REPUBLIC OF TURKEY
AYDIN ADNAN MENDERES UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
MECHANICAL ENGINEERING
2018-M.Sc.-027

THE INVESTIGATION OF SURFACE TOPOGRAPHY FOR MICRO/NANO SCALED SURFACES

Bilginer GÜNDÜZ

Supervisor:

Assoc. Prof. Dr. Pınar DEMİRCİOĞLU

AYDIN

REPUBLIC OF TURKEY
AYDIN ADNAN MENDERES UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
AYDIN

The thesis with the title of **“THE INVESTIGATION OF SURFACE TOPOGRAPHY FOR MICRO/NANO SCALED SURFACES”** prepared by Bilginer GÜNDÜZ, Master Student at the Mechanical Engineering Program at the Department of Mechanical Engineering was accepted by the jury members whose names and titles presented below as a result of thesis defense on 12 July 2018.

	Title, Name Surname	Institution	Signature
President :	Assoc. Prof. Dr. Pınar DEMİRCİOĞLU	Aydın Adnan Menderes University	
Member :	Prof. Dr. İsmail BÖĞREKCİ	Aydın Adnan Menderes University	
Member :	Prof. Dr. Vural CEYHUN	Ege University	

This Master Thesis accepted by the jury members is endorsed by the decision of the Institute Board Members with ………… Serial Number and ………………… date.

Prof. Dr. Aydın ÜNAY
Institute Director

REPUBLIC OF TURKEY
AYDIN ADNAN MENDERES UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
AYDIN

I hereby declare that all information and results reported in this thesis have been obtained by my part as a result of truthful experiments and observations carried out by the scientific methods, and that I referenced appropriately and completely all data, thought, result information which do not belong my part within this study by virtue of scientific ethical codes.

12/07/2018

Bilginer GÜNDÜZ

ÖZET

MİKRO/NANO ÖLÇEKTE TOPOGRAFİK YÜZEY İNCELEMESİ

Bilginer GÜNDÜZ

Yüksek Lisans Tezi, Makine Mühendisliği Anabilim Dalı
Tez Danışmanı: Doç. Dr. Pınar DEMİRCİOĞLU
2018, 73 Sayfa

Hassas bir iş parçasının yüzey karakterizasyonunu belirlemek için en önemli parametrelerden biri pürüzlülüktür. Burada pürüzlük, bir yüzeyin ince düzensizliklerini ifade eder. İmalat sanayindeki diğer tolerans spesifikasyonları gibi, yüzeyin de belirli bir pürüzlülük sınırları içinde olması gerekir. Pratikte iki boyutlu (2B) yüzey karakterizasyonu için en sık kullanılan pürüzlülük parametrelerinden Ra; örnekleme boyu içinde mutlak ordinat değerlerinin aritmetik ortalaması ve Rz; tek bir numune uzunluğu içindeki en yüksek tepe ile en derin vadi arasındaki mesafe değerleri kontrol edilmiştir. Ek olarak, üç boyutlu yüzey parametrelerinin geliştirilmesi, bir ürünün yüzey özelliklerinin daha kesin olarak tanımlanmasına yardımcı olur. Bu tezin amacı, iğne uçlu ölçme cihazı ve 3B optik ölçüm sistemi (Konfokal Mikroskop) kullanılarak, geleneksel talaşlı imalat yöntemleriyle üretilmiş (torna ve freze) farklı yüzey pürüzlülük sınıfına sahip, periyodik ve rastgele profilli on (10) adet referans numunesinin yüzey pürüzlülük değerlerinin doğrulamalarını gerçekleştirmektir. Sonuçta, temaslı sistem ile yapılan ölçme tekniklerinin optik ölçme metotlarına kıyasla daha az doğruluk ve güvenilirlik verdiği görülmüştür.

Anahtar Kelimeler: Yüzey Pürüzlülüğü, Topografi, Ölçüm Bilimi, Konfokal Mikroskop

ABSTRACT

THE INVESTIGATION OF SURFACE TOPOGRAPHY FOR MICRO/NANO SCALED SURFACES

Bilginer GÜNDÜZ

M. Sc. Thesis, Department of Mechanical Engineering
Supervisor: Assoc. Prof. Dr. Pınar DEMİRCİOĞLU
2018, 73 pages

One of the most important parameters for determining the surface characterization of a precision workpiece is roughness. Here, roughness expresses the fine irregularities of a surface. Surface has to be within certain limits of roughness values. The most commonly used parameters for two-dimensional surface characterization in real-world practice are Ra and Rz. Additionally, the development of three-dimensional surface parameters helps out in defining the surface features of a product more precisely.

The purpose of this thesis is to verify the surface roughness values of ten (10) reference samples with periodic and random profiles with different surface roughness classes (turning and milling) produced by traditional machining methods using a pinpoint measuring instrument and a 3D optical measuring system (Confocal Microscope) it is to perform. As a result, it has been found that measuring techniques made by the contact system give less accuracy and reliability than optical measuring methods.

Key Words: Surface Roughness, Topography, Measurement Science, Confocal Microscope

ACKNOWLEDGEMENTS

I would like to thank my supervisor Assoc. Prof. Dr. Pınar DEMIRCIOĞLU because of supporting to me in this master thesis. I would like to thank to Prof. Dr. İsmail BÖĞREKCİ about guiding me with his precious advices.

Bilginer GÜNDÜZ

TABLE OF CONTENTS

LIST OF ABBREVIATIONS

CEN	European Committee for Standardization
CDD	Charge-coupled Device
CSI	Coherence Scanning Interferometry
GPS	Geometrical Product Specification and Verification
GDT	Geometrical Dimensioning and Tolerancing
HEPA	High Efficiency Particulate Air Filter
HVAC	Heating Ventilation and Air-Conditioning
ISO	International Organization of Standardization
LED	Light-Emitting Diode
MNT	Micro-nanotechnology
NA	Numerical Aperture
PSI	Phase-shifting Interferometry
PZT	Piezoelectric Transducer
SEM	Scanning Electron Microscopy
SI	International System of Unit
TC	Technical Committee
TS	Technical Specification
TEM	Transmission Electron Microscopy
2D	Two-dimensional
3D	Three-dimensional
ULPA	Ultra-Low Penetration Air Filter
VIM	International Vocabulary of Basis and General Terms in Metrology

LIST OF SYMBOLS

Rp	Maximum roughness profile peak height within a sampling length
Rv	Maximum roughness profile valley depth within a sampling length
Rz	Maximum height of the roughness profile within a sampling length
Rc	Mean height of roughness profile elements within a sampling length
Rt	Total height of the surface roughness within an evaluation length
Ra	Arithmetical mean deviation of the roughness profile within a sampling length
Rq	Root mean square deviation of the roughness profile within a sampling length
Rsk	Skewness of the roughness profile within a sampling length
Rku	Kurtosis of the roughness profile
RSm	Mean width of roughness profile elements within a sampling length
Rδc	Vertical distance between two section levels of given material ratio
Rmr	Material ratio of the roughness profile
Sq	Root mean square value of ordinates within a sampling area
Sa	Arithmetic mean of absolute height within a sampling area
Ssk	Skewness of topography height distribution within a sampling area
Sku	Kurtosis of topography height distribution within a sampling area
Sp	Maximum surface peak height within a sampling area
Sv	Maximum valley height of surface within a sampling area
Sz	Sum of the largest peek height and the largest pit or valley depth within a sampling area
Sal	Auto-correlation length
Sdr	Developed interfacial area ratio of the scaled-limited surface
Smc	Arial material ratio of the scale-limited surface
Std	Texture direction of the scale-limited surface

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

Every industrial product has to meet given tolerances according to international standards. The need for high-precision surface measurement becomes more crucial as workpieces become smaller. The rapid increase of market globalization requires regulation of international standards in the field of Geometrical Product Specification and Verification. The worldwide approved norms for the requirements and inspections of the geometrical and material qualities of product parts – fundamental standards in the field for lengths and angles, for deviations of form and position, also surface roughness – enable the proper production of workpieces with a high level of functionality, quality and reliability, all of which are made possible independent of the location of the manufacturer.

Modern Production Metrology and its industrial application came out through – the scientific, the technical and organizational work of E. Abbe, W. Taylor and F.W. Taylor and at the end of the twentieth century, -the “Quality Control Century’’. The development has reached the stage of Nanometrology and will soon proceed to Femtometrology (Durakbasa, 2003). Sophisticated measurement techniques have an important role to play in optimizing the quality of all kinds of products and processes through highly accurate geometrical product specification and verification. To survive today’s worldwide challenges in manufacturing, a high level of quality production has to be guaranteed and the reliability of its application and employment must be ensured. This indicates the necessity of measurement throughout the entire manufacturing process.

Metrology can be termed as an “enabling science”, meaning that it is a science that makes other developments initially, forming the basis for inventions (Durakbasa, 2003). It yields essential information on the production and working conditions as well as status of processes.

Prior to the industrial revolution, craftspeople served as fabricators and inspections and were entirely responsible for the quality of their products. Inspection was not a separate function in production (Durakbasa, 2003). In the philosophy of modern productions and of production metrology, inspections were separated from production and this headed to the existence of separate departments in facilities responsible for quality control.

The term product is defined briefly as the result of activities and processes in terms of international standardization (EN ISO 9000). The quality of many industrial products is determined through the properties of their surfaces. An appropriate quality and process control can reduce incident of reject in the production process due to surface defects in production. Thus, this also achieves an avoidance of energy losses while minimizing the unnecessary consumption of raw materials. Here, surface is the separation between a workpiece and its environment that comprises the microstructures of the material and occurring during manufacturing. Surfaces are very important in manufacturing, in the performance of workpieces and the functionality of the produced parts (Whitehouse, 2002). Every industrial product has to meet given tolerances according to international standards. The need for high-precision surface measurements becomes more crucial as the workpiece becomes smaller.

The rapid increase of market globalization requires regulation of international standards in the field of Geometrical Product Specification and Verification. The worldwide approved norms for the requirements and inspection of the geometrical and material qualities of product parts –fundamental standards in the field for lengths and angles, deviations of form and position, also surface roughness – enable proper production of workpieces with a high level functionality, quality and reliability, all of which are made possible independent of the location of the manufacturer.

Quality Control and Quality Management consisting of a diversity of tasks, measures and activities extending over the entire product life cycle (EN ISO 9004) for each product must accompany in all phases (Osanna et al., 2006). Quality Management is not only about measurement techniques but –quality control is impossible without measurement techniques. Technical measurement has a crucial role in forming the fundamental basis for manufacturing and it is one of the main parts of every quality management systems regarding the manufacture of products and the operation of technical plants as well.

One of the most important parameters for determining the surface characterizations of a precision workpiece is roughness. Here, roughness expresses the fine irregularities of a surface. Again like other tolerance specifications in the manufacturing industry, surfaces have to be within certain limits of roughness. The most useful parameters for two-dimensional surface parameters are Ra and Rz. Additionally, the development of three-dimensional surface parameters helps out in defining the surface features of a product more precisely. The naked eye can tell quite a lot about larger-scale features. The resolution of the human eye is limited to slightly under 100 μm (Durakbasa et al., 2009). Therefore, it is essential to apply more accurate measurement methods, which can be used for evaluating of surface roughness.

2. LITERATURE REVIEW

To survive amidst the challenges in manufacturing requires achieving required workpiece accuracy within related tolerances in series fabrication in order to decrease the consumption of energy and material. In other words, these requirements are crucial to avoid unnecessary retouching work and the undesired usage of raw material and energy that comes with the rejection of workpieces. When the machined parts are considered as whole, deviations in position occur because of the interaction between the different features forming the periphery. Understanding deviations of dimensions, roughness, form and position is important for the accuracy and function of the workpiece and these deviations must hold to certain upper limits in order to fulfill their expected purposes.

2.1. Nanotechnology

The onset of modern age of nanotechnology was inaugurated in 1959 with the lecture “There’s Plenty of Room at Bottom” by Richard Feynmann. He made the scientific community aware of the untapped potential of nanomaterials. It was for a call to manipulate and control things on a small scale.

Nanotechnology is about the controlled assembly and structuring of matter of the scale of approximately 1-100 nm in order to exploit the unique properties that manifest that level (Stepnova et al., 2012). It is well recognized that this field will enable a vast range of new capabilities in healthcare, new materials for transportation, new categories and capabilities in consumer products, new processes for industry, new devices and sensors for information technology and much more.

Nanotechnology can also be defined in terms of the manipulation, control and integration of atoms and molecules to form materials, structures, components, devices and systems at a nano-scale, which applies nanoscience, especially its industrial and commercial objectives (Hornyak et al., 2009).

Nanotechnology is a multi-disciplinary field covering physics, biology, chemistry, engineering and the medical sciences. Therefore, it is difficult to identify one common unique definition for all these fields. Nanotechnology can be approached differently. The cultural core of nanotechnology stands at the crossroads of new concepts and new architectures (inspired by biological and natural systems) with new materials (in most cases properly functionalized and engineered at nanoscale) and new nanoscale fabrication, manipulation and measuring processes and instruments.

One of the (considerably important) nanotechnology areas is mechanical engineering. Nanoproduction, nanomanufacturing and nanomachining enable the construction of new machines and instruments for implementation in Nanotechnology applications. In addition to nanomeasurements, nanometrology, which partly belongs to mechanical engineering, has an important role in the control processes running through Nanotechnology. These aspects will be considered in the following chapters in closer detail.

Applying nanoscience below:

Automotive Industry:	Step assists, bumpers, coatings, paints.
Recreation:	Lighter, stronger tennis racquets, golf shafts, skis.
Personal use and Food:	Sunscreen, cosmetics, umbrella (based on lotus leaf), cutting boards, pans
Medicine, Therapeutics and Hygiene:	Medical imaging with quantum dots, drug delivery, dental-bonding agents, burn and wound dressing.
Structural Materials and Industrial lighter Applications:	Wear-resistant nanocreamics, stronger, polymers, self-cleaning glasses.

Electronics and computing: Organic LEDs and organic electroluminescent displays, cordless power tool batteries, cellular memory.

Nanotechnology requires increased resolution for observation. This requires seeing atoms and gauging the level of material behavior at the molecular level without any environmental effects. Collaboration, integration and interaction are key points for new design. Therefore, a new advanced technology building must have built-in flexibility in order to meet all of the requirements within one building or complex. Every research or manufacturing center consists of technical or non-technical spaces. Technical spaces are the places where laboratory work and manufacturing occur and which is more important for designing new buildings. These include clean rooms, imaging facilities, production and metrology centers. Non-technical spaces are offices, meeting rooms etc.

Environmental stability is an important issue for laboratories and manufacturing facilities. Respectively, the parameters affecting it are temperature, humidity, contamination, air velocity and vibration. It is either defined over space (uniformity) or over time (drift). Uniformity is influenced by the extent to which the room is “in or out”. On the other hand, drift is influenced by measurement or control systems. The room temperature for precise measurement should be kept at 20° C ± 0.01° C to 25° C and the temperature drift should be less than 0.5° C h^{-1} and additionally the air velocity should not exceed 5 $m.min^{-1}$. In order to achieve these conditions, internal heat sources such as lightening and heat transfer through walls must be minimized. A heated floor pad aids in maintaining this precise level of temperature control.

A clean room is an isolated space within which a high level of particulate contaminant control is in effect. Environmental pollutants such as dust, microbes, aerosol particles and chemical vapors are limited according to ISO 14644. The outside air in a typical city has an order of $3.5x10^7$ $particle.m^{-3}$ of 500 nm or larger (Hornyak et al., 2009). Some products require a controlled environmental clean room. For instance, a hard disk manufacturing requires a clean room which should have no more 100,000 particles larger than 0.1 μm (ISO 14644-1 Class 100) (Hornyak et al., 2009). Air entering inside the room from outside is filtered for dust and air circulated inside being passed through high efficiency particulate air (HEPA) and ultra-low penetration air (ULPA) filter.

In the structural and mechanical design of advanced technology facilities vibration sensitivity must be considered. Many laboratory works are sensitive to vibration. These include metrology, high-end imaging (TEM, SEM), photolithography and probe development (Hornyak et al., 2009). There are other methods that are impacted by vibration to some degree such as optical microscopy, mass spectrometry and other characterization methods. In designing such advanced facilities with respect to vibration requirements, there must be a balance with cost-effectiveness, the facility's mission, facility operation costs and future flexibility. Furthermore, vibrations may be classified as *continuous vibrations* (e.g. machinery, road traffic and continuous construction activities), *impulsive vibrations* (e.g. dropping heavy equipment, loading and unloading supplies) and *intermittent vibrations* (e.g. passing heavy vehicles and trains).

Another aspect to be considered in advanced technology buildings is mechanical noise. The primary sources of mechanical noise arise from HVAC (heating, ventilation and air-conditioning) noises and vibrations. Operation equipment and air ducts can be hinder reaching the desired conditions. In most advanced technology buildings placing mechanical equipment inside the building (cooling towers, exhaust fans, scrubbers and pumps) is avoided. Considering all of the parameters mentioned, all of which affect the requirements for the desired conditions of advanced technology facilities, we should first clarify the activities, which are going to take a place in given area, in order to design the sites. This allows us to know what is required and expected from such sites with the aim of achieving a suitable result from them.

2.2. Engineering Metrology

Metrology is the science of weight and measures, including the development of measurement standards and systems for absolute and relative measurements (Hornyak et al., 2009). It concerns the application in manufacturing and other processes and ensuring the suitability of measurement instruments, their calibrations and the quality control of measurements. There are several terms within metrology, of which one should be aware and which are defined in ISO VIM (ISO VIM, 2004). In many cases, the true value is estimated as the mean value of repeated measurements. The terms used in metrology are as follows;

- *The measurand* is the quantity that is the aim of measurement (e.g. current, length, roughness etc.).
- *Accuracy* determines how close the measured quantitative value is to the true value. *Precision* indicates the dispersion of the quantitative values from repeated measurements on equivalent or similar objects.
- *Error* is the difference between the true value and the measured value. It falls into two categories depending on its origin. *Random errors* are those caused by the environmental condition. *Systematic errors* occur due to alignment error or improperly calibrated measurement instruments.
- *Uncertainty* quantitatively describes the degree of imperfection of a measurement. In other words, it is a confidence level within which the measured value is thought to reside.
- *Traceability* is the process whereby the measured value can be compared to a standard for specific measurand of one or many stages.
- *Calibration* is the determination and documentation of the deviation of a measurement result from that of an accepted standardized true value.

In considering the importance of measurement needs and devices, a quote from Lord Kelvin, Sir William Thomson comes to mind: “In physical science the first essential step in direction of learning any subject is to find principles numerical reckoning and practical methods for measuring some quality connected with it

(Sadat, 2005).” If you can measure what you are working on and express it numerically, then that means that you know something about it.

Billions of euros, yen, dollars and pounds of sale demand worldwide each year depend directly on metrology and measurement techniques. In any case, measurement and characterization are placed at the top of any process, especially when it is on the micro- and/or nano-scale (Whitehouse, 2003). These relate to shape, volume, surface area and topography, adsorption, porosity, resistivity, resilience and force. Additionally, it is necessary that all measurements must be made in the International Systems of Units (SI).

The quality demands on any kind of product develop further with an increase in manufacturing accuracy. This trend continually persists in the move from micro-technological manufacture towards nanotechnology which was first introduced by Taniguchi N. in 1974 (Taniguchi, 1974). Figure 2.1 depicts which special measurement techniques and production methods are required for attaining manufacturing accuracy in the nanometric range.

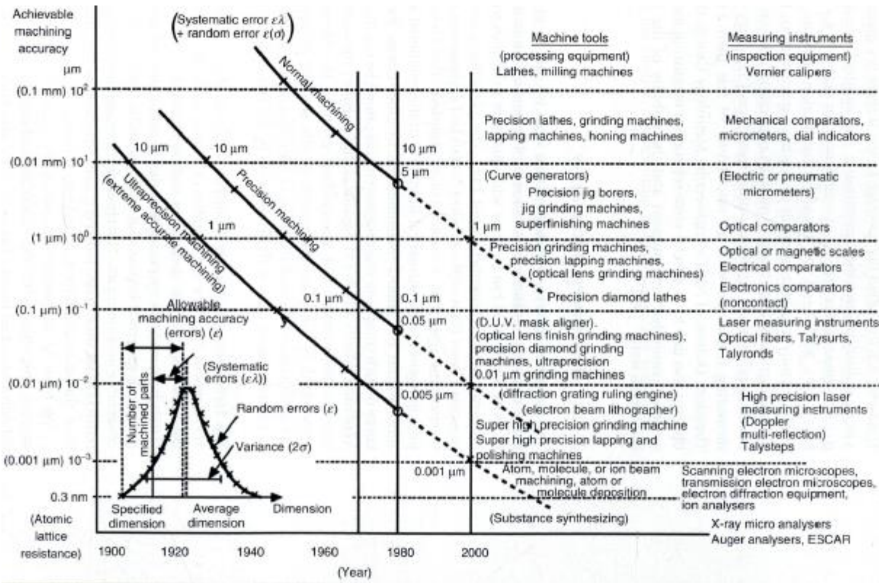


Figure 2.1 Development of dimensional metrology and achievable manufacturing accuracy (Taniguchi, 1974)

Extrapolating specification from existing and past machine tools, such as precision lathes and grinders, to the new generation of machine tools it was correctly held that before 2000 an accuracy of between 0.1 µm and 1 nm would be needed to cater to the needs of industry. Taniguchi N. was too pessimistic for this has been already state of the art before 1995 (Osanna et al., 2006). This goal can be achieved through the application and development of high precision manufacturing processes and high precision measurement techniques.

The production tolerances of a workpiece decrease in connection to the increasing demands of customers and consumers in reference to the quality of products and the quality management of processes. The ongoing development of more accurate ISO tolerances is evidence of this. It is necessary to incorporate very sophisticated instrumentation and metrology to achieve surface finishes and part tolerances. In this thesis, the surface characterization (roughness) will be the focus of the following chapters.

The workpiece is set into production via Geometrical Product Specification and Verification (GPS) in technical drawing on basis of shape (geometry), dimension tolerances and surface characterization through all of which the optimal functions of the workpiece is guaranteed. However, the production of the workpiece fulfilling all of these requirements cannot be easily realized. At this point, the measurement of the workpiece becomes more necessary in comparison to specifications in the design-, production- and finishing phases. Therefore, the standards have been developed in the field of Geometrical Product Specification and Verification.

A set of requirements concerning the geometry of a workpiece (or of assembly of some workpieces) is known as the “Geometrical Product Specification and Verification” and this covers size and dimension requirements, geometrical tolerances and geometrical properties of the surface (Durakbasa, 2003).

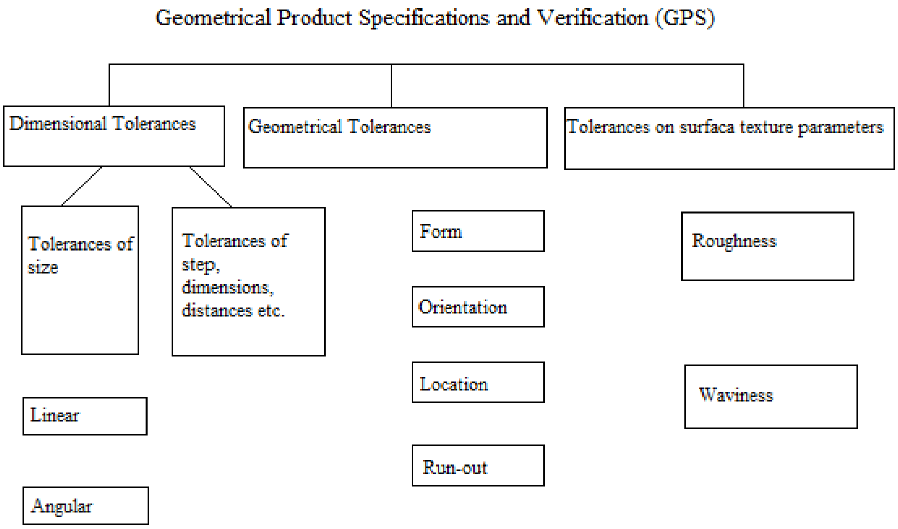


Figure 2.2 Geometrical tolerances and tolerances of dimension and geometrical properties of the surface (Durakbasa, 2003)

Figure 2.2 shows the division of the tolerances defined by the Geometrical Product Specification and Verification, set out to achieve the optimal limits of the workpiece and maximal functionality.

2.3. Chain of GPS-Matrix-Model

The Geometrical Product Specifications and Verification sets forth the following:

- Fundamental rules of specifications, global principles and definitions and geometric characteristics.
- Geometric characteristics covering size, distance, angle, form, location, orientation and roughness standards.
- The standards for manufacturing processes and specific machines.
- All of these kinds of standards are considered at several steps of product life cycle such as design, manufacturing, metrology, quality assurance and etc.

Figure 2.3 depicts four different kinds of GPS standards.

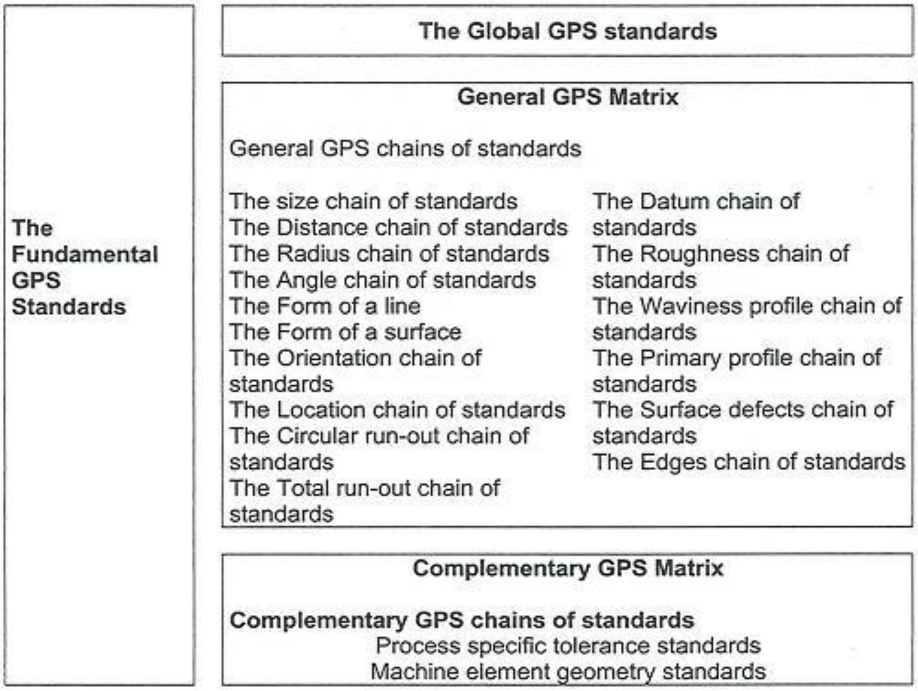


Figure 2.3 The GPS-Matrix-Model (ISO/TR 14638, 1995)

The group of fundamental GPS standards contains very essential rules for dimensioning and tolerances. The global GPS standards are however more related to many other GPS standards, which mean that they influence general GPS chains. For instance, the standard reference temperatures (ISO1) as well as definitions of terms and geometrical features are the most important global GPS standards. These standards are contained also in General GPS standards. Complementary GPS standards contain technical rules for drawing indications, definitions and verification principles for specific categories of features or elements. Some of the rules regard the type of manufacturing process in question, such as machining, welding, casting, forming, while others are more about the geometry of machine elements like screw treads, splines or gears (Oprean et.al., 2009). General GPS standards are the core of the “Masterplan”. They are ordered in a matrix in which rows constitute chains of standards and columns concern various characteristics of geometrical features. Due to the structure of this part of Masterplan, the whole system is known as the GPS matrix model (Durakbasa, 2003).

2.4. International Standardization of GPS

For years, there had been many standards concerning GPS which were developed by various technical committees within the International Organization of Standardization (ISO). However, this led to the problem of different aims and representations of standards as well as sometimes inconsistent determinations. Founded in 1996, the technical committee ISO/TC 213 on "Dimensional and Geometrical Product Specification and Verification" has been working towards harmonizing previously standardized tolerances and related metrology. This technical committee is working in collaboration with a similar committee of the European Organization CEN/TC 290 and according to the Vienna Agreement these two technical committees are working in parallel in order to prepare identical documentation for GPS.

2.5. Geometric Dimensioning and Tolerancing

Geometric Dimensioning and Tolerancing (GDT) is a method for precisely defining the geometry of mechanical parts. It introduces tools which allow mechanical designers, fabricators and inspectors to effectively communicate complex geometrical descriptions.

A good example of why GDT is needed can be found the automobile stamped chassis shown in Figure 2.4. The rear quarter panel must fit snugly in order to allow spot welds and in this competitive business, cosmetic appearance and noise abatement are critical. Computer modeling of these complex surfaces continues to increase the complexity of interface shapes.

Figure 2.4 The automobile stamped chassis (Anonymous, 2018a)

The automotive industry, with its high volumes, has benefited greatly from GDT. The computer industry, in particular in mass-storage manufacturing, has used GDT extensively to increase their yields of high-volume and low-margin hard disk drives. However, as with most engineering and scientific methodologies, GDT was not rigorously formulated and documented until later in the twentieth century.

A tolerance is the total amount by which a specific dimension may acceptably vary. Thus, the tolerance value is the difference between the maximum and minimum limits. Roughness, waviness and primary profile will be explained in detail in the following chapter.

2.6. Geometrical Tolerances

As has been mentioned several times before in this thesis, it is impossible in production engineering to manufacture machined parts with absolutely accurate dimensions and geometry. Therefore, it is not practicable to achieve geometrically perfect shaped workpieces because there are always deviations within various features of workpieces (e.g. cylinder, cone, plane and torus in the case of rotational parts) occurring from their nominal shapes. These differences from the ideal shape of the workpiece as designed are called form deviations. Form tolerances exist in order to keep the form deviation of the real form of a feature within a desired range and these are given in technical drawing. In general, they are applied to a single geometrical feature. For example, for form deviations of cylindrical workpieces, there exists different types of form deviation (e.g. in the direction of the axis there are deviations of the straight direction of the axis (Osanna, 1982)).

These can have the form of a barrel, a cone or a double bell and a section in the plane perpendicular to the axis can look like an ellipse.

In contrast to form deviations, deviations of location and orientation can be seen if the machined parts are considered as whole. The geometrical shape of a workpiece is often complex and consists of various features. In this regard, to keep the accuracy of a workpiece within given desired values, it is necessary to know the proper orientation and location of individual elements of the workpiece in manufacturing. For instance, the surfaces of a cylindrically formed part must have a common axis. Unfortunately, it is not achievable in reality due to manufacturing circumstances. In order to set the permissible limits pertaining to the common location and orientation of the elements, three kinds of related tolerances are defined as in follows:

- *Orientation tolerances,*
- *Location tolerances,*
- *Run-out tolerances.*

The classification of geometrical tolerances is presented in Figure 2.5.

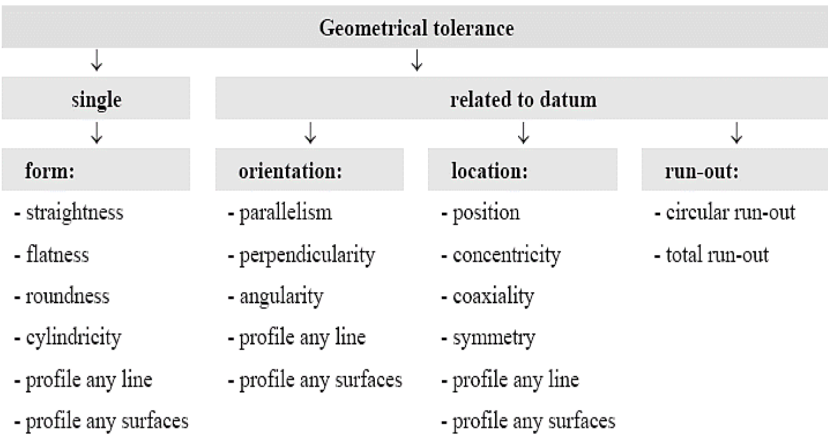
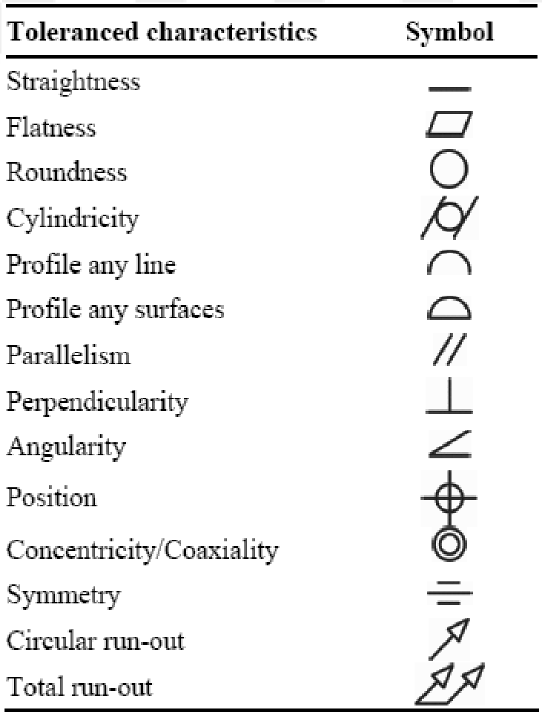


Figure 2.5 Classification of geometrical tolerances (Osanna, 2005)

The international standard ISO 1101 is the globally accepted document, which specifies terms and definitions in connection with both geometrical tolerances and geometrical deviations. In this standard, geometrical tolerances are defined as a zone, the so-called "tolerance zone", in which the real element must be contained. The zone may have the form of a circle or a cylinder, such as the area between two straight lines or two concentric circles, the space between parallel planes or two coaxial cylinders for example. As already explained, in most cases the deviations are the result of manufacturing processes, and they are to be identified by measurements, although the term “deviation” is not defined in ISO 1101. The correct definition of "deviation" is the size of a minimum zone enclosing the toleranced feature, having the same form as the tolerance zone.



Toleranced characteristics	Symbol
Straightness	⏤
Flatness	⏥
Roundness	○
Cylindricity	⌭
Profile any line	⌒
Profile any surfaces	⌓
Parallelism	//
Perpendicularity	⊥
Angularity	∠
Position	⌖
Concentricity/Coaxiality	◎
Symmetry	⌯
Circular run-out	↗
Total run-out	⌰

Figure 2.6 Symbols of geometrical tolerances (ISO 1101, 2004)

The symbols used for geometrical tolerances and related deviations are standardized according to ISO 1101 (see Figure 2.6). These symbols are internationally accepted and make production circumstances understandable among the different countries.

In general, the tolerancing of line and surface profiles concerns the form and features of a workpiece. When a datum system is specified with a tolerance, then the feature’s orientation and location may also be constrained.

The three kinds of tolerancing of lines and surfaces in a workpiece are partially independent from each other. The form tolerance of lines and surfaces of a workpiece places a restriction on deviation only from the ideal form (shape) workpiece only. However, here the orientation tolerance is restricted in this manner both in terms of form and orientation. Consequently, the last type of tolerancing of line and surface, location tolerancing, affects all three characteristics (Osanna et al., 2005).

In order to decide on a suitable tolerance among these three, the cost of production and the desired functional properties of the workpiece must be considered. Table 2.1 shows the necessity of datum for different tolerances is shown.

Table 2.1 Profile tolerances in the scope of ISO 1101 (Durakbasa, 2003)

Tolerances	Characteristics	Datum needed
Form	Profile any line	No
	Profile any surface	No
Orientation	Profile any line	yes
	Profile any surface	yes
Location	Profile any line	yes
	Profile any surface	yes

3. MATERIAL AND METHOD

Surface metrology is becoming more and more commonplace in manufacturing across wide range industries and gaining important as surface features get smaller and smaller. This expansion to nanotechnology gives rise to the concerns of using the best technology for inspecting surface features in micron and submicron measurements. *Surface metrology* can be defined as the measurement of deviations of a workpiece from its theoretically ideal form as specified in a technical drawing. This includes deviation of roundness, straightness, flatness, cylindiricity etc. (see Chapter 2) (Trumpold, 1990). Apart from these kinds of deviations, measurement of surface texture is a branch of surface metrology with a huge range of parameters available. This branch of metrology will be touched upon in this chapter in two sections as *Profile Characterization* and *Areal Characterization*.

Profile characterization of surface texture has been standardized for some time but areal characterization is not a completed within metrology as of yet. This chapter will look at the methods which are used for surface texture characterization according to related ISO standards, including various parameters and filtering methods. However, the parameters for areal surface texture are relatively new and might be revised in near future.

3.1. Surface Profile Characterization

In order to discuss the filtering and surface texture parameters, there are some definitions that must be mentioned and delineated. In ISO 4287 three different types of profile are defined (ISO 4287, 2009):

- ***Traced Profile*** is the trace of the center of a stylus tip that has an ideal geometrical form (conical, with spherical tip) and nominal tracing force, as it traverses the surface.
- ***Reference Profile*** refers to the trace that the probe would report as it is moved along a perfectly smooth and flat workpiece – the reference profile arises from the movement caused by an imperfect datum guideway.

- ***Total Profile*** is the digital form of the profile, combining the traced profile and the reference profile.

Other than above mentioned definitions, there are two more required definitions before moving onto filtering and surface parameters.

- ***Evaluation Length*** is the sum of the sampling length, which is the total length on the x-axis of the surface used to assess the profile. To evaluate the roughness and waviness profiles, requires taking several successive sampling lengths. If there is no number specified in the symbol (e.g. Ra6: meaning six sampling lengths), it is then recommended in ISO 4287 to use five sampling lengths for roughness evaluation. However, there is no default specified for waviness. For the primary profile the sampling length is same as the evaluation length.
- ***Total traverse length*** is the total length of surface traversed in the course of measurement, which is usually longer than the evaluation length.

Profile Filtering

Filtering plays an important role in surface texture analysis. In filtration, the aim is selecting a certain range of structures in total profile for analysis that has significance to a particular situation. This requires rejecting information considered irrelevant, for instance, in order to reduce the effect of measurement instrument noise and imperfections. This means filtering select structures along the x-axis given is in term of wavelengths or spatial frequencies. A filter rejecting short wavelengths while keeping the long ones is named *low-pass filter*. However, a *high-pass filter* eliminates long wavelengths while preserving short wavelengths. The combination of these two filters operating for a restricted range of wavelengths is called *band-pass filter*. The wavelength at, which transmission is 50%, is called cut-off for that filter (see Figure 3.1). There are different filters used by instruments for defining roughness, waviness and primary profiles as follows:

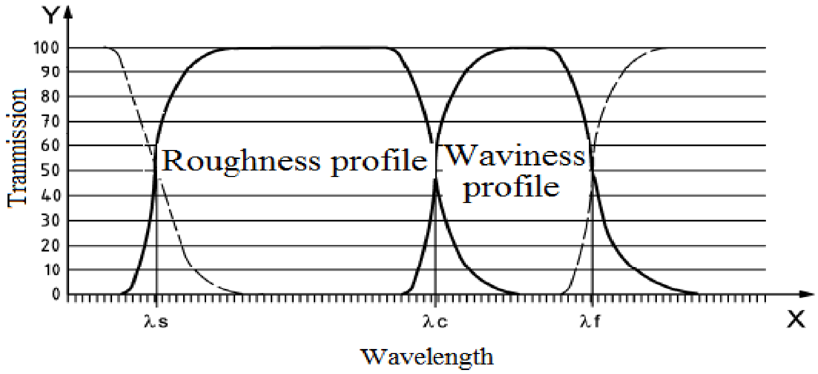


Figure 3.1 Presentation of surface roughness and waviness (ISO 4287, 2009)

The transmission characteristics of a filter size are determined by the weighting function according ISO 11562 (ISO 11562, 1996) as;

$$s(x) = \frac{1}{\alpha\lambda} \exp\left(\frac{x}{\alpha\lambda}\right)^2 \qquad (3.1)$$

α is a constant designed to provide 50% transmission at a cut-off wavelength of λ,

$$\sqrt{\frac{ln2}{\pi}} \approx 0.4687 \qquad (3.2)$$

- ***λs profile filter*** defines where the intersection occurs between roughness and shorter-wavelength components on a surface.
- ***λc profile filter*** defines where the intersection occurs between roughness and waviness components.
- ***λf profile filter*** defines where the intersection occurs between waviness and longer-wavelength components.

In general, modern measurement instruments and software packages use a Gaussian filter according to ISO 16610; however, they may employ some other older forms of filtration such as a 2RC filter.

Primary Profile

The primary profile is gained after the application of a low-pass filter with λs including the effects of the standardized probe. Since stylus sizes vary and the instrument will introduce vibration and other noise into the profile signal with a wavelength shorter than stylus dimensions (mechanical filtration), in practice it is best to apply the λs filtration upon the total profile by default. Figure 3.2 depicts the primary profile.

Roughness Profile

The roughness profile is derived from the primary profile by using the high-pass filter with a cut-off of λc. The roughness profile is the basis for the evaluation of surface roughness of a workpiece (see Figure 3.2).

Waviness Profile

The waviness profile is acquired by applying a band-pass filter to obtain the surface structure at longer wavelengths than the roughness. Filter λf distinguishes the long-wave components and λc is this time needed to suppress the short-wave components on the surface. The waviness profile is the basis for evaluating waviness profile parameters (see Figure 3.2).

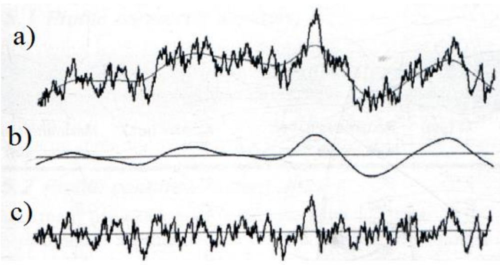


Figure 3.2 a) Primary profile b) Roughness profile c) Waviness profile (Leach, 2010)

3.2. Profile Characterization Parameter

In ISO 4287 and ISO 4288 a number of various values are defined in order to evaluate the surface structure of a workpiece. Table 3.1 shows the relation between cut-off wavelength, tip radius and maximum sampling spacing.

Table 3.1 Relation between cut-off wavelength, tip radius and maximum sampling spacing (ISO 4288, 1996)

λc (mm)	λs (μm)	Roughness cut-off wavelength ratio λc/λs	r_{tip} max (μm)	Maximum sampling spacing (μm)
0.08	**2.5**	**30**	**2**	**0.5**
0.25	**2.5**	**100**	**2**	**0.5**
0.8	**2.5**	**300**	**2**	**0.5**
2.5	**8**	**300**	**5**	**1.5**
8	**25**	**300**	**10**	**5**

If there is no indication stated, in practice the common use of sampling lengths number is five. In general, when a workpiece is produced from a drawing, the sampling length is taken to be 0.8 mm. However, if there is again no specified sampling length in the drawing, the user will require a mean of the most appropriate value for application on surface profile. Therefore, the value should be selected in consideration of the nature of the surface texture and the characteristics being captured by the measurement.

The surface texture parameter is used to give a quantitative value to describe the surface texture on a part of a surface; to compare it with other parts; and to form a suitable measurement for the production quality system. The ideas of "peaks" and "valleys" play an important role in evaluating of surfaces. Standards define that a profile element consists of a peak and a valley. More specifically, a profile element is a section of a profile from the point at which it crosses the mean line to the point at which it next crosses the same direction (Leach, 2010).

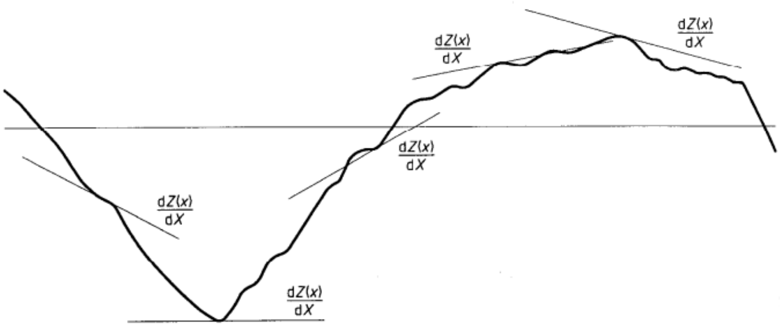


Figure 3.3 Profile element (ISO 4287, 2009)

The capital letter in the parameter symbol defines the type of the profile for evaluation (Figure 3.3). For instance;

- ***Ra*** is calculated from the roughness profile,
- ***Wa*** is from the waviness profile,
- ***Pa*** is gained from the primary profile.

In further chapters of this thesis, the parameters for roughness are defined and evaluated from various samples by two different surface measurement instruments.

Amplitude Profile Parameters

Maximum Profile Peak Height (Rp)

This is defined as the highest point from the mean line within the sampling length of a profile. This value can differ from sample to sample, such that it is unpresentative of the surface. It is more useful to average the values from different samples in order to reduce variation. However, this parameter refers to unusual conditions on the surface such as a sharp spike or burr on the surface due to poor material or poor processing (ISO 5436-1, 2000) (see Figure 3.4).

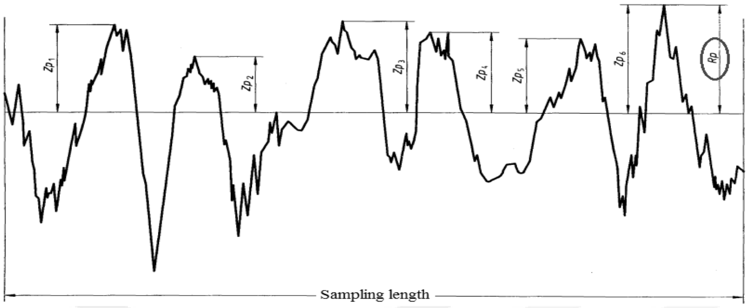


Figure 3.4 Maximum profile peak height from roughness profile (ISO 4287, 2009)

Maximum profile valley depth (Rv)

In contrast to Rp, maximum valley depth Rv is the largest valley depth within the sampling length –the lowest point from the mean line on the profile (see Figure 3.5).

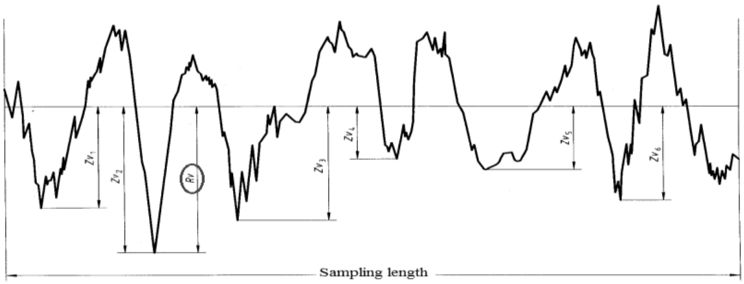


Figure 3.5 Maximum valley depth from roughness profile (ISO 4287, 2009)

Maximum height of the profile (Rz)

This is the sum of the largest profile peak height Rp and largest profile valley depth Rv within a sampling length.

Mean height of profile elements (Rc)

This is the mean value of profile element heights within the sampling length (see Figure 3.6). This parameter requires spacing and height discrimination. If there is no default value specified in the drawing, then the height discrimination shall be 10% of Rz and spacing discrimination shall be 1% of the sampling length. In practice, this parameter is not used often (It is used in the German automotive industry (Leach, 2010)).

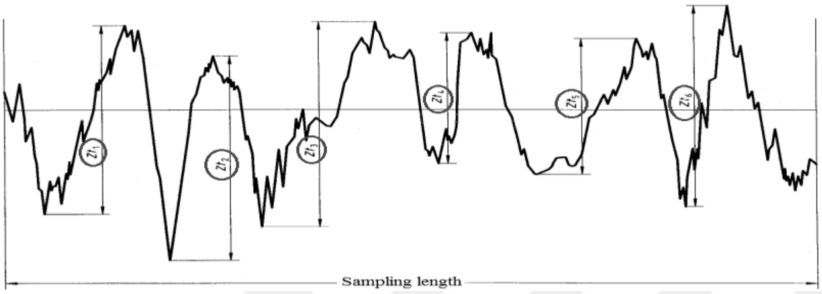


Figure 3.6 Height of profile elements within a sampling length (ISO 4287, 2009)

Total height of the surface (Rt)

This parameter is defined as the sum of the height of the largest profile peak and the largest profile valley depth within the evaluation length.

Average of Ordinate Values of Amplitude Parameters

Arithmetical mean deviation of the profile (Ra)

This is the arithmetic mean of absolute values z(x) within a sampling length *l*,

$$Ra = \frac{1}{l}\int_0^l |z(x)|dx \qquad (3.3)$$

Ra is an important value for the roughness of the texture. It is more rational to average several Ra values from various sequential samples to inspect the roughness of a workpiece. In general, Ra is the commonly used parameter for all of surfaces and it is mainly on most drawings when specifying the surface texture.

Root mean square deviation of the profile (Rq)

This is defined as the root mean square value of the ordinate values z(x) within a sampling length l,

$$Rq = \sqrt{\frac{1}{l}\int_0^l z^2(x)dx} \quad (3.4)$$

Rq is another generally used value in manufacturing and it is always larger than Ra (usually 11% larger than Ra on sinusoidal surfaces (ISO 4288, 1996)).

Skewness of the profile (Rsk)

Skewness refers the distribution of the surface deviations in respect of the centre line. It provides the ratio of the mean cube value of heights and the cube of Rq within a sampling length.

$$Rsk = \frac{1}{Rq^3}\left[\frac{1}{l}\int_0^l z^3(x)dx\right] \quad (3.5)$$

In other words, it describes the symmetry of profile curves in terms of the mean line. While a symmetrical profile results in an amplitude curve, an unsymmetrical profile represents a skewed curve. Zero-, negative- or positive skewness depends on the bulk of the material along the surface distribution. The importance of this parameter is that it can distinguish the two surfaces with same Ra value.

Rsk<0 ………………………… existence of deep valleys
Rsk=0 ………………………… symmetrical distribution of surface deviations
Rsk>0 ………………………… presence of high peaks

For instance, a good bearing surface should have negative skewness value, –i.e. the presence of relatively more peaks than valleys, in order to retain lubricant traces. Surfaces with positive skewness can be turned surfaces.

Kurtosis of the profile (Rku)

This defines the sharpness of the surface height distribution and the ratio of the mean the fourth power of the height values and of the fourth power of Rq within the sampling length.

$$Rku = \frac{1}{Rq^4}\left[\frac{1}{l}\int_0^l z^4(x)dx\right] \qquad (3.6)$$

Spacing Parameters

Mean width of profile elements (RSm)

This defines the mean values of the profile element width within a sampling length. This is the mean value of the lengths on a center line containing a profile peak and a profile valley (see Figure 3.7). This parameter requires height and spacing discriminations. When they are not specified in a drawing, the value for height discrimination is 10% of Rz and 1% of sampling length for spacing discrimination.

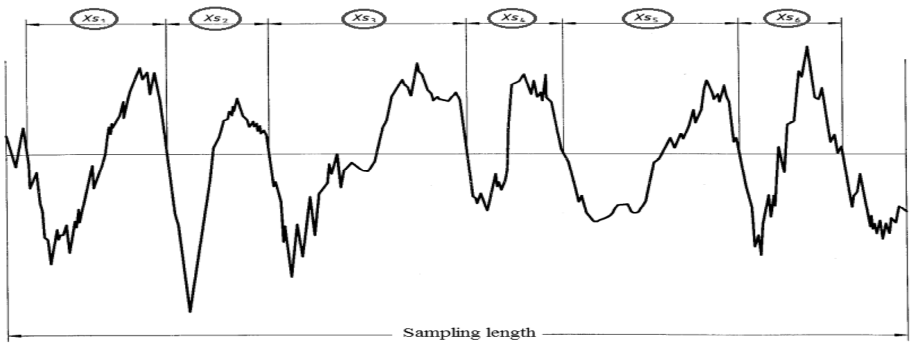


Figure 3.7 Width of a profile element (ISO 4287, 2009)

$$RSm = \frac{1}{m}\sum_{i=1}^{m} Xs_i \qquad (3.7)$$

m………………………. number of profile elements in the sampling length

Xs……………………… width of a profile element

Curves and Related Parameters

The parameters are defined within the sampling length but the further parameters in this section of this thesis are obtained with the evaluation length.

Material ratio of the profile (Rmr)

The material ratio of the profile is the percentage ratio of bearing length to evaluation length. The bearing length can be defined as the sum of section lengths gained by cutting the profile parallel to the center line at a given level. It is assumed that the slice level at the highest peak is 0% and 100% at lowest peek. Use of a material ratio parameter can obtain, -the ratio of bearing length of the profile at a single slice level or nineteen slice levels with even intervals within Rt.

Material ratio curve

This determines the material ratio at a certain depth in a profile which normalized by the total evaluation length. It helps in understanding different shapes in the profile. In manufacturing, the first process forms the surface shape with a relatively coarse finish. The following operations finish the surface to reach the desired surface quality. Refining operations can only eliminate the peaks on the profile while the valleys remain untouched, since this process leads to stratified surfaces, it is difficult to inspect the surface quality of the profile in terms of a single average of Ra values.

Profile section height difference (Rδc)

This is the vertical distance between two section levels of given material ratio.

Relative material ratio (Rmr)

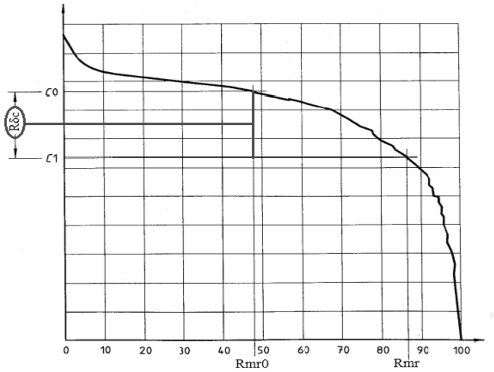


Figure 3.8 Profile section level separation

The relative material ratio is the material ratio C1 determined at a profile section level Rδc relative to a reference C0 (see Figure 3.8). This provides the elimination of spurious peaks from consideration – these peaks wear off in early use. Therefore, reasonable evaluation can be achieved by use of this parameter.

- C1= C0- Rδc
- C0= C(Rδc)

Profile height amplitude curve

This is determined by the sample probability function of the ordinate z(x) within the evaluation length. The amplitude probability curve refers to the probability of surface profile having a certain height at a certain position (see Figure 3.9).

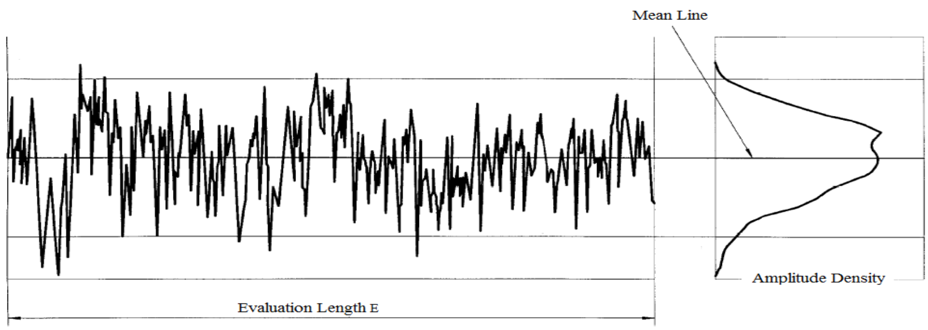


Figure 3.9 Profile height amplitude distribution curve (ISO 4287, 2009)

3.3. Areal Surface Texture Characterization

2D surface measurement and characterization leads to limitations in surface inspection. It does not provide information on the surface functionality. It is possible for two different surfaces composed of two different features and functional properties to have the same commonly used value of Ra in 2D surface measurement after application filtering under the same measurement conditions. It is difficult to measure and determine the exact nature of the topographical feature of the surface. In contrast to 2D surface characterization, areal surface characterization does not require three different groups (i.e. primary, waviness and roughness).

There are two different filters defined in a real surface texture characterization. The first filter, the *S-Filter*, removes small-scale lateral components on the surface, such as measurement noises or irrelevant small features. The second filter, the *L-Filter*, get rid of large-scale components and the *F-operator* removes nominal form. The scale, where the filtering is generated, is controlled via nesting index. It is an extension of the concept of cut-off wavelength and is suitable for all types of filters. These above mentioned filters are applied to acquire SF and SL surfaces.

- ***SF Surface*** is created by application of an S-Filter and F-operator (equivalent to a primary surface).
- ***SL Surface*** is acquired by using L-Filter on an SF surface (equivalent to roughness).

Areal Filtering

The weighting function of general-purposed Gaussian Filter is given by;

$$s(x,y) = \frac{1}{\alpha^2 \lambda cx \lambda cy} exp\left[-\frac{\pi}{\alpha^2}\left(\frac{x^2}{\lambda cx^2} + \frac{y^2}{\lambda cy^2}\right)\right] \qquad (3.8)$$

$$-\lambda cx \leq x \leq \lambda cx, \quad -\lambda cy \leq y \leq \lambda cy$$

x-y… two dimensional distances from the center of the weighting function λc… cut-off length

α …. constant providing 50% transmission characteristics at λc and α is given by,

$$\sqrt{\frac{ln2}{\pi}} \approx 0.4687$$

There are also various types of filters, which are published in a series of ISO/TS 16610 standards, such as linear filters, morphological filters, robust filters and segmentation filters. Filtration plays an important role in both the surface profile and the areal surface characterizations. The simplest but the most important rule for comparing two surface measurements is to use same filtering methods and noting indexes. The relation between the nesting index value, the S-Filter nesting index sampling distance and ball radius is given in ISO 25178-3 (ISO/DIS 25178-3, 2009).

Areal Surface Texture Parameter

Areal parameters can be classified as;

- ***Field Parameters*** are determined with the all of points on scale-limited surfaces.
  - ✓ *Areal height parameters*
  - ✓ *Areal spacing parameters*
  - ✓ *Areal hybrid parameters*
  - ✓ *Functions and related parameters*
  - ✓ *Miscellaneous parameters*

- ***Feature Parameters*** are defined from a subset of predefined topological features from the scale-limited surface.

- ***Fractal Analysis***
  - ✓ *Linear fractal methods*
  - ✓ *Areal fractal methods*

Areal Height Parameters

The root mean square value of the ordinates (Sq)

Sq is the root mean square value of the surface departures z(x, y) within a sampling area.

$$Sq = \sqrt{\frac{1}{A}\iint_A z^2(x,y)dxdy} \tag{3.9}$$

A: sampling area

The arithmetic mean of the absolute height (Sa)

Sa is defined as the arithmetic mean of the absolute value of height within a sampling area.

$$Sa = \sqrt{\frac{1}{A}\int_A |z(x,y)|dxdy} \tag{3.10}$$

The closest relative parameter to Sa is the profile parameter Ra. However, the fundamental difference is the filters used.

Skewness of topography height distribution (Ssk)

Skewness is the ratio of mean cube value of the height values and the cube of Sq within a sampling area.

$$Ssk = \frac{1}{Sq^3}\left[\frac{1}{A}\iint_A z^3(x,y)dxdy\right] \tag{3.11}$$

Kurtosis of topography height distribution (Sku)

The Sku parameter is the ratio of the mean of the fourth power of height values and the fourth power of Sq within a sampling area.

$$Ssk = \frac{1}{Sq^4}\left[\frac{1}{A}\iint_A z^4(x,y)dxdy\right] \tag{3.12}$$

The maximum surface peak height (Sp)

The parameter Sp is the largest peak height value from the mean plane within a sampling area.

The maximum pit height of the surface (Sv)

This is the largest pit or valley depth from the mean plane within a sampling area.

Maximum height of the surface S(z)

It is defined as the sum of the largest peak height values and the largest pit or valley depths within a sampling area.

Areal Spacing Parameters

These parameters are used to signify peak density and texture strength.

Auto-correlation length (Sal)

The parameter Sal is defined along the auto-correlation function (ACF), which is the correlation between a surface and the same surface translated by (tx, ty);

$$ACF(tx,ty) = \frac{\iint_A z(xy)x(x-tx, y-txy)dydy}{\iint_A z(x,y)z(x,y)dxdy} \tag{3.13}$$

Then the Sal is defined as the horizontal distance of the ACF(tx, ty) which has the fastest decay to a specified value s in the range 0≤s≤1,

$$Sal\ min\sqrt{tx^2+ty^2} \tag{3.14}$$

For relatively smooth surfaces, the value for s can be set at 0.2.

Texture aspect ratio of the surface (Str)

The parameter Str clarifies the texture strength (i.e. uniformity of the texture aspect). It can be defined as the ratio of the fastest to the slowest decay to the correlation length of surface ACF.

$$Str = \frac{min\sqrt{tx^2 + ty^2}}{max\sqrt{tx^2 - ty^2}} \qquad (3.15)$$

$0 \leq Str \leq 1$

This parameter is useful in identifying the presence of underlying surface modification in multiple manufacturing processes.

Areal Hybrid Parameters

Areal hybrid parameters are values defined as both the height and spatial properties of the surface. They give information on the hybrid features of surfaces such as the slope or curvature of outliers. They play an important role in surfaces working together such as in the friction and wear between bearing surfaces (Leach, 2010).

Root mean square gradient of the scale-limited surface (Sdq)

This defines the slopes on the surface.

$$Sdq = \sqrt{\frac{1}{A}\iint_A \left[\left(\frac{\partial z(x,y)}{\partial x}\right)^2 + \left(\frac{\partial z(x,y)^2}{\partial y}\right)\right] dxdy} \qquad (3.16)$$

The Sdq parameter is commonly used for sealing application and controlling surface cosmetic appearance (Leach, 2010).

Developed interfacial area ratio of the scaled-limited surface (Sdr)

This is the parameter for the ratio of interfacial area increments of a scale-limited surface within a defined area over a defined area and given as;

$$Sdr = \frac{1}{A}\left[\iint_A \left(\sqrt{\left[1 + \left(\frac{\partial(x,y)}{\partial x}\right)^2 + \left(\frac{\partial(x,y)}{\partial y}\right)^2\right]} - 1\right) dxdy\right] \quad (3.17)$$

Like the Sdq parameter, Sdr is useful in distinguishing surfaces with similar amplitudes and Ra values. It will increase with the complexity of the surface texture independent of Ra values.

Functions and related parameters

Areal material ratio of the scale-limited surface

This is a function of the material ratio of the scale-limited surface defined as a function of height. The related parameters are calculated from three sections of the areal material ratio curve; -the peaks above the mean plane, the mean plane and the valleys under the mean plane.

Areal material ratio of the scale-limited surface (Smc(c))

This is the ratio of material at a certain height c (see Figure 3.10).

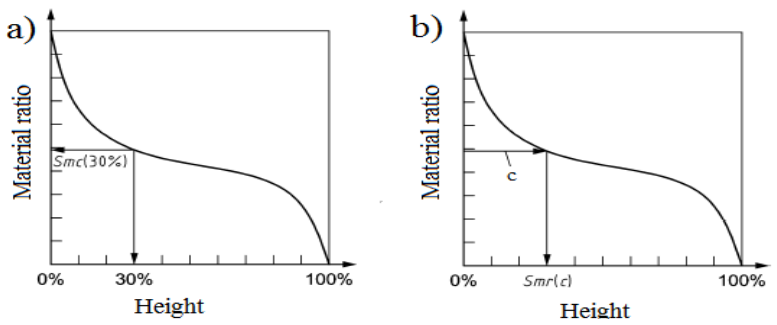


Figure 3.10 a) Areal material ratio curve b) Inverse areal material ratio curve (ISO/DIS 25178-2, 2008)

Void volume (Vv(mr))

The volume of voids per unit area for a given material ratio is obtained thusly,

$$Vv(mr) = \frac{K}{100\%} \int_{mr}^{100\%} [Sdc(mr) - Sdc(q)]dq \qquad (3.18)$$

K……………………… constant for converting to mm per square meter.

The valley volume of material ratio p is;

$$Vvv = Vv(p) \qquad (3.19)$$

The difference of void volume (core void volume) between material ratio p and q is,

$$Vvc = Vv(p) - Vv(q) \qquad (3.20)$$

where by, the default values of p and q are 10% and 80% respectively (ISO/DIS 25178-3, 2009).

Material volume (Vm(mr))

This is the material volume per unit area at a certain material ratio defined by the material ratio curve (see Figure 3.11),

$$Vm(mr) = \frac{K}{100\%} \int_{0}^{mr} [Sdc(q) - Sdc(mr)]dq \qquad (3.22)$$

where the peak material volume at p is,

$$Vmp = Vm(p) \qquad (3.23)$$

The difference of material volume (core material volume) between p and q material ratio is,

$$Vmc = Vm(q) - Vm(p) \qquad (3.24)$$

where the default values for p and q are 10% and 80% respectively (ISO/DIS 25178-3, 2009).

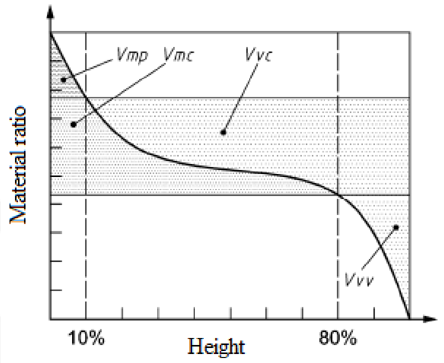


Figure 3.11 Void volume and material volume parameters (ISO/DIS 25178-2, 2008)

Peak extreme height

This is difference of heights of material ratio p% and q%.

$$Sxp = Smr(p) - Smr(q) \tag{3.25}$$

where the respective default values for p and q are defined as 97.5% and 50% according to ISO 251781-3 (ISO/DIS 25178-604, 2010).

Gradient density function

This is the density function calculated from a scale-limited surface representing the relative spatial frequencies against the angle of the steepest gradient α(x, y) and the direction of the steepest gradient β(x ,y) measured in anticlockwise from the x-axis.

$$\alpha(x,y) = tan^{-1}\sqrt{\frac{\partial z^2}{\partial y} + \frac{\partial z^2}{\partial x}} \tag{3.26}$$

and

$$\beta(x,y) = tan^{-1}\left|\frac{\frac{\partial z}{\partial y}}{\frac{\partial z}{\partial x}}\right| \tag{3.27}$$

Miscellaneous Parameters

Texture direction of the scale-limited surface (Std)

The parameter Std is the angle with respect to a specified direction θ of the absolute maximum value of the angular power spectrum. The angular power spectrum, which is the amplitude of the sine wave at a particular spatial frequency, is gained by integrating the amplitudes of each component sine wave as a function of the angle. Std is useful in determining the lay direction of a surface relative to a datum through positioning the part in the measuring instrument in a known orientation.

3.4. Surface Measurement Instruments

As mentioned in previous chapters, a surface is the boundary that a component or a device has with environment, in which the component is housed or in which the device operates. As surface features get smaller, the need for surface control (i.e. surface measurement) becomes increasingly important. Surface topography is defined as the overall surface structure of a part, while surface form is the shape of a part and surface texture is what remains after the form has been obtained. Within MNT, manufactured parts are controlled with regard to their surface texture.

Surface profile measurement

This is the measurement of a line traversing the surface that depicts the amplitude of the surface along a certain distance on the x-axis. Both stylus and optical instruments can acquire the parameters for surface profile measurement with a stylus instrument, measurement is carried out by traversing the stylus along the line on the surface where the measurement is to be taken. However, for optical instruments, profile measurement can be done by extracting the data via software according to ISO standards, after the areal surface measurement (ISO 25178-701, 2010).

The necessary standards are defined in ISO 4287 for acquiring a profile measurement by use of a stylus instrument. Last but not least, the lay of the surface, which derives from the actual production process in manufacturing, should be perpendicular to the direction being traversed.

Areal surface texture measurement

Although it is possible to get information regarding the characteristics of a surface through profile measurement, this provides limited knowledge as to surface functionality. In order to overcome this limitation, areal surface measurements (3D measurement) are applied in order to get more detailed information about surface functionality and nature, which makes it possible to provide manufacturers better understanding of how the surface interacts with its surroundings.

Profile measurement (2D measurement) presents information on the height of profiles within a sampling length or an evaluation length. However, surfaces having some commonly used profile parameter Ra value can be entirely different. Here, 3D measurement is needed more in order to distinguish these two surfaces with very different features and very different functional properties. With the completion and publications of the ISO 25178 series concerning areal measurement, areal measurement will be more commonly used measurement method in comparison to profile measurement (Demircioglu et al., 2013).

In this chapter, the principles of stylus instruments and optical microscopes used in this experimental study were explained. Besides these instruments, there are many other instruments used in the field of surface topography measurement.

3.4.1. Stylus Instruments

Despite of all of the benefits of areal surface measurement in MNT, stylus instruments are still common for measuring surface texture today. A typical stylus instrument consists of a stylus contacting the surface physically and traversing it. A transducer converts the vertical movement of the stylus along the profiles of the surface into an electrical signal. Figure 3.12 shows the components of a typical stylus instrument.

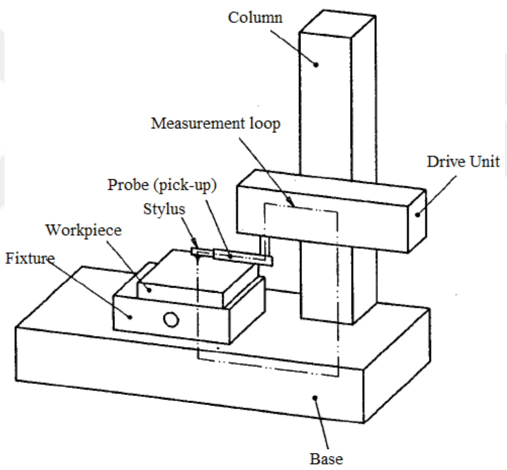


Figure 3.12 Schema of a typical stylus instrument (ISO 3274, 1996)

A motor and gearbox drives the probe at a constant speed in order to move the stylus about the surface. An electronic amplifier boosts the signal from the transducer to a useful level. The part of the stylus that touches the surface is a four-sided pyramidal or conical-formed with a diamond tip with a radius varying between 2µm, 5µm and 10 µm. Conical angle is either 60° or 90°. The ideal form of the conical tip is defined as 60° in ISO 3274 (ISO 3274, 1996). Due to having a finite shape, some styli cannot penetrate all of the peaks and valleys on the surface. This causes gap in certain parameters with a filtered or raw surface.

Another important aspect of stylus measurement is the effect of stylus force. It has a significant influence on measurement results. Too much force can cause damage to smooth surfaces. ISO 3274 determines a default value of 0.75 mN. This can leave some scratches in aluminum with a tip radius of 2 μm. However, smaller forces can increase measurement speed with the risk of “stylus flight”.

As the stylus traverses the peaks and valleys of the surface profile, a transducer converts the up- and- down -movements into a signal, which is then exported to a processor in order to obtain a numeric visual profile. To cover a true cross-section of the surface, the stylus must follow an accurate reference path with a nominal profile of the surface. Such a datum may give by a mechanical skidway. For this purpose, a skid with a large enough radius to prevent the in- and- out- movement along the surface is located front end of the pickup. Consequently, the result of movement of the stylus and skid together in a given direction are taken to be the difference of their movement. Figure 3.13 illustrates stylus and pickup working on surface.

Figure 3.13 Stylus and Pickup working on surface (Anonymous, 2011)

Figure 3.14 illustrates the movement of the skid and stylus.

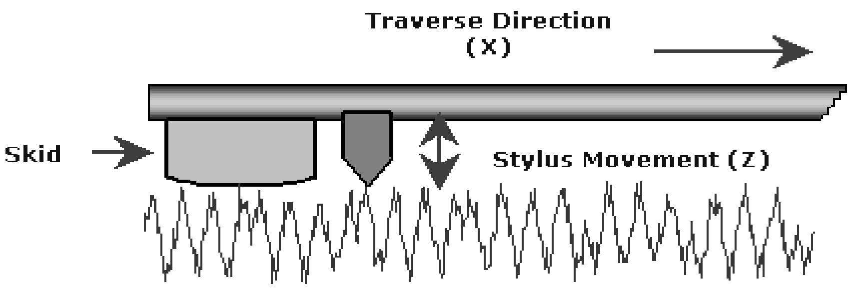


Figure 3.14 The movement of skid and stylus (Anonymous, 2011)

The main sources of possible error are listed as follows;

- *Surface deformation*
- *Amplifier distortion*
- *Finite stylus dimensions*
- *Lateral deflection*
- *Effect of skid or other datum*
- *Relocation upon repeated measurements*
- *Effect of filters – electrical or mechanical*
- *Quantization and sampling effects*
- *Dynamic effects*
- *Environmental effects*
- *Effect of incorrect data-processing algorithms*

Modern stylus instruments may be able to measure surface texture with sub-nanometer resolution. The lateral resolution of a stylus instrument of a sinusoidal profile is given as,

$$\lambda = 2\pi\sqrt{ar} \tag{3.28}$$

3.4.2. Optical Instruments

There are various types of optical instruments for measuring surface topography, surface texture and surface form. The techniques fall into main two groups as scanning beams or viewing the field of a surface (profile and areal methods) and analyzing the distribution of scattered light (area integrated methods). The primary advantage of optical instruments is that they do not contact the surface such that they have no risk of damaging to the surface being measured. Secondly, non-contact instruments can lead to faster measurement times. However, interpreting the results is relatively more complex than doing so with a stylus measurement whereby the tip of a stylus traverses a surface and for this reason it is much easier to make assumptions. There are some limitations for optical instruments. Many optical instruments utilize the microscope objectives varying from 2.5x to 100x in order to magnify the surface feature being measured. The main fundamental limitation is the numerical (or angular) aperture (NA) (Figure 3.15). This gives the largest slope angle that can be measured and affects the optical resolution.

$$NA = n sin\alpha \tag{3.29}$$

n………… index of the medium between the surface and lens

α …………half of the acceptance angle of the aperture

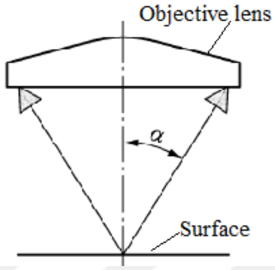


Figure 3.15 Numerical aperture of a microscope (ISO 25178-602, 2010)

Acceptance angle: the limitation of the slope that allows the reflection of light from the surface back to the objective lens.

Another limitation is the optical resolution of the objective determining the minimum distance of lateral features on the surface that can be measured, given as,

$$r = \frac{\lambda}{2NA} \tag{4.3}$$

where λ is the wavelength of the incident radiation.

Scanning Optical Techniques

Scanning techniques acquire surface measurements by physically scanning a light spot along a surface. In some applications, this leads to time problems like those occurring with stylus measurement instruments. This thesis covers only the techniques used in this experimental application in the *Laboratory at the Mechanical Engineering Department*.

Confocal Instruments

Confocal instruments benefit from the addition of two pinholes, one of which is located in front of a light source and the other which is placed in front of a detector, thus yielding an increase in lateral resolution. Another aspect in confocal microscopy is setting up depth discrimination. Total image energy decreases when the object moves out of focus, while staying constant in a conventional bright field microscope. These results in only points on focal planes being bright, while the points out of focus stay dark (Bogrekci et al., 2017).

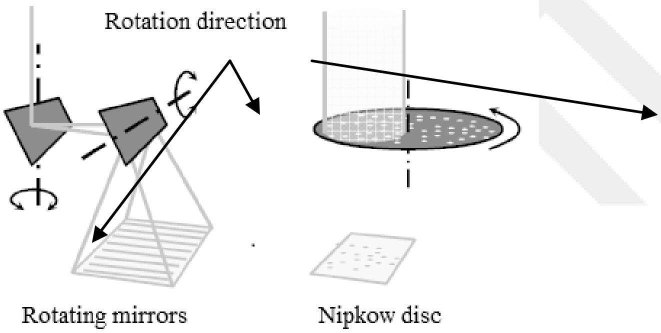


Figure 3.16 Confocal scanning technology

A surface measurement by a confocal instrument requires a lateral scanning since one point on a surface can be scanned at a time (see Figure 3.16). There are two different techniques used here. The first technique, a pair of *rotating mirrors*, is generally found in laser scanning microscopes while the second, a *Nipkow Disc*-, is often seen in practice. The Nipkow disc is placed at an intermediate image in the optical path. In this system, it guides most suitable white light spots onto a complete area within one revolution. However, the rotational movement of these two systems leads to some disadvantages like *vibrations*, *non-linearity*, *measurement noise*, and *mechanically sensitivity*. Contemporary commercial systems have scanning rates of 100 frames per second, making full 3D scans of typically 200 to 300 frames in a few seconds (Leach, 2010). In order to avoid the disadvantages mentioned above, the optical measurement instrument used in these experiments has a digital scanning via Micro-Display (Demircioglu, 2017).

The main limitation of confocal microscopes is the working distance – defined as the distance along the optical axis between the closest element to the surface and the surface point in the middle of the vertical distances according to ISO 25168-602 (ISO 25178-602, 2010). The working distance varies in range from 100 µm to a few millimeters according to the objective used. An increase of the working distance causes a decrease of the numerical aperture angle (NA), hence lateral and axial resolution is also reduced. Therefore, the choice of NA in measurement has an important role. For this reason, the NA below 0.4 x are generally not used for measuring roughness. With low objective magnification levels like 10 x to 20 x, it is impossible to acquire high resolution imaging in deep valleys on the surface due to the limitation of the working distance. As the magnification of the microscope objective gets higher, the field of view gets smaller (e.g. the field of view is for 10x to 20 x about one square millimeter, while approximately 150 µm x 150 µm for high objective magnification with 100 x (Leach, 2010)).

Depth resolution can be obtained from the repeatability of axial measurements and in a suitable environment optimally has a standard deviation of a few nanometers on smooth surfaces (Webinar, 2011).

Confocal chromatic probe instrument

A confocal chromatic probe instrument uses a non-color-corrected lens and a white light source dispersing light with different wavelengths focused at different distances from the objective onto the surface. By use of a spectrometer during the analysis of reflected lights, the confocal curve can be obtained. The spectrometer includes a prism or an optical grating and a CCD-line sensor. The design of the chromatic system allows a micrometer resolution in deep valleys with a working distance up to a few centimeters.

3.5. Calibration and Traceability of Surface Measurement Instruments

Calibration and traceability are the main issues affecting measurement accuracy for each kind of surface measurement instrument. There are several methods covering calibration and traceability published in the ISO standards. The traceability of a surface measurement instrument falls into two types as traceability of the instrument and the traceability of the analysis algorithms and parameter calculations. The first type of traceability deals with calibrating the axes of operation of the instrument and is achieved by using the calibration artifacts referred to in ISO standards. The traceability of the analysis algorithms and parameter calculation is accomplished by using a calibrated artifact with related parameters and this should be verified using required software measurement standards.

Uncertainties in Surface Measurement Instruments

The determination of uncertainties in surface texture measuring instruments is the most complex issue in this area due to the effect of the surface being measured. However, it is possible to calculate an instrument uncertainty in terms of profile (x, z) and areal (x, y, z) but it would obviously be increased if the effect of the surface were taken into account. It is also essential to consider the uncertainty of parameter calculation when calculating instrument uncertainty. In the case of the roughness parameter Ra, an uncertainty of 1% of the vertical calibration ends up with an uncertainty of 1% of the Ra value (Leach, 2010). Some characteristics of roughness measuring instruments have an obvious influence on the roughness parameter. However, uncertainty is unpredictable if the sample is measured with a probe diameter 5 µm or 10 µm instead of the standard 2 µm.

For many other examples, repeated measurement should be performed on a sample and the results should include the standard deviation or the standard deviation of mean, because it is not simple to calculate an uncertainty value of an instrument for all surfaces.

4. RESULTS AND DISCUSSION

4.1. Measurement Laboratory

The *experimental studies of this thesis were performed at the Measurement Room of Aydın Adnan Menderes University*.

4.1.1. Surface Measurement Instruments

In the experimental part of this thesis, inspection and assessment of surface roughness of various machined samples were done by using a roughness tester and an optical instrument. The contact instrument uses a stylus traversing the sample surface in order to assess the surface profile while the optical instrument utilizes a light beam for scanning the sample surface in order to acquire surface roughness data. As a result, measurement results for sample surfaces of separate chosen samples with different machining techniques will be analyzed and the possible reasons for differences in surface roughness from these two instruments will be discussed in the next chapter.

4.1.2. Measurement Results and Evaluation

In order to understand surface measurement, it is necessary to define roughness and waviness. Roughness is a deliberate, controllable element of component design produced by the action of the cutting tool or machining process while waviness is an undesirable machine tool effect resulting from vibration, lack of stiffness or other instabilities in the machining process. In this thesis, a decision was made to obtain surface roughness measurements of given samples by using mentioned measuring instruments and comparing the acquired values of commonly used roughness parameters, Ra and Rz. Rz is the sum of the largest profile peak height and largest profile valley depth within a sampling length and Ra is the arithmetic mean of the absolute values z(x) within a sampling length. Once again, the sampling lengths in measurements vary from 0.8 mm to 0.25 mm according to the geometrical form of the specimen being measured.

4.1.2.1. Evaluation of Roughness Measurement Results

4.1.2.2. Presentation of Roughness Measurement Process in iGrafx®2009

The roughness measurement process of this experimental study is presented by utilizing the professional process management software toolbox '*iGrafx*'. The aim here is modeling a flowchart of the measurement process in order to obtain the roughness result for a certain measurement point of a given sample. This designed model of the measurement process explains the following measurement characteristics:

Determination of the sample being measured

Choosing seventeen different samples with different geometrical forms, different contrasts – shiny and browned, different roughnesses, different machining techniques or different materials, such as aluminum or steel.

Preparation of surface measurement

- *As performed by Roughness Tester (Portable Surface Roughness Tester TR200)*

Defining the evaluation length and the sampling length as well as the required parameters like the measurement speed and measurement force; choosing the desired type of measurement – roughness or waviness; specifying the kind of filtering (Gaussian Filter) and adjusting the gauge height by using the knob on the vertical adjustment unit – the manufacturer "Portable Surface Roughness Tester TR200" recommending maintaining a value of ±30 µm.

- *As performed by NanoFocus µsurf explorer* (NanoFocus, 2011)

Placing the specimen to the in-focus position utilizing the image taken by the CCD camera on the display of µsurf explorer software through the mouse control of the instrument; specifying the necessary parameters such as the objective, the measurement area, Z Scanning parameters, the length of scan along the z-axis, the light source parameters and so forth.

Acquiring the surface roughness measurement

This transaction proceeds automatically once the measurement preparation was successfully completed.

Decision of 'OK'

Each instantaneous measurement results acquired from the different instruments are controlled by means of related ISO standards to proceed with the following transaction.

Surface roughness characterization

- *For the Portable Surface Roughness Tester TR200*

The software illustrates the roughness profile of the sample being measured. Each measurement result is exported into an external drive in .PDF format in order to serve as the measurement data for this thesis.

- *For the NanoFocus μsurf explorer* (Anonymous, 2018b).

The 3D texture parameters are exported to the analysis software '*MAP*' in order to obtain the 2D characterization. The required data are saved in Windows format for presenting measurement results in this thesis.

Comparison

Each 2D measurement parameter is listed on an Excel Worksheet as along with the calculation of the mean and the standard deviation of each measurement result for a given sample.

Evaluation and interpretation

This model of the measurement process also takes into consideration what resources are needed for acquiring this particular measurement and how long it takes.

iGrafx®2009 – Process Map (iGrafx, 2009)

By opening the program iGrafx, the '*Process*' must be chosen in order to create a flowchart. All of the necessary tools for creating this measurement process are located on the very left column of the screen (see Figure 4.1). This toolbar can be customized at any time by clicking the right mouse button and then the *Shape Library* option. In the example of this measurement process, there are two different departments – *Laboratory Work* and *Paperwork*. In order to do this, one must click the *Department Tool* from the toolbox. In the opened dialog box, a new department can be inserted or an existing can be renamed.

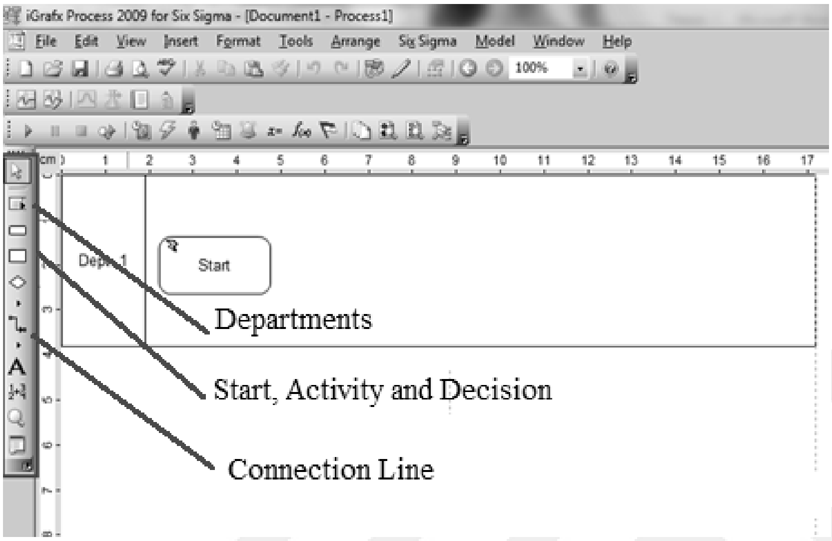


Figure 4.1 Display screen of a process map in iGrafx

The first rectangle shape with the round edges shows the *starting point* of the process. In this example, it is the choice of a sample and this takes place in both departments. In order to create a *cross-department activity*, the starting shape must be selected and the bottom of the shape must be dragged to expand the shape across all two departments while also pressing the Ctrl key. The diamond shape indicates a *decision*. This process chart includes two decision activities referring to the control of the measurement results obtained from contact and non-contact instruments.

By clicking the right mouse button on the decision shape and then the properties, the type of the activity can be determined in the dialog box (see Figure 4.2). In this case, it was defined as the decision (control of measurement results). The determination of ‘OK’ is given in a statistical form.

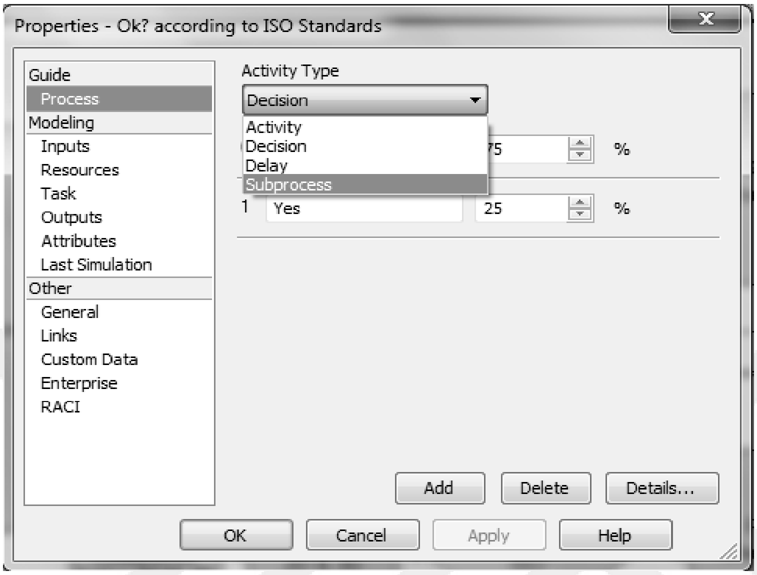


Figure 4.2 Properties dialog box of a decision

The principle here is that every activity occurring in this process must be connected with the others – each one has to have at least one input and one output, except for the last activity, which has only an input, appears as the end of the process. Each of transactions mentioned in the previous section were defined as an activity and connected with others by using the *connection line*.

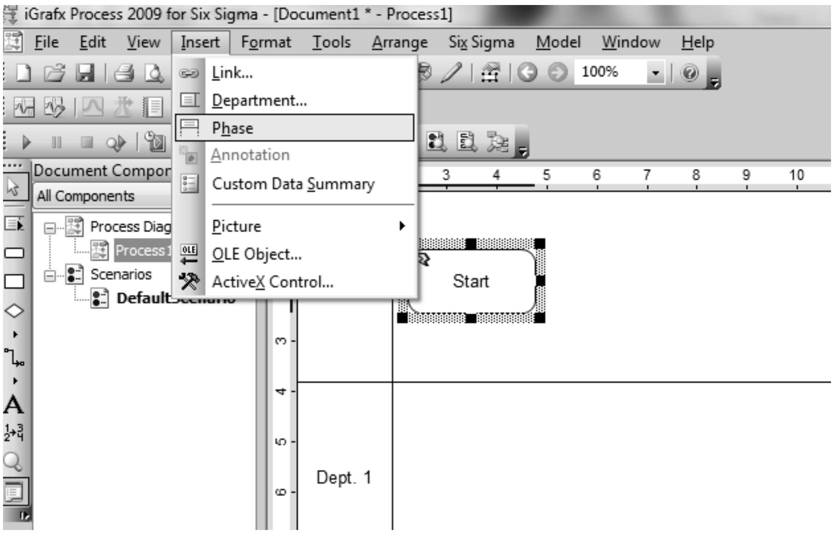


Figure 4.3 Insert menu in iGrafx

There are two phases defined in this example of the process map – *contact Instrument* and *Optical (non-contact) Instrument*. In order to do this, the *Insert* must be selected from the *Tools Menu* (see Figure 4.3). By clicking the *Format* and then the *Numbering* from the tools menu, the all of the symbol numbers can be defined and the number field can be changed as request.

The basic features for creating a process map in iGrafix are shown. There are more options by which the process map can be visually modified. Figure 4.4 depicts all of the activities that took place in the process of the roughness measurement.

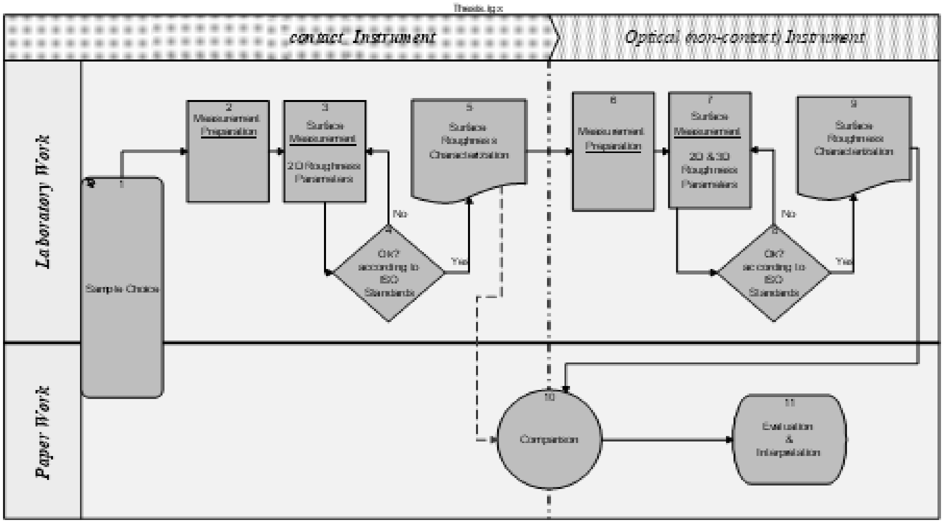


Figure 4.4 Process map for surface measurement performed at the Measurement Room of Aydın Adnan Menderes University

iGrafx®2009 – Simulation

The scenario in process map defines the simulation environment for the model. The simulation of this measurement process includes the resources being used and time duration for each activity. In this simulated example, there are three workers responsible for the laboratory work. The measurement activities that took place in the Measurement Room of Aydın Adnan Menderes University were executed by myself and two co-worker while this study was accomplished.

In this simulation, it refers to three different people responsible being for the performing this process. Table 4.1 depicts the parameters for each activity involved in this measurement process at a single point for a given sample.

Table 4.1 Parameters defined in the simulation of a measurement process

Nr.	Activity	Time Duration	Expression of "OK"	Resources (Workers)
1	Sample Choice	30-60 min	-	1
2	Measurement Preparation	5-10 min	-	2
3	Surface Measurement 2D Roughness Parameters	1-3 min	-	2
4	Decision of **"OK"**	5-10 min	75% "**No**" 25% "**Yes**"	1
5	Surface Roughness Characterization	10-17 min	-	2
6	Measurement Preparation ***NanoFocus µsurf explorer***	15-20 min	-	2
7	Surface Measurement 2D & 3D Roughness Parameters	2-4 min	-	2
8	Decision of **"OK"**	7-15 min	Decision of **"OK"**	1
9	Surface Roughness Characterization	20-28 min	-	2
10	Comparison	15-20 min	-	1
11	Evaluation & Interpretation	10-20 min	-	1

In order to run a simulation of the measurement process, the parameters for *decision*, *resources*, *time* and *generator* must be defined. In this case, the decision of "OK" was expressed in a statistical form in which the 75% of surface measurement results were rejected and measured again while the 25% of them proceeded to the next activity as an input.

By double-clicking on the diamond shape, the dialog box of *Properties* appears (see Figure 4.5). By clicking the *Outputs* page under the *Modeling* category, the decision can be chosen from the drop-down list. In order to define the percentages for **Yes**/**No**, for acceptance and rejection, the *statistical* option must be selected and the values of percentages must be given in the required box.

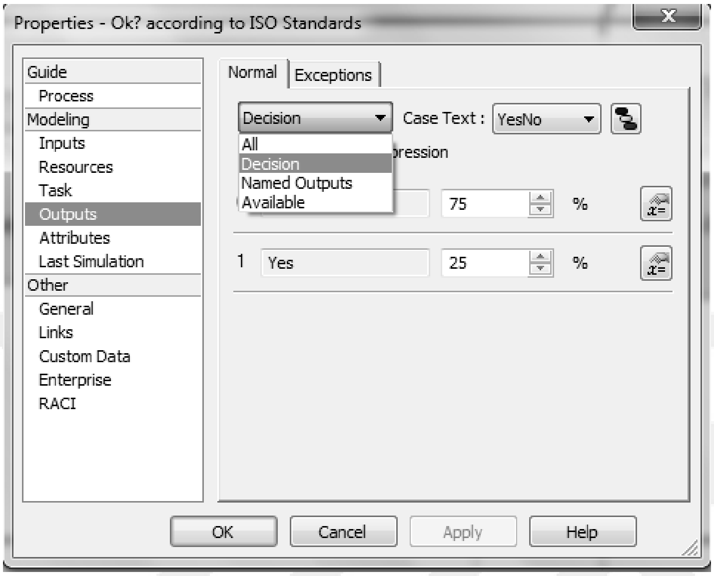


Figure 4.5 Defining parameters for decisions

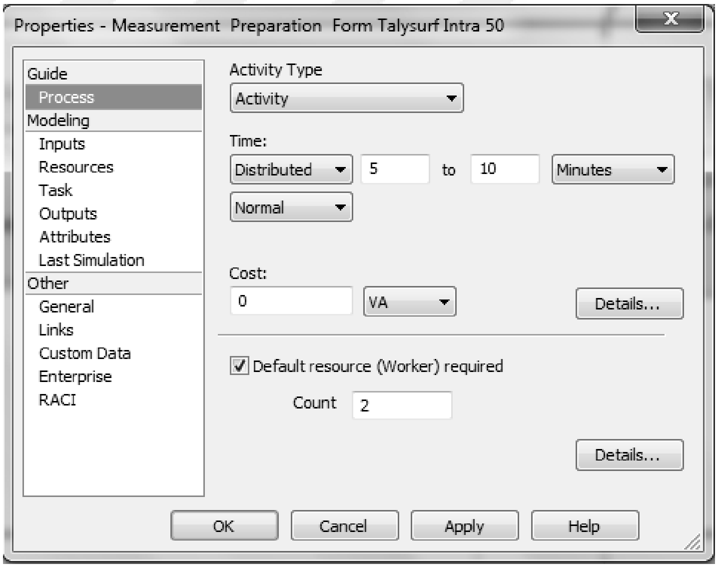


Figure 4.6 Defining the time of process and the workers responsible

The duration time of each activity must be defined (Figure 4.6). Once again in *Properties* dialog box, the *Process* page under *Guide* category must be selected from the menu (see Figure 4.7). As shown in Table 4.1, the time periods for each activity were entered in minutes. Due to differing times depending on the surface of the sample, values were given in a *distributed* form. Additionally, the workers executing the activity must be defined. In the same dialog box, the number of workers is given in the *Count* box.

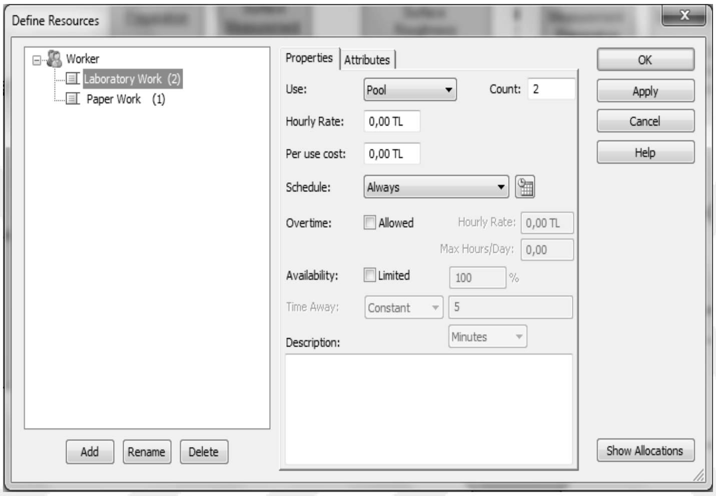


Figure 4.7 “Define Resources” dialog box

In order to define the resources (workers) for each department, the *Resource* option from *Model Menu* must be chosen. Two workers were defined in laboratory work and one was defined in paperwork. These workers were continually scheduled. The simulation of the measurement process includes a successful measurement of a single measurement point. Therefore, for the *generator* type the option *completion* must be selected and the count for each transaction must be one.

Once the *Start/Resume* button on the toolbox is clicked, the screen is changed automatically into the *Report* screen. The results obtained from the simulation can be arranged according to the demands and wishes of the user. The version that I prepared for this measurement process consists of three different statistics tables related to resource statistics, transaction statistics and activity statistics (see Table 4.2). The abbreviations for each term used in the table are given as follows.

Total Average Utilization (Tavg Util.) *:* Percentage of time the resource was in the schedule in which the resource was acquired.

Total Average Non-waiting Utilization (Tavg NW Util.): Percentage of time the resource was in the schedule and was not waiting for other resources to be acquired.

Average Busy Time (Avg. Busy) : Amount of time the resource was acquired.

Average Idle Time (Avg. Idle) : Amount of time the resource was in the schedule but not acquired.

Acquired Count (Acq. Count) : Number of times the resource was acquired.

Resource Count (Count) : Number of resources defined.

Count : Number of transactions that passed through activities and successfully completed during the simulation.

Average Cycle Time : Amount of time or simulated "wall-clock" time that transactions were in activities. This includes work and wait.

Average Work Time : Amount of time work was actively being performed on transactions. This was calculated from activity task duration times.

Average Service Time : Amount of time spent servicing transactions. This includes working and waiting time but not inactive time.

Table 4.2 Simulated statistics for the measurement process in iGrafx

Thesis1.igx

Resource Statistics (Hours)

	Tavg Util	Tavg NW Util	Avg Busy	Avg Idle	Acq Count	Count
Worker	59,54	59,54	1,71	1,16	18	3

Transaction Statistics (Hours)

	Count	Avg Cycle	Avg Work	Avg Serv
Paper Work	1	2,56	1,43	2,56
Laboratory Work	1	2,48	2,12	2,48

Activity Statistics (Minutes)

	Avg Cycle	Avg Work	Avg Serv	Count
Laboratory Work - 1 - Sample Choice	51,51	51,51	51,51	1
Laboratory Work - 2 - Measurement Preparation	6,85	6,85	6,85	1
Laboratory Work - 6 - Measurement Preparation	18,87	18,87	18,87	1
Laboratory Work - 3 - Surface Measurement 2D Roughness Parameters	2,01	2,01	2,01	1
Laboratory Work - 7 - Surface Measurement 2D & 3D Roughness Parameters	2,78	2,78	2,78	2
Laboratory Work - 4 - Ok ? according to ISO Standards	8,61	8,61	8,61	1
Laboratory Work - 8 - Ok ? according to ISO Standards	11,04	0,00	11,04	2
Laboratory Work - 5 - Surface Roughness Characterization	10,82	10,82	10,82	2
Laboratory Work - 9 - Surface Roughness Characterization	22,68	22,68	22,68	1
Paper Work - 1 - Sample Choice	51,51	51,51	51,51	1
Paper Work - 10 - Comparison	18,53	18,53	18,53	2
Paper Work - 11 - Evaluation & Interpretation	49,08	15,23	49,08	2

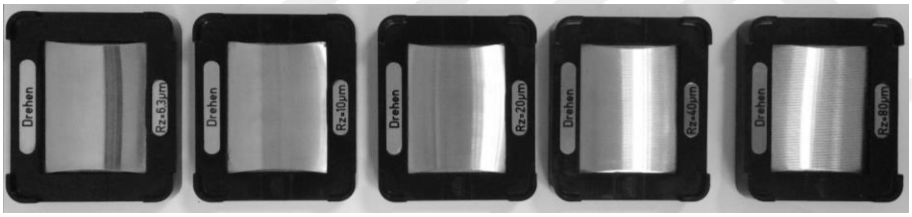
4.2. Roughness Measurement Results

The measurement and assessment processes of this research work were carried out in Aydın Adnan Menderes University, Mechanical Engineering Department, Measurement Laboratory. The experiments were done by preparing flat specimens. Ten flat samples with different machining processes (turning and milling), with periodic and random profiles of different roughness value classes were used in this study.

Measurements of Reference Samples by Roughness Tester

Milled steel sample having random surface profile was illustrated in Figure 4.8 and the technical drawing of one of the reference samples was shown in Figure 4.9. The results of these samples taken from the roughness tester (Figure 4.10) are given in the following tables (Tables 4.3 and 4.4).

(a)



(b)

Figure 4.8 Milling (a) and Turning (b) steel samples

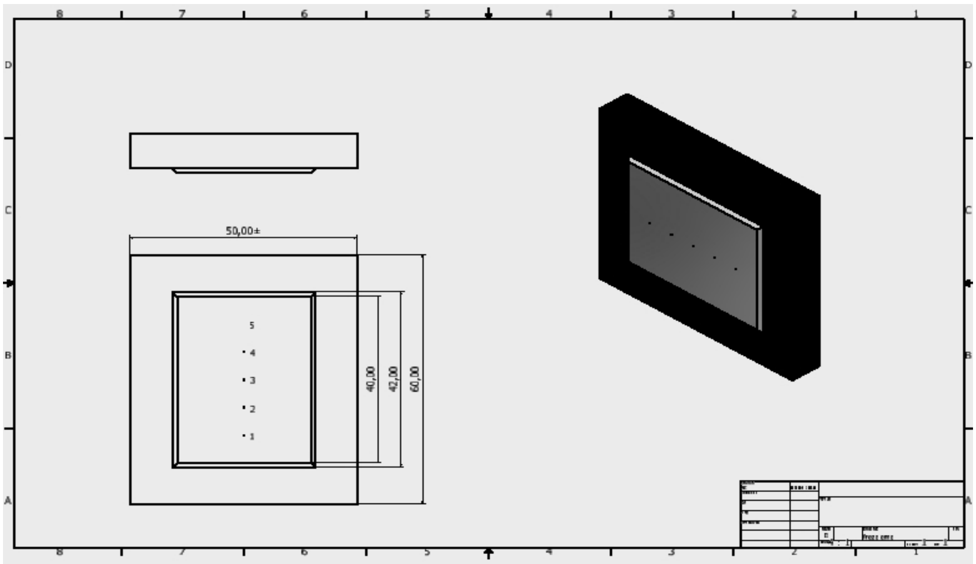


Figure 4.9 Technical drawing of one of the reference samples

Figure 4.10 Surface roughness tester

Table 4.3 Roughness measurement results by Roughness Tester (Turned Samples)

Ra	1.3	6.5	2.2	9.8	5.4	20	10	41	20	78
	Ra=1.3\Rz=6 .5		**Ra=2.2\Rz=9.8**		**Ra=5.4\Rz=20**		**Ra=10\Rz=41**		**Ra=20\Rz=78**	
	Ra	*Rz*	*Ra*	*Rz*	*Ra*	*Rz*	*Ra*	*Rz*	*Ra*	*Rz*
1	1.387	4.141	2.630	11.500	4.450	16.100	8.700	40.700	17.200	70.200
2	1.763	4.971	2.560	11.500	4.520	16.400	9.230	40.700	16.100	70.900
3	0.907	5.184	2.580	11.400	4.730	17.100	8.700	39.500	15.830	70.700
4	0.702	6.102	2.520	11.200	4.780	17.000	7.360	41.200	15.300	67.900
5	1.024	6.751	2.440	11.800	4.770	17.800	8.490	38.700	18.300	70.200
Std Dev	0.421	1.016	0.071	0.217	0.154	0.661	0.691	1.029	1.201	1.203

Table 4.4 Roughness measurement results by Roughness Tester (Milled Samples)

Ra	0.89	6.5	2.1	11	4.8	20	9.8	41	18	78
	Ra=0.89\Rz=6.5		**Ra=2.1\Rz=11**		**Ra=4.8\Rz=20**		**Ra=9.8\Rz=41**		**Ra=18\Rz=78**	
	Ra	*Rz*	*Ra*	*Rz*	*Ra*	*Rz*	*Ra*	*Rz*	*Ra*	*Rz*
1	0.898	5.230	2.190	10.300	4.900	19.000	8.010	38.700	10.700	74.000
2	0.843	5.040	2.130	10.700	5.000	18.800	8.450	38.900	10.600	74.300
3	0.891	5.080	2.160	9.080	5.310	19.500	8.130	39.300	10.700	73.900
4	0.811	4.990	2.170	10.100	5.010	19.100	8.620	40.500	10.900	75.500
5	0.872	4.800	2.060	9.930	4.940	19.000	8.030	38.800	10.600	74.200
Std Dev	0.036	0.156	0.051	0.600	0.162	0.259	0.273	0.740	0.122	0.646

Measurements of Reference Samples by NanoFocus µsurf explorer

Five consecutive measurements were performed for milled and turned steel samples, respectively. The results of these samples taken from NanoFocus µsurf explorer (Figure 4.11) are given in the following tables (Tables 4.5 and 4.6). Figure 4.12 indicates 2D topography and roughness parameters, Figure 4.13 shows a 3D topography and Figure 4.14 presents the roughness profile taken from NanoFocus µsurf explorer.

Table 4.5 Roughness measurement results by Optical Instrument (Turned Samples)

Ra	1.3	6.5	2.2	9.8	5.4	20	10	41	20	78
	Ra=1.3\Rz=6 .5		**Ra=2.2\Rz=9.8**		**Ra=5.4\Rz=20**		**Ra=10\Rz=41**		**Ra=20\Rz=78**	
	Ra	*Rz*	*Ra*	*Rz*	*Ra*	*Rz*	*Ra*	*Rz*	*Ra*	*Rz*
1	1.297	6.410	2.213	9.910	5.445	20.110	10.171	40.970	19.620	78.120
2	1.363	6.710	2.256	9.880	5.510	20.240	10.030	40.550	19.810	77.950
3	1.257	6.840	2.258	9.880	5.412	20.210	9.997	41.150	20.130	78.750
4	1.322	6.520	2.252	10.120	5.378	20,01	10.096	41.200	20.300	78.870
5	1.324	6.510	2.244	10.180	5.477	20.180	10.290	40.870	19.940	78.110
Std Dev	0.039	0.173	0.018	0.144	0.052	0.056	0.118	0.259	0.266	0.418

Table 4.6 Roughness measurement results by NanoFocus µsurf Explorer (Milled Samples)

Ra	0.89	6.5	2.1	11	4.8	20	9.8	41	18	78
	Ra=0.89\Rz=6.5		**Ra=2.1\Rz=11**		**Ra=4.8\Rz=20**		**Ra=9.8\Rz=41**		**Ra=18\Rz=78**	
	Ra	*Rz*	*Ra*	*Rz*	*Ra*	*Rz*	*Ra*	*Rz*	*Ra*	*Rz*
1	0.899	6.430	2.190	10.990	4.990	19.900	9.710	40.700	17.870	77.960
2	0.893	6.440	2.180	10.798	4.890	18.800	9.850	40.900	17.760	77.790
3	0.891	6.480	2.185	11.080	4.981	19.890	9.830	40.400	17.790	77.990
4	0.891	6.490	2.210	11.001	5.010	19.100	9.720	40.500	17.900	78.090
5	0.892	6.500	2.215	10.980	4.899	20.000	9.630	40.800	17.860	78.110
Std Dev	0.003	0.031	0.016	0.104	0.055	0.088	0.091	0.207	0.059	0.128

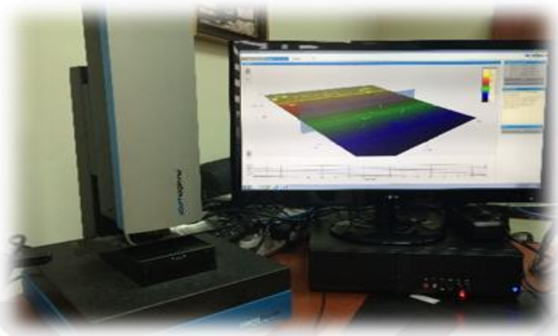
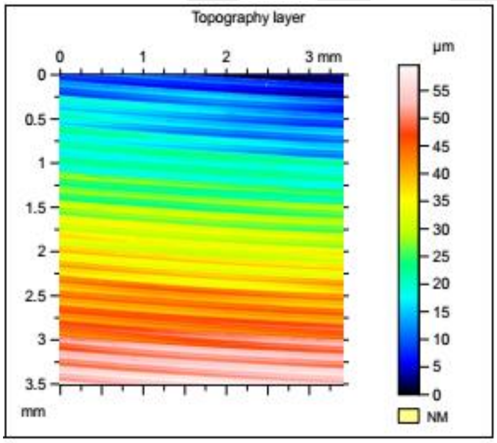


Figure 4.11 NanoFocus µsurf explorer



ISO 25178		
Height Parameters		
Sa	12.1	µm
Sq	14.2	µm
Sp	28.9	µm
Sv	30.7	µm
Sz	59.6	µm

ISO 4287			
Amplitude parameters - Roughness profile			
Ra	2.19	µm	Gaussian filter, 0.8 mm
Rq	2.53	µm	Gaussian filter, 0.8 mm
Rp	5.12	µm	Gaussian filter, 0.8 mm
Rv	5.14	µm	Gaussian filter, 0.8 mm
Rz	10.3	µm	Gaussian filter, 0.8 mm
Rc	7.48	µm	Gaussian filter, 0.8 mm

Figure 4.12 2D Topography and Roughness Parameters from NanoFocus µsurf explorer

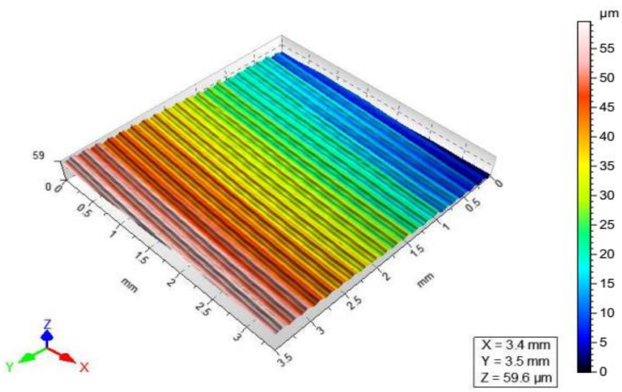


Figure 4.13 3D Topography

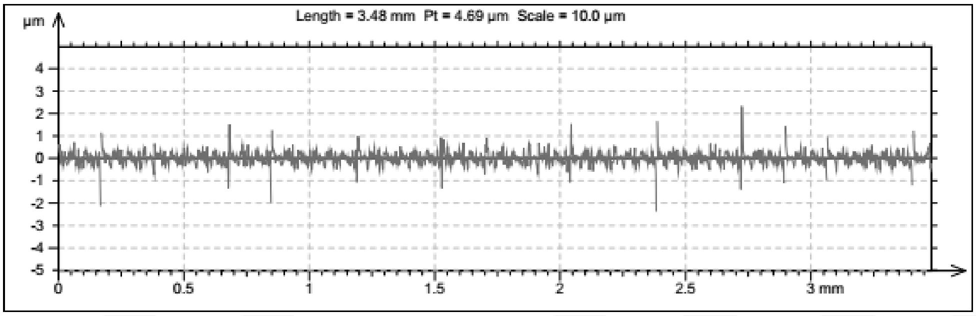


Figure 4.14 Roughness Profile

4.3. Interpretation of Measurement Results

In order to compare the surface roughness measurements performed on various given samples, the measurement results obtained by using the contact tester were less accurate than those by optical instruments. First of all, it should be made clear that periodicity and manufacturing process play an important role in surface measurements. Before everything else, correctly deciding upon an appropriate filter with regard to the surface measurement type helps in obtaining accurate measurement results. In order to obtain a roughness profile for a surface being measured, a high-pass filter with a cut-off λc must be applied to the primary profile. In practice, the primary profile is derived from the total profile by applying a low-pass filter with λs in order to reduce the effect of vibration and measurement noise naturally introduced by the instrument during the measurement. Therefore, deciding on the cut-off λc is the key point in the filtration of the surface profile roughness measurement. As mentioned earlier, if there is no specification given in the technical drawing, ISO 4287 and 4288 recommend using a value of 0.8 mm for Gaussian filtration. The remaining two other filters for a stylus tip radius of 2 µm have cut-offs of 0.25 mm and 0.08 mm respectively (see Table 3.1). From understanding the limitations of the roughness tester, the sampling length (i.e. cut-off of the Gaussian filter) is taken as being 0.25 µm on the surfaces within this thesis. The reason here is that when applying this filter the measurement results were relatively closer to the range defined in ISO 4288 rather than the ones obtained by applying a filter with a cut-off of 0.08 mm.

Once the measurement results of periodic surfaces (turned surfaces) are seen, this shape limitation of the roughness tester is obviously recognizable from Rz values. Rz values obtained from two different instruments correspond less than the ones from random surfaces (milled surfaces). On periodic surfaces, there are relatively extreme high peaks and deep valleys on surfaces compared to random surfaces. As Rz is the sum of the highest peak and the deepest valley within a sampling length, this limits stylus penetration and affects the degree of match of the measurement results obtained by these two measuring instruments as a result.

The reference samples machined with different production techniques but which have the same steel material, the measurement results show relatively better matching. As a result, it could be said that the surface profile roughness measurements obtained by using two different types of measuring instruments on these reference surfaces with different machining techniques show quite good matching. Nevertheless, there are some effects, which might lead to different measurement results, such as the relocation of a measurement point of a sample upon the measurement with two different measuring instruments, dynamic and environmental effects, effects owing to the analysis of algorithms and parameter calculation as well as, different calibrations of the measuring instrument.

As a result, it should be noted that none of these measurement results for these measuring instruments are wrong. First of all, at this point these two instruments employ different operating principles. A tester acts like a ball touching a surface while an optical instrument benefits from the reflection of an electromagnetic wave of LED light beams delivered to the surface. Nevertheless, it is possible to get more precise measurement results from using an optical instrument as opposed to a roughness tester.

5. CONCLUSIONS

One of the most important parameters for determining the surface characterization of precise reference workpieces is roughness. Here, roughness expresses the fine irregularities of a surface that occur with the action of the cutting tool or the machining process. In surface metrology, the measuring instruments for acquiring surface roughness measurement fall into two types. In this thesis, examples of each type of measuring instrument are examined with regard to the surface roughness profile parameters on varying surfaces in order to understand the capability of these measuring instruments.

Both measuring instruments have limitations in practice. Penetration of the styli in all of peaks and valleys of the surface is the major point in surface measurement since it collects data by traversing the surface. Due to its finite shape, it is not always possible to obtain measurement data from some points being measured in the surface. On the other hand, numerical aperture (NA), which is the largest slope angle that can be measured and affects optical resolution, as well as the working distance of the microscope objective are the main limitation for the optical instruments.

From understanding the limitations of the roughness tester, the sampling length (i.e. cut-off of the Gaussian filter) is taken as being 0.25 µm on the surfaces within this thesis. The reason here is that when applying this filter the measurement results were relatively closer to the range defined in ISO 4288 rather than the ones obtained by applying a filter with a cut-off of 0.08 mm. Despite of keeping the filter cut-off and type in order to acquire the roughness profile parameters, the optical instrument proceeds with the roughness profile of the surface from 3D measurement data. At this point, the confocal microscope, which was the optical instrument for this thesis, extracts the profile parameter from the SL surface. Here, the SL surface is equivalent to roughness and is acquired by using an L-filter (removes the large-scale components) on an SF surface. The SF surface (equivalent to primary surface) is obtained by applying an S-filter (removes small-scale lateral components on the surface such as irrelevant small features or ones caused by measurement noise) and an F-operator (removes nominal form).

The instruments used in this experimental practice are a roughness tester, which is a contact instrument, and a confocal microscope, a non-contact and optical instrument. Ten different samples make it possible to examine the different types of measurement instruments in terms of surfaces with differing forms and machining techniques.

The both instruments show a good degree of similarity (0.1-3% in standard deviations) in the measurement results on these reference samples with random surface lays. The deviations of the mean values of the measurement results acquired by the different instruments are in the sub-micrometer range and relatively small with respect to Ra distribution. However, this similarity in measurement results does not occur for periodic flat surfaces. Different materials and feed rates (i.e. roughness) negatively affect the consistency of the measurement results. This category of sample distinguishes the stylus penetration ability where the measurement force is an effect.

There are additional common reasons for all of these surfaces being measured for getting differing measurement results performed by using different measuring instruments such as relocation of same measurement points upon the measurement, analyzing algorithms, calculating parameters, as well as dynamic and environmental effects. The measurements in this thesis make it possible to understand the advantage of the optical (confocal microscope) instrument on a conventional measuring instrument. Furthermore, as the publication of the standards for areal surface characterization is completed within metrology, 3D parameters and measuring instruments will completely take the place of conventional 2D methods which fill in the gaps of these measurement parameters by providing information on functionality and determining the exact nature of the topographical features of the surface.

REFERENCES

Anonymous. 2018a. http://www.efunda.com/designstandards/gdt/introduction.cfm, Last accessed in May 2018.

Anonymous. 2018b. http://www.nanofocus.com/products/usurf/usurf-explorer/, Last accessed in May 2018.

Anonymous. 2011. https://www.taylor-hobson.com/-/media/ametektaylorhobson/files/learning%20zone/exploring%20surface%20texture%202014.pdf?la=en, Last accessed in May 2018.

Bogrekci, I., Demircioglu, P. 2017. Evaluation of Surface Finish Quality Using Computer Vision Techniques. In: Hashmi, M.S.J. (ed.), Reference Module in Materials Science and Materials Engineering, from Comprehensive Materials Finishing, vol. 3, pp. 261–275. Oxford: Elsevier, UK.

Demircioglu, P., Bogrekci, I., Durakbasa, M.N. 2013. Micro Scale Surface Texture Characterization of Technical Structures by Computer Vision. **Journal of the International Measurement Confederation**, 46:6.

Demircioglu, P. 2017. Topological Evaluation of Surfaces in Relation to Surface Finish. In: Hashmi, M.S.J. (ed.), Reference Module in Materials Science and Materials Engineering, from Comprehensive Materials Finishing, vol. 3, pp. 243–260. Oxford: Elsevier, UK.

Durakbasa, M.N. 2003. Geometrical Product Specifications and Verification for the Analytical Description of Technical and Non-technical structures, ISBN 3-901888-26-8, Austria.

Durakbasa, M.N., Osanna, P.H., Aksoy, P., Kraeuter L. 2009. Contact and Non-contact Measurement and Analysis of the Surface of High Precision Workpieces, In Proceedings of the **12th International Conference on Metrology and Properties of Engineering Surfaces**, Poland.

Hornyak, G.L., Moore, J.J., Tibbals, H.F., Dutta, J. 2009. Fundamentals of Nanotechnology, ISBN 978-1-4200-4779-0, USA.

ISO VIM. 2004. International Vocabulary of Basic and General Terms in Metrology (International Organization of Standardization).

ISO/TR 14638. 1995: Geometrical Product Specification (GPS) – Masterplan (International Organization of Standardization).

ISO 1101. 2004. Geometrical Product Specification (GPS) – Geometrical Tolerancing- Tolerancing of Form, Orientation, Location and Run-out (International Organization of Standardization).

ISO 4287. 2009. Geometrical Product Specifications (GPS) – Surface Texture: Profile Method - Terms, Definitions and Surface Texture Parameters (International Organization of Standardization).

ISO 11562. 1996. Geometrical Product Specifications (GPS) –Surface Texture: Profile Method - Metrological Characteristics of Phase Correct Filters (International Organization of Standardization).

ISO 4288. 1996. Geometrical Product Specifications (GPS) – Surface Texture: Profile Method - Rules and Procedures for the Assessment of Surface Texture (International Organization of Standardization).

ISO/DIS 25178-3. 2009. Geometrical Product Specifications (GPS) – Surface Texture: Areal - Part 3; Specification Operators (ISO).

ISO/DIS 25178-2. 2008. Geometrical Product Specifications (GPS) – Surface Texture: Areal - Part 2; Terms, Definitions, Surface Texture Parameters (International Organization of Standardization).

ISO 3274. 1996. Geometrical Product Specifications (GPS) – Surface Texture: Profile Method- Nominal Characteristics of Non-contact (stylus) Instruments (International Organization of Standardization).

ISO 25178-602. 2010. Geometrical Product Specifications (GPS) – Surface Texture: Areal - Part 602; Nominal Characteristics of Non-contact (Confocal Chromatic Probe) Instruments (International Organization of Standardization).

ISO/DIS 25178-605. 2011. Geometrical Product Specifications (GPS) –Surface Texture: Areal - Part 605; Nominal Characteristics of Non-contact (Point Autofocus Probe) Instruments (International Organization of Standardization).

ISO/DIS 25178-604. 2010. Geometrical Product Specifications (GPS) –Surface Texture: Areal - Part 604; Nominal Characteristics of Non-contact (Coherence Scanning Interferometry) Instruments (International Organization of Standardization).

ISO 5436-1. 2000. Geometrical Product Specifications (GPS) – Surface Texture: Profile Method - Measurement Standards- Part 1; Material Measures (International Organization of Standardization).

ISO 25178-701. 2010. Geometrical Product Specifications (GPS) – Surface Texture: Areal - Part 701; Calibration and Measurement Standards for Contact (Stylus) Instruments (International Organization of Standardization).

iGrafx®2009 Tutorials.

Leach, R.K. 2010. Fundamental of Principles of Engineering Nanometrology, ISBN 978-0-008-096454-6, USA.

NanoFocus. 2011. Manual version 3.2, Germany.

Oprean, C., Gruenwald, N., Kifor, C.V. 2009. Entrepreneurship: a sustainable and transferable attribute of essential value to personal and professional development of engineering and business graduates. Conference Proceedings Volume 1, Balkan Region Conference on Engineering and Business Education and International Conference on Engineering and Business Education Conference proceedings, ISBN 978-973-739-848-2, Romania.

Osanna, P.H., Durakbasa, N.M. Kraeuter, L. 2006. Development in Technology, Sustainability and Medical Engineering on the Basis of Precision and Nanometrology, the 1st Korean-Austrian Automation Day, Korea.

Osanna, P.H. 1982. Deviations in Form and Workpiece Accuracy, Austria.

Osanna, P.H., Durakbasa, M.N., Sadat, A.A. 2005. Measurement of Geometrical Properties, Measurement in Technology Vol.2, Austria.

Osanna, P.H., Durakbasa, M.N., Sadat, A.A. 2005. Geometrische Produkt-Spezifikation und - Verifikation-GPS, Austria.

Sadat, A.A. 2005. Nanotechnology and Nanometrology in Modern Production, In Proceedings of the **4th International Congress on Precision Machining**, Poland.

Stepnova, M., Dew, S. 2012. Nano-fabrication, ISBN 978-3-7091-0423-1, Austria.

Taniguchi, N. 1974. On the Basic Concept of Nanotechnology. In Proceedings of the **International Conference on Production Engineering**, pp.18-23, Tokyo.

Trumpold, H. 1990. Bedeutung der Gestaltabweichungen aus funktioneller und fertigungstechnischer Sicht, Germany.

Webinar: 2011. Applications of Confocal Microscopy and Interferometry in Surface Metrology and Inspection", USA. https://asminternational.webex.com/cmp0306ld/webcomponents/jsp/docshow/closewindow.jsp/webinar), Last accessed in May 2018.

Whitehouse, D.J. 2002. Surface and Their Measurement, Hermes Penton Science, ISBN 1-9039-9660-0, UK.

Whitehouse, D.J. 2003. Handbook of Surface and Nanometrology, ISBN 0-7503-0583-5, UK.

RESUME

Personal Information

Name Surname	: Bilginer GÜNDÜZ
Place and Date of Birth	: Aydın - 1987

Education

Undergraduate	: Anadolu University Metallurgical and Materials Eng
Post Graduate	: Aydın Adnan Menderes University
Foreign Languages	: English (Advanced)

Contact

E-mail	: bilginergunduz@gmail.com
Date	: 12/07/2018