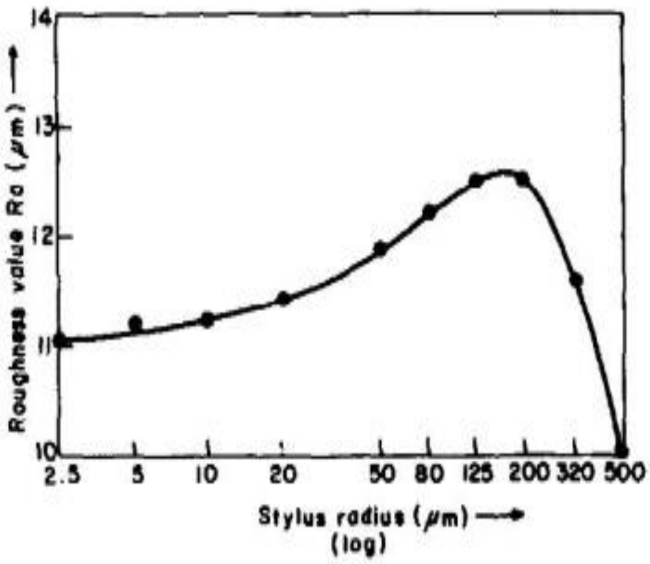


Fig. 29 Actual readings from a planned surface profile showing the extent of increase in Ra value with increasing stylus radius [38].

1.4.4 Handheld surface roughness measurements tester and gauges

The handheld device includes a Bluetooth communication method. The measurement is transmitted by Bluetooth to the handheld unit and a live profile of the measurement is generated and the results appear on the screen of the handheld device, using the settings to select large character mode for better visibility or select a mode that will show five measurement parameters per screen (Ra, Rz, Rp, Rv, Rt), the device can be docked in its second configuration to protect the stylus [39].

Fig. 30 Handheld device [39].

The surface roughness gauge set is a reliable and easy way to check and identify a specific degree of surface roughness of the machined parts.

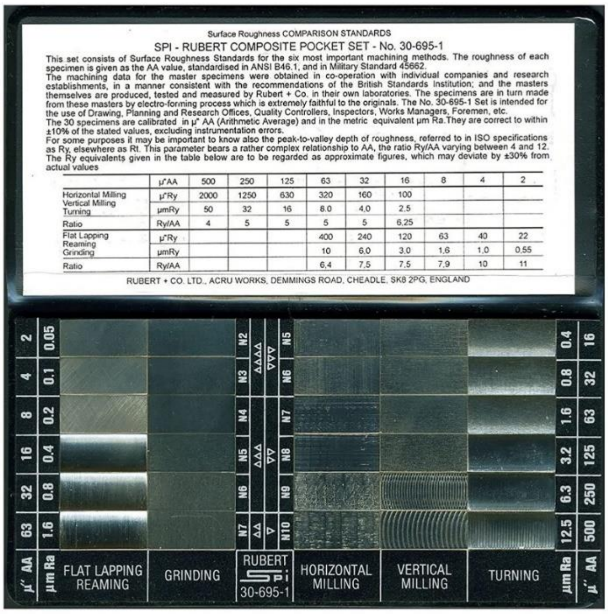


Fig. 31 Surface roughness gauge set [40].

2 PRACTICAL PART

In the practical part of this thesis a sample tube, which will be used for future optical measurements, was designed. It attaches by a thread to an existing objective lens so that the optical assembly can be reused from a different project.

The sample tube was designed in such a way, that the surface roughness of its inner surface will affect the amount of stray light in the system. For each of the 19 manufactured samples, the inner surface was machined by turning under different cutting conditions such as feed rate, tip radius, and depth of cut (see Tab.3, Tab.4). After manufacturing, the roughness was measured by Optacom VC-10 measurement machine (see 1.4.2).

The effect of surface roughness on stray light elimination will be studied and evaluated in the future.

2.1 Sample tube design

The prototype was designed in cooperation with an optical engineer. An existing objective lens was used as a part of the test assembly. As shown in Fig. 34 the assembly consists of the reused objective lens from a different project and the prototype sample tube, designed by the author of this thesis. The geometry of the sample tube is optimized for future optical measurements.

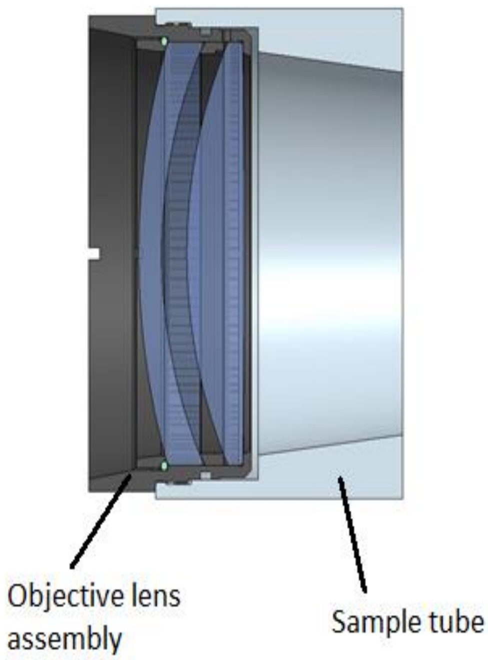


Fig. 32 The assembled optical device (objective lens assembly and sample tube).

Part of the drawing of the sample tube can be seen in Fig. 33 The part was designed using Inventor and Creo software.

These guidelines needed to be followed during the design process,

- Compatibility with counterpart (M48 thread and 47 g6 diameter), these dimensions are for connecting with the objective lens assembly and ensuring concentricity.
- Suitability for stray light evaluation (based on the optical design), cutting conditions for the conical part are different for each sample.
- Material choice according to Meopta standards: EN AW-6082 T651, surface treatment is black anodizing, according to MIL-A-8625 TYPE II, CLASS II-BLACK standard.

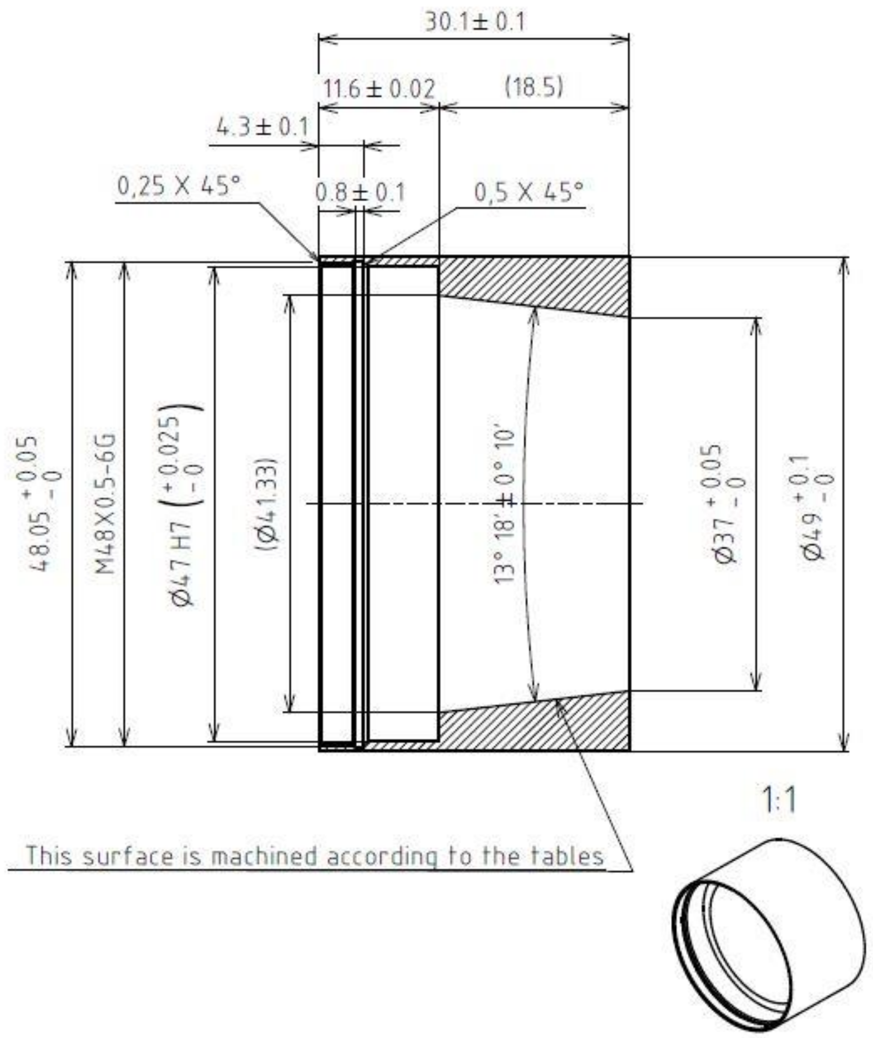


Fig. 33 Part of the sample tube drawing.

2.2 Sample tube manufacturing

The sample tube was machined using a CNC lathe Schaublin CCN 180. The lathe is equipped with Fanuc 0i series control system (Fig. 35). This lathe has been designed to produce prototypes and workpieces in small to medium-sized lots. It is ideal for hard turning [41]. In Meopta, s.r.o company is primarily used a precise manufacturing prototype, which is not used for roughing and other operations that could generate a lot of wear on the machine.

Fig. 34 Schaublin machines [42].

Fig. 35 Control panel (FANUC system).

A bar of EN AW-6082 T651 material with ⌀50 mm diameter was used as a blank material. The bar was mounted in a three-jaw chuck and each sample was parted off.

2.2.1 Cutting conditions

Spindle speed was 1000 RPM for all operations (constant RPM turning regime), but the tip radius of the tool and feed per revolution was variable, according to Tab. 5.

Following inserts were used for finishing the inner surface:

- VCGT110301 - AK
- VCGT110302 - AK
- VCGT110304 – AK

Fig. 36 Information about the inserts.

All three inserts are suitable for turning aluminium alloys with a recommended cutting speed of 100 – 200 m/min. For the inner conical surface, the cutting speed is within recommended range:

$$v_c = \frac{\pi \cdot d \cdot n}{1000} = \frac{\pi \cdot 41.33 \cdot 1000}{1000} = 129{,}8\ \mathrm{m/min}$$

As can be seen in Tab. 5, the recommended feed rate was exceeded with some samples, this is not unexpected, since the desired surface has higher roughness than is usual.

The depth of cut was chosen in such a way that the entire surface of the conical part was transformed with the single passage (this is not true for the samples with the lowest depth of cut).

The cutting conditions for machining the samples are described in Tab. 5.

Tab. 5 Cutting conditions.

Sample number	Tip radius [mm]	Feed rate [mm/rev]	Depth of cut [mm]
1	0,1	0,2	0,05
2	0,1	0,2	0,10
3	0,1	0,2	0,15
4	0,1	0,4	0,05
5	0,1	0,4	0,10
6	0,1	0,4	0,15
7	0,2	0,2	0,15
8	0,2	0,3	0,15
9	0,2	0,3	0,10
10	0,2	0,4	0,15
11	0,2	0,4	0,10
12	0,2	0,5	0,15
13	0,4	0,2	0,15
14	0,4	0,3	0,15
15	0,4	0,5	0,15
16	0,4	0,4	0,15
17	0,4	0,6	0,15
18	0,1	0,3	0,15
19	0,1	0,3	0,15

Fig. 37 The samples which were machined
under different cutting conditions.

Following tools (Tab.6, Fig. 38, 39, and 40) were used during the manufacturing process:

Tab. 6 List of used tools during the manufacturing process.

Tool name / properties	ISO code (insert)	ISO code (holder)	Manufacturer
External finish tool	VCGT110302 - AK	SVJCR 2020K-11	Korloy
Internal finish tool (R0.1)	VCGT110301 - AK	A20R-SVUCR11	Korloy
Internal finish tool (R0.2)	VCGT110302 - AK	A20R-SVUCR11	Korloy
Internal finish tool (R0.4)	VCGT110304 - AK	A20R-SVUCR11	Korloy
Thread cutting tool	MMT16IRA60 VP10MF	SNR0016M16	Mitsubishi
Outer roughing tool	DCMT11T304 NX2525	SDNCN1212H11	Mitsubishi
Inner roughing tool	XCNT 10T304EN CTPP430	ECC-20R-2.25D-10	Ceratizit
Parting off tool	DGR 2000Z6-6D IC908	DGTR 20B-2D35	Iscar

The thread and H7 hole were checked with GO/NOGO gauge (see Fig. 38)

Fig. 38 GO-NOGO gauges.

Other tools were used during manufacturing, such as deburring swivel blade Noga, GO-NOGO gauges, and the VDI tool holder according to DIN 69880 (see Fig. 40).

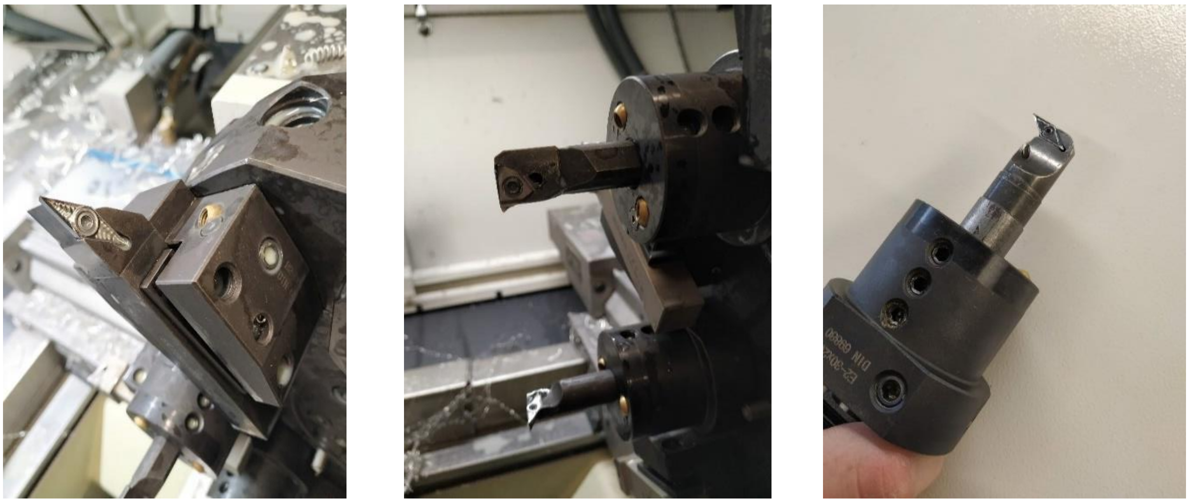


Fig. 39 Machining tools including external, internal, and thread finish.

Fig. 40 Machining tools including insert, drill, VDI tool holder.

2.3 Measurements and evaluation of surface roughness

The measurements of surface roughness were carried out using the Optacom machine with a conical stylus tip 3 mm (see Fig. 41), which respects order number 101-430-035, and is made from carbide.

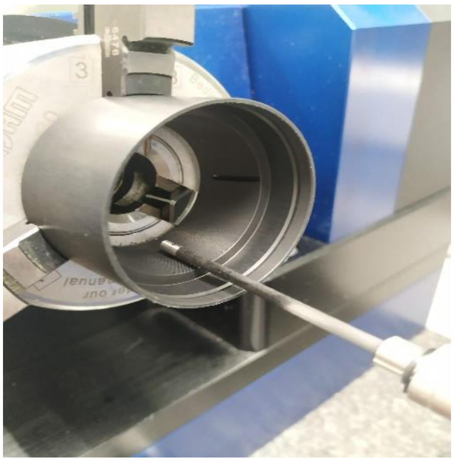


Fig. 41 Measurement uses stylus.

The measurments of surface roughness was done by using VC-10 Optacom machine as shown in Fig. 42. The methodology of measurment was according to ČSN EN ISO 4288 [44].

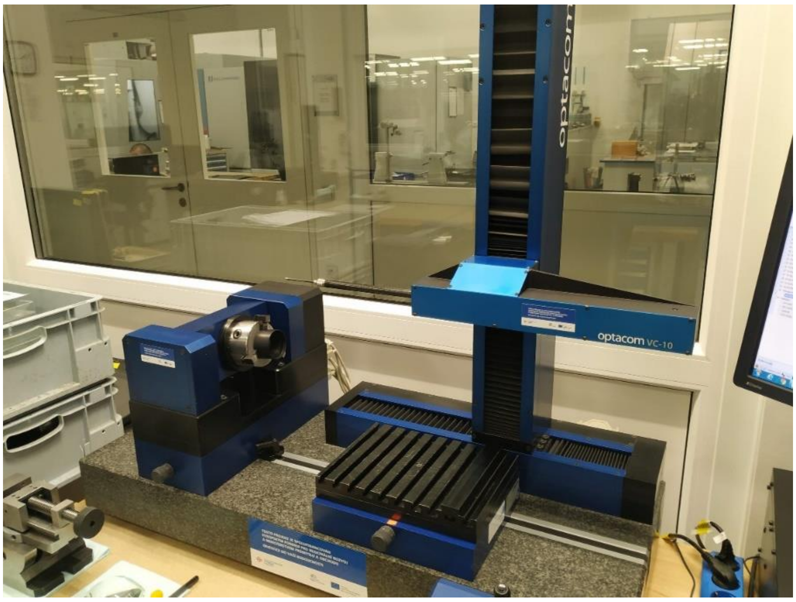
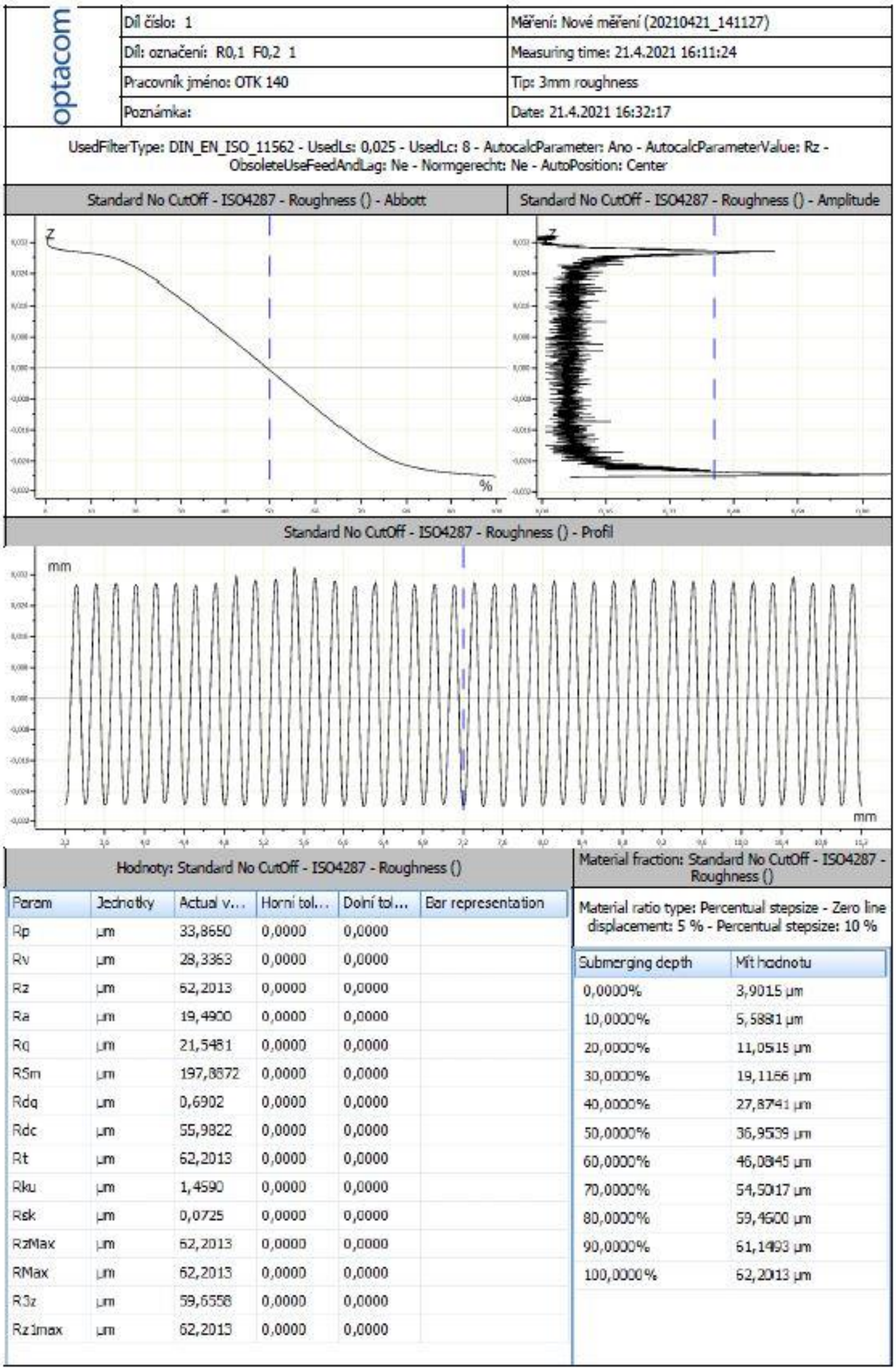


Fig. 42 The Optacom VC-10 measurement machine.

As shown in Fig. 43, which describes the values of surface roughness measurments for the first sample, obtained after machining process and it includes the values of R_a, R_z, and other parameters. However, other measurments are provided in the attachment including measurments after machining and measurments after surface treatment.



optacom

Díl číslo: 1	Měření: Nové měření (20210421_141127)
Díl: označení: R0,1 F0,2 1	Measuring time: 21.4.2021 16:11:24
Pracovník jméno: OTK 140	Tip: 3mm roughness
Poznámka:	Date: 21.4.2021 16:32:17

UsedFilterType: DIN_EN_ISO_11562 - UsedLs: 0,025 - UsedLc: 8 - AutocalcParameter: Ano - AutocalcParameterValue: Rz - ObsoleteUseFeedAndLag: Ne - Normgerecht: Ne - AutoPosition: Center

Standard No CutOff - ISO4287 - Roughness () - Abbott

Standard No CutOff - ISO4287 - Roughness () - Amplitude

Standard No CutOff - ISO4287 - Roughness () - Profil

Hodnoty: Standard No CutOff - ISO4287 - Roughness ()

Param	Jednotky	Actual v...	Horni tol...	Dolní tol...	Bar representation
Rp	µm	33,8650	0,0000	0,0000	
Rv	µm	28,3363	0,0000	0,0000	
Rz	µm	62,2013	0,0000	0,0000	
Ra	µm	19,4900	0,0000	0,0000	
Rq	µm	21,5481	0,0000	0,0000	
RSm	µm	197,8872	0,0000	0,0000	
Rdq	µm	0,6902	0,0000	0,0000	
Rdc	µm	55,9822	0,0000	0,0000	
Rt	µm	62,2013	0,0000	0,0000	
Rku	µm	1,4590	0,0000	0,0000	
Rsk	µm	0,0725	0,0000	0,0000	
RzMax	µm	62,2013	0,0000	0,0000	
RMax	µm	62,2013	0,0000	0,0000	
R3z	µm	59,6558	0,0000	0,0000	
Rz1max	µm	62,2013	0,0000	0,0000	

Material fraction: Standard No CutOff - ISO4287 - Roughness ()

Material ratio type: Percentual stepsize - Zero line displacement: 5 % - Percentual stepsize: 10 %

Submerging depth	Mít hodnotu
0,0000%	3,9015 µm
10,0000%	5,5881 µm
20,0000%	11,0515 µm
30,0000%	19,1166 µm
40,0000%	27,8741 µm
50,0000%	36,9539 µm
60,0000%	46,0845 µm
70,0000%	54,5017 µm
80,0000%	59,4600 µm
90,0000%	61,1493 µm
100,0000%	62,2013 µm

Fig. 43 Surface roughness measurements for the first sample part after machining measured by Optacom.

2.3.1 Theoretical calculation of surface roughness

The surface roughness of the machined part can be predicted using different formulas. For Ra, there is a widely used empirical formula [42]:

$$R_a = \frac{f^2 \cdot 32.5}{r_\varepsilon} \tag{6}$$

So, if we consider the value of the first machined piece with a tip radius of $r_\varepsilon = 0.1mm$ and feed rate of $f = 0.2\ mm/rev$, then we will be able to measure the theoretical value of Ra roughness, as follows:

$$R_a = \frac{0.2^2 \cdot 32.5}{0.1} = 13\ \mu\text{m}$$

For Rz, the most used formula is [43]:

$$R_z = 1000 \cdot \frac{f^2}{8 \cdot r_\varepsilon} \tag{7}$$

So, if we consider the value of the first machined piece with a tip radius of $r_\varepsilon = 0.1mm$ and feed rate of $f = 0.2\ mm/rev$, then we will be able to measure the theoretical value of Rz roughness, as follows:

$$R_z = 1000 \cdot \frac{0{,}2^2}{0{,}1 \cdot r_\varepsilon} = 50\ \mu\text{m}$$

Practical values of (R_a, R_z) are compared with theoretical values, so for this reason a calculation of deviation is done by using formula 7, which is helpful to judge the accuracy of the parameters and it's defined as [42]:

$$\Phi_\text{i} = \frac{\left|R_{a,z\,(practical)} - R_{a,z\,(theoretical)}\right|}{R_{a,z\,(theoretical)}} \cdot 100\% \tag{8}$$

Where:

i : represents the sample number, i ∈ (1:19).

2.4 Results of surface roughness parameters

The surface roughness of the samples was measured right after machining (see Tab. 7) and after surface treatment (see Tab. 8). This is due to the possibility of marginal smoothing of the surface, which can happen during anodizing.

Tab. 7 The results of surface roughness after machining process.

Sample number	Tip radius [mm]	Feed rate [mm/rev]	Depth of cut [mm]	Ra exp. [μm]	Rz exp. [μm]	Ra theo. [μm]	Rz theo. [μm]	Ra error [%]	Rz error [%]
1	0,1	0,2	0,05	19,49	62,20	13,00	50,00	49,92	24,40
2	0,1	0,2	0,10	27,34	173,98	13,00	50,00	110,31	247,96
3	0,1	0,2	0,15	51,91	276,68	13,00	50,00	299,31	453,36
4	0,1	0,4	0,05	18,16	60,25	52,00	200,00	65,08	69,88
5	0,1	0,4	0,10	26,40	120,37	52,00	200,00	49,23	39,82
6	0,1	0,4	0,15	37,54	207,57	52,00	200,00	27,81	3,78
7	0,2	0,2	0,15	9,04	40,36	6,50	25,00	39,08	61,44
8	0,2	0,3	0,15	22,81	85,68	14,63	56,25	55,97	52,32
9	0,2	0,3	0,10	14,58	60,32	14,63	56,25	0,31	7,24
10	0,2	0,4	0,15	26,56	77,08	26,00	100,00	2,15	22,92
11	0,2	0,4	0,10	21,23	111,80	26,00	100,00	18,35	11,80
12	0,2	0,5	0,15	28,62	153,72	40,63	156,25	29,55	1,62
13	0,4	0,2	0,15	3,64	15,77	3,25	12,50	12,00	26,16
14	0,4	0,3	0,15	7,84	32,74	7,31	28,13	7,21	16,41
15	0,4	0,5	0,15	23,87	103,30	20,31	78,13	17,51	32,22
16	0,4	0,4	0,15	14,34	60,24	13,00	50,00	10,31	20,48
17	0,4	0,6	0,15	32,12	103,89	29,25	112,50	9,81	7,65
18	0,1	0,3	0,15	20,23	59,24	29,25	112,50	30,84	47,34
19	0,1	0,3	0,15	33,60	166,24	29,25	112,50	14,87	47,77

Tab. 8 The results of surface roughness after surface treatment.

Sample number	Tip radius [mm]	Feed rate [mm/rev]	Depth of cut [mm]	Ra exp. [µm]	Rz exp. [µm]	Ra theo. [µm]	Rz theo. [µm]	Ra error [%]	Rz error [%]
1	0,1	0,2	0,05	18,50	61,73	13,00	50,00	42,31	23,46
2	0,1	0,2	0,10	28,87	178,08	13,00	50,00	122,08	256,16
3	0,1	0,2	0,15	63,22	269,30	13,00	50,00	386,31	438,60
4	0,1	0,4	0,05	19,18	61,11	52,00	200,00	63,12	69,45
5	0,1	0,4	0,10	29,00	129,37	52,00	200,00	44,23	35,32
6	0,1	0,4	0,15	37,37	201,04	52,00	200,00	28,13	0,52
7	0,2	0,2	0,15	8,03	41,60	6,50	25,00	23,54	66,40
8	0,2	0,3	0,15	22,14	88,04	14,63	56,25	51,38	56,52
9	0,2	0,3	0,10	13,99	58,31	14,63	56,25	4,34	3,66
10	0,2	0,4	0,15	25,76	77,93	26,00	100,00	0,92	22,07
11	0,2	0,4	0,10	21,65	91,61	26,00	100,00	16,73	8,39
12	0,2	0,5	0,15	27,10	154,50	40,63	156,25	33,29	1,12
13	0,4	0,2	0,15	3,61	25,27	3,25	12,50	11,08	102,16
14	0,4	0,3	0,15	7,42	37,72	7,31	28,13	1,47	34,12
15	0,4	0,5	0,15	23,24	101,02	20,31	78,13	14,41	29,31
16	0,4	0,4	0,15	13,86	59,50	13,00	50,00	6,62	19,00
17	0,4	0,6	0,15	31,28	108,20	29,25	112,50	6,94	3,82
18	0,1	0,3	0,15	20,73	63,85	29,25	112,50	29,13	43,24
19	0,1	0,3	0,15	32,62	171,28	29,25	112,50	11,52	52,25

From the results, it is clear, that used formulas for calculating Ra and Rz do not provide a reliable prediction in this case.

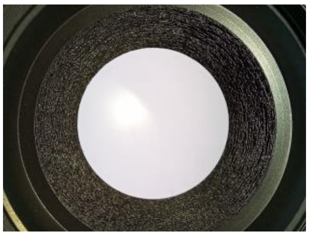
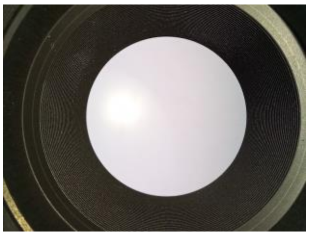
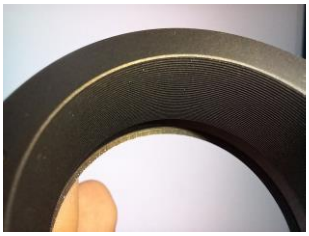
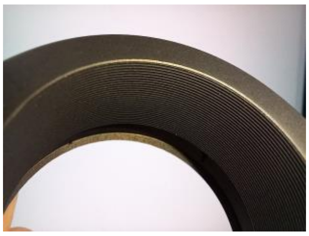
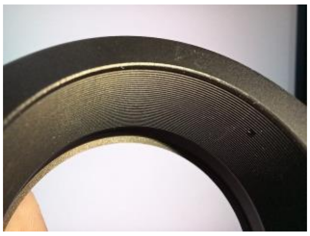
There may be many reasons behind this fact, some of them are obvious:

- The machined surface has much higher surface roughness than is typical for finishing, this is caused by the high value of feed rate.
- Depth of cut is not a variable in the used formulas, it becomes an important factor for higher feed rates.
- Exceeding feed limit recommended by the manufacturer.

2.5 Visual evaluation

Although optical measurements could not be carried out yet, visual control was carried out. Results can be seen in Tab. 9 below. It is important to emphasize, that these results are only approximate since the images were not taken in laboratory environment. Four samples for comparison were chosen: One of the worst samples, two good samples and a reference sample. It seems that samples 15 and 17 are even better in terms of low reflectiveness than the reference sample with traditional optical grooving.

Tab. 9 Visual evaluation of the samples.

Sample number	Front View	Rear View
Sample 1: R0.1 F0.2 • Visually one of the worst (highly reflective) • Obviously damaged surface		
Sample 15: R0.4 F0.5 • Visually one of the best (lowest reflection from front and the rear) • Slightly better than reference sample		
Sample 17: R0.4 F0.6 • Visually one of the best (lowest reflection from front and the rear) • Slightly better than reference sample		
Reference sample: Optical grooving		

DISCUSSION

Next steps

Prototype samples will undergo through series of optical measurements, primarily measurements of stray light using an integrating sphere.

Stray light will be measured for:

- 19 prototype samples
- 1 reference sample

The reference sample has traditional optical grooving, this optical grooving is proprietary. It will be evaluated if the proposed method of machining the surface with specific cutting conditions can produce similar results in terms of stray light as the proprietary grooving. Cutting conditions, which produce the best surface will be prescribed in the technical drawing.

Economical evaluation

Although the optical performance of prototype samples cannot be evaluated yet, costs can be compared (see Tab. 10).

Tab. 10 Comparison between the machining of prototype samples and reference sample

Description/Type of sample	Prototype samples	Reference sample with proprietary optical grooving
Machining time	8 min 2 sec	8 min 47 sec
Cost (Kč)	107,1	117,1

When compared, the proposed technology saves 7,6 % of machining time, which results in 45 sec. time savings per part. The costs were calculated from hour rate of 800 Kč/hour for simple CNC turning. Also, a special insert, which is being used for manufacturing proprietary optical grooving, does not have to be used. This insert is costly and prone to fast deterioration because of a very fine radius of the tip.

The samples 15 and 17 appear less shiny and less reflective than the optical grooving sample according to the visual inspection (see Tab. 9). However, a stray light test will be applied in the future for more accurate result. Other benefits are considered based on machining cost of the samples, since the optical grooving sample require higher cost for machining than the rest of the samples. (see Tab. 10).

To be considered

If the optical results are satisfying, not negligible savings can be achieved. However, other factors need to be examined before implementing in series production:

- Repeatability of the process
    - Multiple batches of material need to be tested.
- Zero burr policy
    - No burrs are allowed.
    - If the machining process produces an increased amount of burring (was the case for some cutting conditions), it is not viable options for applications with high demand for optical cleanliness, particles clinging on optical surfaces can result in a rejected device at quality control.

CONCLUSION

This bachelor thesis is part of a bigger issue, which is stray light elimination and the correlation between surface roughness and stray light. Stray light does not carry any information about the displayed subject; therefore, it is unwanted. Sometimes it is called “parasitic light” This thesis brings an introduction to stray light and brings an overview of methods of its elimination. Summary of turning and surface roughness measurement follows.

The practical part of this thesis focused on the design and the production of a technological sample tube, which is machined by turning since it is rotationally symmetric. 19 samples were manufactured, each with different surface roughness parameters. This was achieved by changing the cutting conditions for each sample. The surface roughness of each sample was measured and real values of Ra and Rz were compared with theoretical values. Results show, that used formulas are not suitable for these samples. That is because the samples have much higher roughness than is typical for finishing and therefore the errors are in some cases exceeding 100 %.

Optical measurements of the samples will follow in the future. These tests will provide values of stray light for each sample and the 20^{th} sample with usual optical grooving will be used as a reference. If the experimental manufacturing method, proposed by the author, achieves similar results to the reference sample, it could be considered a viable option. This method of manufacturing rough surfaces can lead to cost savings since on the sample tube it saves 7,6 % of machining time.

For this method to be applied in series production, more factors need to be examined. For example, repeatability of the process and amount of burrs generated. Since these problems were beyond the possibilities of this bachelor thesis, it leaves many directions open for future studies.

LIST OF SYMBOLS AND ABBREVIATIONS

Abbreviation	Description
UV	Ultraviolet
IR	Infrared
SPM	Scanning probe microscope

Symbol	Unit	Description
$\mathbf{v_c}$	[m/min]	Cutting speed
D	[mm]	Diameter of the workpiece
n	[1/min]	Workpiece revolutions
$\mathbf{v_f}$	[m/min]	Feed rate velocity
f	[mm/rev]	Feed rate
$\mathbf{R_a}$	[μm]	Arithmetical mean roughness
$\mathbf{R_z}$	[μm]	Maximum height
$\mathbf{R_p}$	[μm]	Maximum profile peak height
$\mathbf{R_v}$	[μm]	Maximum profile valley depth
$\mathbf{R_{zjis}}$	[μm]	Ten-point mean roughness
$\mathbf{R_q}$	[μm]	Root mean square deviation RMS
$\mathbf{R_{sk}}$	[μm]	Skewness
$\mathbf{R_{ku}}$	[μm]	Kurtosis
$\mathbf{\Phi}$	[%]	Percentage deviation of one sample
$\bar{\mathbf{\Phi}}$	[%]	Average percentage deviation of all samples

BIBLIOGRAPHY

[1] The CIE international lighting vocabulary. 4th ed. Austria: CIE, 1987. ISBN 978-3-900734-07-7.

[2] Textbook of practical physiology. 1st ed. Amazon: Pal, G.K.; Pal, Pravati, 2001. ISBN 978-81-250-2021-9.

[3] Vision. 1st ed. Spain: Pierre A. Buser, Michel Imbert, R. H. Kay (Translator), Roy H. Kay, 1992. ISBN 978-0-262-02336-8.

[4] Origins and grand finale: How the Bible and science relate to the origin of everything. Illustrated edition. Amazon: iUniverse, 2014. ISBN 9781491732571.

[5] The visible light spectrum [online]. [cit. 2021-04-10]. Dostupné z: https://www.once.lighting/cn/visible-light-spectrum/

[6] Limits of light - the secrets of nature. Youtube [online]. Youtube: The Secrets of Nature, 2014 [cit. 2021-02-26]. Dostupné z: https://www.youtube.com/watch?v=jnGTCaiZqOE&ab_channel=TheSecretsofNature

[7] What are 7 basic properties of light? [online]. Physics About: Physics About, 2020 [cit. 2021-02-26]. Dostupné z: https://physicsabout.com/light/

[8] When light meets matter [online]. [cit. 2021-04-10]. Dostupné z: http://weeklysciencequiz.blogspot.com/2011/09/when-light-meets-matter.html

[9] Behaviour of light as a wave [online]. [cit. 2021-04-10]. Dostupné z: https://www.ducksters.com/science/physics/light_as_a_wave.php

[10] Understanding of light dispersing elements in a spectrometer [online]. [cit. 2021-04-10]. Dostupné z: https://lab-training.com/2017/09/26/understanding-of-light-dispersing-elements-in-a-spectrometer/

[11] Stray light and performance verification [online]. Switzerland, 2016 [cit. 2021-02-26]. Dostupné z: https://www.mt.com/dam/non-indexed/po/ana/uvvis/UVVIS_V01.16_StrayLight_Whitepaper_2016_LR.PDF. White paper. Mettler-Toledo GmbH, Analytical.

[12] Adventurer in thought. First Edition. Cambridge university: Cambridge university press, 1992. ISBN 9780521566698.

[13] Isaac Newton the last sorcerer. First edition. Amazon: 1997. ISBN 978-0-7382-0143-6.

[14] National geographic telescope Newton 130|650n sph. [online]. [cit. 2021-04-11]. Dostupné z: https://www.mironet.cz/national-geographic-telescope-newton-130650n-sph-prumer-130-mm-ohniskova-vzalenost-650-mm-zvetseni-26x195x+dp414432/

[15] Telescopes types: optical schemes [online]. [cit. 2021-04-11]. Dostupné z: https://lookforword.net/telescopes/types-of-telescopes/

[16] Stray light control in Newtonian telescopes [online]. 2009 [cit. 2021-02-26]. Dostupné z: https://www.cloudynights.com/articles/cat/articles/optical-theory/stray-light-control-in-newtonian-telescopes-r2006

[17] Optical techniques for studying Stray light in spectrophotometers. A.W.S. Tarrant, 1978, 1167-1174. Dostupné z: doi:10.1080/713819727

[18] Baffle design and analysis of Stray-light in multispectral camera of a Brazilian satellite [online]. Brazil and China, 2006 [cit. 2021-02-26]. Dostupné z: http://www.sbf1.sbfisica.org.br/procs/2006/pdfs%20optics/Interferometry,%20Holography%20and%20Applied%20Optics/299.pdf. Academic article. Instituto de Física de São Carlos – IFSC-USP (2) Opto Eletrônica S.A.

[19] Light baffle attenuation measurements in the visible [online]. R. P. Heinisch and C. L. Jolliffe, 1971 [cit. 2021-02-26]. Dostupné z: https://www.osapublishing.org/ao/abstract.cfm?uri=ao-10-9-2016

[20] Field guide to astronomical instrumentation. Christoph U. Keller, Ramón Navarro, Bernhard R. Brandl, 2015. ISBN 9781628411775.

[21] Black coatings to reduce Stray Light [online]. University of Arizona, , 13 [cit. 2021-03-09]. Dostupné z: https://wp.optics.arizona.edu/optomech/wp-content/uploads/sites/53/2016/10/Black-Coatings-to-Reduce-Stray-Light.pdf

[22] Technologie 1 - technologie obrábění [online]. HUMÁR, A., 2003 [cit. 2021-04-11]. Dostupné z: http://ust.fme.vutbr.cz/obrabeni/opory-save/TI_TO-1cast.pdf

[23] Turning [online]. [cit. 2021-04-10]. Dostupné z: https://www.custompartnet.com/wu/turning

[24] External and internal turning [online]. [cit. 2021-04-10]. Dostupné z: https://www.manufacturingguide.com/en/ordlista/external-and-internal-turning

[25] Machinery's Handbook pocket companion by Pohanish. Amazon: Pohanish, Richard P, McCauley, Christopher J, 2000. ISBN B011WA5XA8 (ASIN).

[26] Aluminum alloys 101 [online]. [cit. 2021-04-11]. Dostupné z: https://www.aluminum.org/resources/industry-standards/aluminum-alloys-101

[27] Anodised aluminium Anodizing process, properties and uses [online]. [cit. 2021-04-11]. Dostupné z: https://www.stacbond.es/en/anodised-aluminium-anodizing-process-properties-and-uses/

[28] Anodising [online]. [cit. 2021-04-11]. Dostupné z: https://www.alumeco.com/knowledge-technique/surface-treatment/anodising

[29] Applications of electrolysis: anodising [online]. [cit. 2021-04-11]. Dostupné z: https://monomole.com/basic-electrochemistry-13/

[30] Basics of surface roughness [online]. Youtue: Indian institute of technology madras, 2017 [cit. 2021-03-09]. Dostupné z: https://www.youtube.com/watch?v=dzhh82H2Nuk&ab_channel=nptelhrd

[31] Surface roughness. Arknovin [online]. [cit. 2021-03-09]. Dostupné z: http://arknovin.com/en/quality-control/surface-quality/surface-roughness.html

[32] Introduction to surface roughness measurement [online]. [cit. 2021-04-10]. Dostupné z: https://sernia.ru/upload/pdf_files/ Introduction%20to%20surface%20roughness%20measurement.pdf

[33] Surface Roughness Measurement—Parameters [online]. [cit. 2021-04-10]. Dostupné z: https://www.olympus-ims.com/en/metrology/surface-roughness-measurement-portal/parameters/

[34] Various measurement Instruments are capable of measuring surface roughness [online]. [cit. 2021-04-11]. Dostupné z: https://www.olympus-ims.com/en/metrology/surface-roughness-measurement-portal/terms-and-standards/

[35] Surface measuring systems [online]. [cit. 2021-02-05]. Dostupné z: https://www.accretech.eu/en/surface-measuring-systems.

[36] 3D white-light interferometry for surface-roughness measurement. [online]. [cit. 2021-04-11]. Dostupné z: https://www.researchgate.net/figure/ 3D-white-light-interferometry-for-surface-roughness-measurement_fig3_324280464

[37] Optacom complete catalogue [online]. 2016 [cit. 2021-04-11]. Dostupné z: https://www.merici-pristroje.cz/files/ckeditor//5_Produkty/5-26_optacom/Optacom_2016.pdf

[38] Does the stylus radius affect surface roughness measurements?, tribology International,. 10. V. Radharkrishnan, 1977, 101-104. ISSN 0301-679X. Dostupné také z: https://doi.org/10.1016/0301-679X(77)90117-7

[39] Surtronic Duo [online]. [cit. 2021-04-11]. Dostupné z: https://www.taylor-hobson.com/-/media/ametektaylorhobson/files/product-downloads/hand-held-surtronic/surtronic-duo-surface-roughness-tester-en.pdf?dmc=1&la=en&revision=640c8d0f-39dc-44e4-8b37-f199ad538bf5

[40] Rubert surface roughness comparator set [online]. [cit. 2021-04-14]. Dostupné z: https://www.amazon.in/Rubert-Surface-Roughness-Comparator-Set/dp/B072M1M31H

[41] Optimization of turning parameters for surface roughness. Samya Dahbi, Haj El Moussami, Latifa Ezzine., 7, 7. [online]. [cit. 2021-4-27]. Dostupné z: https://hal.archives-ouvertes.fr/hal-01260818/document

[42] SCHAUBLIN MACHINES [online]. [cit. 2021-4-26]. Dostupné z: https://www.directindustry.com/prod/schaublin-machines/product-24715-592171.html

[43] Korloy Metric Catalogue - Technical Information [online]. [cit. 2021-5-14]. Dostupné z: https://issuu.com/rbjtooling/docs/2008_catalogue_metric_technical_information

[44] Geometrické požadavky na výrobky (GPS) - Struktura povrchu: Profilová metoda - Pravidla a postupy pro posuzování struktury povrchu: ČSN-EN ISO 4288 [online]. 1996 [cit. 2021-5-17]. Dostupné z: http://www.technicke-normy-csn.cz/inc/nahled_normy.php?norma=014449-csn-en-iso-4288&kat=55360

LIST OF ATTACHMENTS

ATTACHMENT 1