Master Thesis

Master's Programme in Mechanical Engineering, 60 credits

Qualitative and quantitative study of existing surface parameters and their correlation to CWS parameters in Automobile Industry

Surface texture parametric study of CWS

Master thesis, 15 credits

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PREFACE

This report is based on the final thesis to be submitted as a part of a one-year Master’s in Mechanical Engineering at Halmstad University. The thesis is accompanied at QISAB, QSO Interferometer systems AB.

We would like to thank our industrial supervisor Prof. Lars Bååth for choosing us to do this thesis, also for his valuable time and support throughout the thesis. We would also like to thank our university supervisor Dr. Sabina Rebeggiani for her guidance as well sharing her knowledge in all the academic aspects and moral support throughout the thesis. Without their support and guidance this thesis wouldn’t have been successful.

For the theoretical support we used few sketches from 2 books, few articles and a website. We would like to thank Prof. David Whitehouse, David W. Hahn, François Blateyron and Richard Leach that we had used their books and article for the theoretical support. We would like to thank Keyence Corporation for providing the information regarding the surface roughness theories that we had used some sketches and information from there.

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ABSTRACT

Surface roughness is an important parameter in the automotive Industry. This thesis is a study conducted in collaboration with QSO Interferometer systems AB (QSAB), Halmstad. The study is focused on the existing surface roughness parameters used in the automotive industry and the relationship to the CWS parameters of QISAB. The study also investigates the scope of CWS instrument developed by QISAB as a next generation automated surface testing inline instrument. The initial study which has been conducted had 5 stages, those are the history of roughness measurement, the basic CWS parameters, the currently used surface testing instruments in the automobile industry, the use of surface metrology in the manufacturing industry and the basic principle and theory of the CWS. As the final stage to achieve the aim of the thesis a quantitative study has been conducted to compare the existing parameters with CWS parameters. The three type of comparison were done on a test piece having different range of surface roughness after different stages of grinding. These three comparisons that had been done were CWS v/s White light interferometer v/s visual inspection. The results from those quantitative analysis did support the results from the qualitative analysis.
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Terminology

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<tbody>
<tr>
<td>QISAB</td>
<td>QSO Interferometer systems AB</td>
</tr>
<tr>
<td>CWS</td>
<td>Coherent Wave Scattering</td>
</tr>
<tr>
<td>CLA</td>
<td>Central Line Average</td>
</tr>
<tr>
<td>Ra</td>
<td>Roughness Average</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>-------------</td>
</tr>
<tr>
<td>OEM</td>
<td>Original Equipment Manufacturer</td>
</tr>
<tr>
<td>ISO</td>
<td>International Standard Organization</td>
</tr>
<tr>
<td>CAD</td>
<td>Computer Aided Design</td>
</tr>
<tr>
<td>Sq</td>
<td>Areal/ Surface Root Mean Square</td>
</tr>
<tr>
<td>R</td>
<td>Roughness</td>
</tr>
<tr>
<td>P</td>
<td>Primary Profile Obtained</td>
</tr>
<tr>
<td>W</td>
<td>Waviness profile</td>
</tr>
<tr>
<td>T</td>
<td>Type of profile</td>
</tr>
<tr>
<td>N</td>
<td>Number of cut-offs or the sampling length</td>
</tr>
<tr>
<td>l_r</td>
<td>The sampling length</td>
</tr>
<tr>
<td>Rq</td>
<td>Root mean Square Deviation for the roughness profile</td>
</tr>
<tr>
<td>Wa</td>
<td>Arithmetic mean waviness for the waviness profile</td>
</tr>
<tr>
<td>Wq</td>
<td>Root-mean-square deviation waviness for the waviness profile</td>
</tr>
<tr>
<td>Wv</td>
<td>Maximum profile valley depth for the wave profile</td>
</tr>
<tr>
<td>Wp</td>
<td>Maximum profile peak height for a wave profile</td>
</tr>
<tr>
<td>Wt</td>
<td>Total height for waviness profile</td>
</tr>
<tr>
<td>Pa</td>
<td>Arithmetic mean waviness for the primary Profile</td>
</tr>
<tr>
<td>Pq</td>
<td>Root mean square deviation for the primary profile</td>
</tr>
<tr>
<td>Pv</td>
<td>Maximum profile valley depth for the primary profile</td>
</tr>
<tr>
<td>Pp</td>
<td>Maximum profile height for the primary profile</td>
</tr>
<tr>
<td>Pt</td>
<td>Total height of the primary profile (max peak to max valley)</td>
</tr>
<tr>
<td>Rv</td>
<td>Maximum profile valley depth of roughness profile</td>
</tr>
<tr>
<td>Rp</td>
<td>Maximum profile height for the roughness profile</td>
</tr>
<tr>
<td>Rt</td>
<td>Total profile height for the roughness profile</td>
</tr>
<tr>
<td>Rz</td>
<td>The average maximum peak to valley of five consecutive sampling lengths</td>
</tr>
<tr>
<td>Rz (JIS)</td>
<td>the average maximum peak to valley of five consecutive sampling lengths as per JIS</td>
</tr>
<tr>
<td>R_{ti}</td>
<td>Highest – lowest point from mean line</td>
</tr>
<tr>
<td>R_{max}</td>
<td>Maximum roughness depth</td>
</tr>
<tr>
<td>JIS</td>
<td>Japanese’s Industrial Standard</td>
</tr>
<tr>
<td>Zp</td>
<td>Largest profile peak height</td>
</tr>
<tr>
<td>Zv</td>
<td>Largest profile Valley Depth</td>
</tr>
<tr>
<td>R_{sm}</td>
<td>The mean spacing of the Roughness profile</td>
</tr>
<tr>
<td>W_{sm}</td>
<td>The mean spacing of the Waviness profile</td>
</tr>
<tr>
<td>P_{sm}</td>
<td>The mean spacing of the primary profile</td>
</tr>
<tr>
<td>P_{c}</td>
<td>Peak count</td>
</tr>
<tr>
<td>S_{td}</td>
<td>The texture direction of a scale limited surface</td>
</tr>
<tr>
<td>( R_{\lambda q} )</td>
<td>Average wavelength of roughness</td>
</tr>
<tr>
<td>R_{sk}</td>
<td>Skewness of roughness</td>
</tr>
<tr>
<td>R_{ku}</td>
<td>Kurtosis of roughness</td>
</tr>
<tr>
<td>S</td>
<td>Areal parameter</td>
</tr>
<tr>
<td>Sa</td>
<td>Areal Roughness Average</td>
</tr>
<tr>
<td>Sq</td>
<td>Areal Root Mean Square</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
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<tr>
<td>--------</td>
<td>--------------------------</td>
</tr>
<tr>
<td>Ssk</td>
<td>Areal Surface Skewness</td>
</tr>
<tr>
<td>Sz</td>
<td>Areal maximum height</td>
</tr>
<tr>
<td>Sku</td>
<td>Areal Surface Kurtosis</td>
</tr>
<tr>
<td>Sp</td>
<td>Maximum areal peak height</td>
</tr>
<tr>
<td>Sv</td>
<td>Maximum areal pit height</td>
</tr>
<tr>
<td>Str</td>
<td>Texture aspect ratio</td>
</tr>
<tr>
<td>CCD</td>
<td>Charge Couple Device</td>
</tr>
<tr>
<td>EM</td>
<td>Electromagnetic</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Phase Error Angle</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Standard deviation of the phase error</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Standard deviation of heights</td>
</tr>
<tr>
<td>$\varepsilon_{MB}$</td>
<td>Main lobe efficiency</td>
</tr>
<tr>
<td>$V_0$</td>
<td>Initial Voltage</td>
</tr>
<tr>
<td>$V_{scatter}$</td>
<td>Scattered Amplitude in voltage</td>
</tr>
<tr>
<td>$R_{q,eq}$</td>
<td>Root mean square equivalent in CWS</td>
</tr>
<tr>
<td>Rint</td>
<td>Roughness above 500nm</td>
</tr>
<tr>
<td>dB</td>
<td>Decibel</td>
</tr>
<tr>
<td>$\mu$m</td>
<td>Micrometer</td>
</tr>
<tr>
<td>nm</td>
<td>Nanometer</td>
</tr>
<tr>
<td>WLI</td>
<td>White light interferometer</td>
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</tbody>
</table>
1. INTRODUCTION

In the fast-growing automotive industry, surface roughness plays an important role (Mathew, et al., 2018). E.g. surface parameters decide the action due to friction on the recognized surface quality and adhesion. The right friction on the surface is important for efficient working of parts. This is being achieved by different machining operations at different production stages and by inspecting them using the right measurement techniques/instruments (Lee, et al., 2015). The surface of the earth looks round when viewed at a distance but while looking closer it looks completely different; it consists of mountains, valleys and plains. Similarly, any surface that looks perfectly plain would have irregularities when analyzing at microscopic level. (Liam & Xiangqian, 2003).

During the designing of a product a designer assumes the surface to be perfectly smooth, the so called nominal surface. It is impossible to make as per drawing without any micro scale fingerprint caused by the manufacturing process; this nature of surface having "fingerprint" is referred to as the surface texture or surface topography of the component. The type of manufacturing and machining process directly affect the surface texture of the component. A surface texture is commonly made up of structures defined as roughness, waviness and form (Liam & Xiangqian, 2003).

There are many instruments that measures the form of a surface at really fast pace, what is missing is something that measures the surface irregularities/characteristics at a fast pace like in a production line. QISAB has come up with a solution with their instrument called CWS 640. But to become successful on the market they wanted to correlate their parameters with the existing instruments that measure similar parameters in the automobile industry. This thesis aims to evaluate this issue.

1.1. Background

Initially assessment of surface finish was made just by running a fingernail across the surface. The “light section microscope” was the first ‘quantitative’ measuring instrument (Liam & Xiangqian, 2003). Later a simple profilometer was developed by Professor Schmalz to permit the deviations on a certain line of a surface to be measured and documented (Bernardin, 1996). This was a process by which a simple stylus was drawn across a surface, while recording the vertical deviations of the surface. This will be magnified and recorded in photosensitive paper and will be then presented on a circular arc, so that the screen can be rotated while the stylus moves over the surface. The roughness can be measured by evaluating the peaks to valleys distance and making the less average of the five highest peaks and the five lowest valleys (Liam & Xiangqian, 2003).

The first electronic surface profile instrument was produced by the British company Taylor & Hobson in 1941. In this instrument the “central line average” (CLA) could be calculated using computers and it became popular in the industrial world (Dagnall, 1996). This CLA become the first standard that was accepted by all companies in the world. Now this CLA is termed the average roughness Ra (Liam
Since then surface roughness Ra became a widely used and acceptable parameter in the industrial world and still it is used in different ways in modern instruments by digital processing. The studies regarding surface characteristics were started in the academic communities by the end of 1960s. Some of the researches were regarding the system digitalizing by using mainframe computers. Here computers compute the surface parameters by analyzing and converting the electrical output from the Profilometers (Whitehouse, 1996). During this time as per the trend most of the countries which were involved in manufacturing had used various roughness parameters independently or all together, but all these had some limitations. By the end of 1970s mechanical devices supported by digital electrical computer had replaced the analogue instruments and these innovation lead to a dramatically increase of scope of surface roughness over the engineering world, both in industry and academic research. During 1980s almost one hundred numerical parameters were developed due to the fast development and the use of computers. These parameters were added in many national standards but most of these were poorly defined and had limited usage (Whitehouse, 1981).

The research with the 3-dimensional surface characteristics of surface was started in the early 1980s. This lead to the arranging, investing and organizing programs to define the three-dimensional parameters and related filters. During this period in an aim to increase the performance of their product in automotive industry, many companies had developed their own parameters. These developments became a land mark for surface measurements in the industrial world and from then on, 3D measurement systems catch attention from the industries to the academic research. The first prototype for the commercial software package and the comprehensive range of surface visualization techniques with hardware system was developed by a group at Coventry. In the beginning of the 1990s using the OEM software package developed by Coventry was a 3D stylus instrument which was released by Rank Taylor Hobson (Bergstrom, et al., 2010).

Within the last three decades there has been an elevated need to relay from surface texture to surface function. A profile measurement provides few functional parameters regarding a surface. To determine functional information the whole work piece need to be measured rather than taking few line measurement across the workpiece nor few micron level areal measurements at different points on a workpiece. (Bååth, 2015).

### 1.1.1. Presentation of the client

QISAB, Interferometer Systems AB, is a Swedish ground-breaking company based in Halmstad, Sweden. It is a derivative from the research of professor Lars Bååth and professor Bengt-Göran Rosén at Halmstad University in 2013. The company product, the CWS (Coherent wave scattering instrument), is entirely developed and patented by them. The product works by using the coherent light scattering measurement technique which can detect the root mean square Rq equivalent from 0.01- 0.60 µm. The surface is scanned by the robot arm or similar setup with the help of CAD file of the part to be scanned. An automated in-line production process
is one of the major applications/roles of the CWS. The information such as equivalent, structure, structure angle, asymmetry, asymmetry angle, intensity can be displayed using this instrument. The target of QISAB is to develop the existing practice in industry towards the next generation industrial process, there by replacing manual instants by the new automatic methods of QISAB. By introducing the CWS640 in the production line online surface monitoring of each product will be performed thereby the cost due to product rejection waste and individual manual inspection labor. Thereby reduced time for production. As per the company estimation the machining and measuring time will be reduced and thereby saving a lot of cost to the company. This would be achieved by reducing the defective workpiece in the production line, as CWS measures the whole workpiece and give a real-time measurement so the defects can be identified and eliminated quickly. CWS can be fixed in the production line so the quality inspector need not take the workpiece to a separate room and check for the readings. It’s also possible to measure all the workpiece as this measurement method is quicker and take almost the same time to measure the whole batch in the production line as it would take to measure and compute the reading with any other surface measuring method for a single piece from the batch.

The future aim of the company is to become a leader within in-line inspection of the surface around the world of industrial processes, also the in-line quality control of goods and tools by schedule maintenance. (Bååth, 2015).

1.1.2. Patent study

QSO Interferometer systems AB received a patent on a method and apparatus for quantitative measurement of surface accuracy of an area on 10/01/2018. The inventor is Dr. Lars Bååth and the patent number is EP2956743B1. He discusses about other similar existing methods and their limitations in the patent and explains how he have overcome the same. See (Bååth, 2014) for more detailed information.

1.2. Aim of the study

The aim of this thesis is to analyze and analytically describe the parameters measured by the CWS to determine the surface characteristics and their connection to the existing parameters in ISO standards used in Automobile Industry. Further, a quantitative study on the same will be performed.

1.2.1. Research questions

- What are the characteristics of a surface and how can a manufacturing process be controlled using surface parameters?

- What existing surface parameters are used in the automobile industry and how can they be related them to the CWS parameters used at QISAB?

- What is the future scope for the CWS 640 in the automobile Industry?
1.2.2. **Problem definition**

The main problem here is that QISAB finds it difficult to step into the automotive industry by introducing the Coherent wave scattering (CWS) technique instead of the existing time-consuming setup. A proper relationship between the existing techniques have not been established yet. This thesis will help the company to find a relationship with current standards.

1.3. **Limitations**

- The project is focused on the automotive industry, so the other areas where surface roughness measurement are practiced are not included here.

- Due to the confidential requirements of the automotive companies, the actual surface texture requirement could not be analyzed. So, this thesis was confined to the data from published articles, books and catalogues.

- Quantitative study was based on visual inspection, white light interferometer and CWS because of availability of instrument so other instruments couldn’t be analyzed.

- White light interferometer and CWS measurements varies a lot in the measurement area so direct comparison was not possible with the parameters.

1.4. **Individual responsibility and efforts during the project**

Two students have worked together, and they have equally contributed to this thesis.
2. METHOD

The method used in this thesis was a combination of a qualitative and a quantitative study. The study was initially done in a qualitative approach, later on a quantitative study was carried out to supporting the qualitative studies that have been done. During the qualitative study, the method consists of brainstorming, literature selection, theoretical book selection, literature review, international standard search, patent search, discussion, notes from university and company guides. This information was then analyzed.

2.1. Brainstorming

The brainstorming is a method used to crack a problem or to find a new idea. While doing the thesis there where several stages were the group members had used this method to solve major and minor issues. This method has been used in a way that taking the problem as question, writing down the different solutions individually, discussed the solutions and selected the best of them.

2.2. Literature review

The first step was collecting data on relevant literatures. Literatures include journals, conference processing and books. For about the last three decades there are lots of studies, theories and books that have been published. The major challenge faced while doing this method was to select the best and useful materials. While searching on the library and online databases, different materials were found based on the surface roughness texture. Specific key words had been used while searching the literature for sorting the available database. From these selected literatures by reading the abstract of the materials few research papers and three books had been selected. These literatures and books are being reviews and the useful information from those were taken.

2.2.1. Standard selection

For the background study, it was necessary to know about the existing standards used for surface parameters according to the ISO standards and also the existing patents related to this topic. Related ISO files were searched on ISO website and (e-nav) the university online database for purchased ISO standards. The main ISO standard that was related to this thesis was ISO 25178 (ISO , 2012). The patent that the company owns had been taken in to consideration as well.

2.3. Work structure for thesis

The thesis can be divided into three stages as in the Figure 2.1, each one of it is followed by another sequence and these stages will be ultimately driven into the proposed solution of the project. The three stages are system understanding, problem understanding and solution.
The system understanding has three parts

*Existing parameters:*
Here all the existing parameters of a surface and relevant ISO standards are being studied

*Physical surface properties:*
Detailed study of automobile surfaces physical properties

*CWS parameters:*
Detailed study of CWS instrument working principle and output parameters

---

Figure 2.1 work structure of thesis

In Problem Understanding the existing parameters and CWS parameters are compared and analyzed. For this a work piece was selected which was measured using White light interferometer and CWS as well as a visual inspection was conducted. These were then compared to reach a conclusion.

In solution part the connection of CWS parameters with the existing surface parameter were established.
3. THEORY

The following section describes the theoretical research on surfaces

3.1. Surface metrology

Surface metrology has mainly two roles, one is to support and regulate manufacturing processes and the other one to help optimize surface functions. These two have a great impact on quality. While regulating the manufacturing process, the repeatability can be increased and thereby quality conformance. Optimization of these function help the designer and in turn to improve the design quality.

Roughness can be said as the marks/fingerprint from a process. A profile can be mainly approximated in 2 forms triangular form Figure 3.1 or sine wave form Figure 3.2 (Whitehouse, 2002)

\[ R_a = \frac{A}{2} \]  

(3.1)

and for sine wave profile:

\[ R_a = \frac{2A}{\pi} \]  

(3.2)

where A is the depth from the mean line.

With the help of \( R_a \) the quality of a surface can be predicted after a process. It is not easy to find the role of surface parameters in machine tool monitoring. For that an intended tool path need to be followed by the stylus of the instrument. Unfortunately, in practice it does not. Typically, on the surface at a fixed space one or more profiles are taken as in Figure 3.3. (Whitehouse, 2002)
Surface metrology plays an important role in functional performance. To test this the direct method is to test it by mimicking the function. This is not always feasible. An alternative method is by virtualizing the effect by some theory or experience. But even this method has limitations due to insufficient in experience. Wrong interpretations happen due to giving $Ra$ as a process control parameter, a functional role which were never its intended function. (Whitehouse, 2002)

Roughness normally comprehended as the heights of the machining marks. This is what engineers usually use to estimate tolerances, assembling or even to check the process. The heights are smaller than the length of the workpiece. So more vertical magnification is required than horizontal to get a clarity of the structure of a surface. 120° is a human viewing angle. To be able to visually correlate the pattern it should be within this angle. Because of this it looks steeper than it is in figure 3.4

![Figure 3.4 Actual and magnified graph (Whitehouse, 2002)](image)

Most of the surfaces exhibit roughness and waviness. Waviness usually happens due to the tool path error caused by numerous reasons like vibrations. Waviness is elastic deflections under load unlike crushing in case of roughness.

![Figure 3.5 Roughness, waviness and form (Whitehouse, 2002)](image)

### 3.2. Existing Basic parameters

Basically, there are three types of profiles while measurement takes place, those are roughness profile (R), Waviness profile (W) and Primary profile (P) obtained by a
transducer. In equations the type of profiles is mentioned as ‘T’, parameter suffix is mentioned as ‘n’ and number of cut-offs or the sampling length is mentioned as ‘N’ (David, 2002).

Parameters are mainly classified into amplitude, spacing and hybrid. Example for hybrid is slope. It is not exactly stated which parameter can be used for measuring the surface roughness. The clear fact is that all parameters are used for inspecting the quality of a part or to control the production inside the needs.

Figure 3.6 Roughness parameter types

The major industries use styles instruments to measure the roughness, which is measured and derived from a line. There are some areal parameters or 3D parameters which are taken from an area, but the values are similar to the line parameters (Whitehouse, 1994).

3.2.1. Amplitude parameters

One of the traditionally practiced amplitude parameters is roughness average (R_a) which is “the arithmetic mean of the profile deviation from the mean line” (Bernardin, 1996) It is also known as center line average. For calculating R_a, the first step to be done is to consider all the negative deviations (pit) into positive and taking the mean from the base line. It is not possible to determine the surface waveforms with a R_a value because different wave forms have the same R_a values as shown in Figure 3.7. So, basically it is not a good process to use this derived value for controlling the production quality (David, 2002).

Figure 3.7 Example of Wave forms with equal Ra values (David, 2002)
The general formula used for finding the Ra value is:

\[
R_a = \frac{1}{l_r} \int_{0}^{l_r} |z(x)| dx
\]

(3.3)

Where, ‘\(||\)’ means that the sign is ignored and at a position \(x\) of the mean line for the profile measured is ‘\(z(x)\)’ and \(l_r\) is the sampling length as in Figure 3.8.

The next amplitude parameter is root mean square (rms) parameter. It takes the reading in a similar principle to calculate Ra, but it will dominate the Ra.

The formula for finding the Rq is.

\[
R_q = \sqrt{\frac{1}{l_r} \int_{0}^{l_r} |z(x)^2| dx}
\]

(3.4)

The waviness equation which is derived from Ra is

\[
w_a = \frac{1}{l_w} \int_{0}^{l_w} |z(x)| dx
\]

(3.5)

Similar to the formula of Rq and Wa the waviness parameter Wq, Wpt, Wv primary profile parameter Pa, Pq, Pv, Pp, Pt and roughness parameters such as Rv, Rp, Rt are derived.

Where, Rv: within the specimen length and below the mean line with the maximum depth of the profile.

Rp: Within the specimen length and above the mean line with the maximum height of the profile.

Rti: in the valuated length the maximum peak to valley height of the profile.

Wv, Wpt, Pv, Pp and Pt: equivalent parameters of waviness and primary profiles

![Diagram of various profile parameters](image)

*Figure 3.8 Basic existing parameters representation (David, 2002)*

The maximum peak to the valley height of the profile with in a sample (Rz) will be equivalent or nearby to the mean of the maximum peak to valley height in a sample
Rtm and Rti is not standardized as per ISO but, as per the Japanese’s Industrial Standard (JIS) which is similar to ISO standard. The formula for Rz is mentioned in a different way by picking five highest peaks (Zp) and five lowest valleys (Zv) in a specimen length.

\[
R_z = R_{tm} = \frac{R_{t1} + R_{t2} + R_{t3} + R_{t4} + R_{t5}}{5} = \sum_{i=1}^{N} R_{ti} 
\]  \hfill (3.6)

\[
R_z (JIS) = \frac{(Z_{p1} + Z_{p2} + Z_{p3} + Z_{p4} + Z_{p5}) - (Z_{v1} + Z_{v2} + Z_{v3} + Z_{v4} + Z_{v5})}{5} 
\]  \hfill (3.7)

\[
= \frac{1}{5} (\sum_{i=1}^{5} Z_{pi} - \sum_{i=1}^{5} Z_{vi})
\]

### 3.2.2. Space Parameters

From the book surface metrology and manufacture roughness, waviness and primary profile have the space parameter which is basically the space between the profiles. Within the specimen length at the mean line the mean spacing is,

\[
RS_m = \frac{1}{n} \sum_{i=1}^{n} S_i = \frac{S_1 + S_2 + S_3 + \ldots + S_n}{n}
\]  \hfill (3.8)

Where, n is the number of peak spacing.

![Space parameter for the profile](Figure 3.9 Space parameter for the profile (David, 2002))

Similar to the RS_m WSm and PSm are formulated from the waviness and primary profile. The high spot count can be calculated by counting the peaks which is above the mean line or the parallel line to mean line or the peak below this line. By counting the number of peaks which comes inside a specific band above the mean line the Peak count (Pc) is calculated.

### 3.2.3. Miscellaneous parameter

Under miscellaneous parameter the parameter under consideration is

**Texture direction (Std):**

As per the ISO 25178-2 definition the texture direction of a scale limited surface (Std) is an angle. “With respect to a specified angle θ, Std is the absolute maximum value of the angular spectrum”. From each special frequency energy content on the sampling length lr Figure 3.9 Space parameter for the profile (David, 2002)
surface is taken using Fourier spectrum. On the Fourier spectrum amplitudes are plotted as colour codes or grey level (ISO, 2012).

### 3.2.4. Hybrid Parameters

Hybrid parameters are used for analyzing the reflectivity, friction and vibration by inspecting the angular slope of a profile. Hybrid parameters are made by the combination of amplitude and space parameters. Hybrid parameters are average wavelength $R_{\lambda q}$ ($\lambda q$ is rms), skewness $R_{sk}$ and Kurtosis $R_{ku}$. Similar to roughness, waviness and primary profile amplitude factors are derived. (Whitehouse, 2002)

#### Skewness ($Ssk$):

$Ssk$ shows how much the roughness of a certain area is symmetrically different from the major surface roughness structure. There are 3 major cases as shown below:

- $Ssk < 0$: Here the height distribution is tilted above the mean line as in Figure 3.10
- $Ssk = 0$: Here the height distribution is equally distributed around mean line as in figure 3.10
- $Ssk > 0$: Here the height distribution is tilted below the mean line as seen in figure 3.10

$$Ssk = \frac{1}{sq} \left[ \frac{1}{A} \iint_A Z^3(x,y) \, dx \, dy \right]$$  \hspace{1cm} (3.9)

#### Kurtosis ($Sku$):

$Sku$ shows how sharp the roughness structure is. $Sku$ can be mainly classified as:

- $Sku < 3$: The height of the roughness is more distributed as in Figure 3.11 and do not have sharp ends.
- $Sku = 3$: The height distribution is normal, i.e. Peak and valley coexist.
- $Sku > 3$: The height distribution is more like spikes as in Figure 3.11

![Figure 3.10 Skewness graph](image)
\[ Sku = \frac{1}{S^4} \left[ \frac{1}{A} \int_A Z^4(x, y) dx dy \right] \quad (3.10) \]

**Maximum peak height (Sp):**

Sp is similar to Rp. It is the highest peak within a defined area. The figure 3.12 shows Rp as its similar to Sp the difference is Sp is an areal extension of Rp

![Maximum peak height](image)

*Figure 3.12 Maximum peak height (Keyence corporation, 2018)*

**Maximum pit height (Sv):**

Sv is similar to Rv. It is the highest pit within a defined area. The figure 3.13 shows Rv as its similar to Sv the difference is Sv is an areal extension of Rv

![Maximum pit height](image)

*Figure 3.13 Maximum pit height (Keyence corporation, 2018)*
3.2.5. Areal Parameters

As said by (Whitehouse, 2002), the 3D parameters are formed as on the same principle used to make the 2D parameters. The term (3D) roughness parameter is misleading; it should be called areal (2D) as compared to the profile (1D). The measured reading is taken from a single line of specimen and for areal (3D) the measurement values will be taken from an area (a bunch of sampling length). The areal measurement is used to find the tool path error (David, 2002).

The letter R for profile parameters, the areal parameters are mentioned using the letter S which stands for surface, for example arithmetic average (Sa) formula is similar to Ra. This will be alike for the other parameters such as root mean square in 3D (Sq), Skew (Sk), Kurtosis (Sku), Ten-point height (Sz)

\[
S_a = \frac{1}{L_1 L_2} \int_{L_1}^{L_2} \int_{0}^{L_2} |f(x, y) - \bar{f}| \, dx \, dy \tag{3.11}
\]

\[
S_q = \sqrt{\frac{1}{L_1 L_2} \int_{L_1}^{L_2} \int_{0}^{L_2} (f(x, y) - \bar{f})^2 \, dx \, dy} \tag{3.12}
\]

Where, \( \bar{f} \) the mean plate height; \( L_1 \) and \( L_2 \) the range of the same plate; \( f(x, y) \) surface height at \( x, y \). (David, 2002)

**Str (Texture aspect ratio):**

Str is almost vital parameters when describing a surface in an areal manner as it indicates the isotropy of a surface under ISO 25178.

Str is calculated from the \( r_{\min} \) and \( r_{\max} \) which are minimum and maximum radii respectively from the central lob of the autocorrelation plot as in Figure 3.14 after applying a threshold of 0.2.

\[
Str = \frac{r_{\min}}{r_{\max}} \tag{3.13}
\]

![Figure 3.14 minimum and maximum radii measured from center lob of autocorrelation plot (leach, 2013)]
The auto correlation function measures the matching proportion between the images rendered from original image and different coordinates.

![Figure 3.15 Autocorrelation value in different case (Keyence corporation, 2018)](image)

In the Figure 3.15 shows how the autocorrelation is achieved in different overlapping scenarios. Original data is shown in yellow area.

A sharp difference in height immediately decreases the autocorrelation as even a small difference causes large change in the shape. Alternatively, if the change is gradual autocorrelation also decreases slowly until the difference becomes large. (Keyence corporation, 2018)

Str does not have a unit and it ranges between 0 to 1 or if expressed in percentage 0 to 100.

If Str is close to one, then the surface is isotropic which means the surface have same property irrespective of the direction. If it’s close to zero, the surface is anisotropic which means that the surface has a texture direction.

### 3.3. The general use of surface metrology in Automobile

In the industry the surface inspection is mainly done for maintaining the quality by reducing the scrape formed due to diversion of precision from the actual need of the user because of the faulty machining.

The commonly used machining process are basically subdivided into

- The cutting process with single and multi-tool (plaining, milling, broaching plaining etc.)
- The machining using abrasives (horning, polishing, grinding etc.)
- Machining using chemical and physical (electro discharge, electrochemical etc.)
- Forming, casting, extrusion and other microscopic machining (High-power water jet, laser machining etc.)
• The advanced machining such as ultra-fine machining or nanomachining (energy beam machining, iron beam milling etc.)

There are some processes which can produce very fine surfaces such as diamond turning and abrasive polishing.

Traditionally in the industries the $R_a$ is taken as a key parameter for controlling the surface finish but when these practice are looked in depth, it is not a good way for finding the actual figure of a surface. The reason is that it is not possible to imagine how the actual texture will be with an $R_a$ value, as explained in chapter 3.2.1.

![Figure 3.16 The existing range of surface roughness control in machining process (David, 2002)](image)

3.4. **The conventional process of calculating the roughness**

Turning, milling, grinding, horning, polishing and broaching are the commonly used machining processes for the manufacturing of automobile components. As per the theory the roughness are defined by the tool geometry and the feed (David, 2002).

3.4.1. **Turning**

In the turning process the general factors that influence the part surface roughness are cutting speed, tool axial feed, and depth of cut. As per the theory and the method of assigning roughness in automobile industry the roughness of an angular tool of
turning is defined by the depth of cut and not by the feed as can be seen in the following equations (Whitehouse, 1981).

The equation will be

\[ R_t = d \]  \hspace{1cm} (3.14)

\[ R_a = \frac{d}{4} \]

For a curved tool in the turning machine feed is taken as an important parameter and the ratio between Ra and Rt will be taken as 1:4. The equation of roughness is taken as (Whitehouse, 2002)

\[ R_t = r - \sqrt{r^2 - \frac{f^2}{4}} = r(1 - \sqrt{1 - \frac{f^2}{4r^2}}) \]  \hspace{1cm} (3.15)

\[ R_t \approx \frac{f^2}{8r} \quad , \quad R_a \approx \frac{0.03f^2}{R} \]

3.4.2. Milling

In the milling process mainly for iron milling the feed \((f)\), cutting radius \((R)\) and number of teeth in cutter \((n)\) are taken into consideration for fining the roughness (David, 2002).

As per the theory the equation comes as,

\[ R_t = \frac{f^2}{8[R \pm \left(\frac{fn}{\pi}\right)^{\frac{1}{3}}]} \]  \hspace{1cm} (3.16)

3.4.3. Abrasive grinding

Both abrasive powder and tool grinding are of similar machining process and so as per the theory the speed ratio \((q)\) and the value \(K\) which is known as ‘characteristic grinding value’ taken as an important parameter for finding the roughness. The value of \(q\) in normal grinding will be taken within 20-100 and for high speed and creep feed grinding \(q\) value will be within 1000-20000 (Salje, 1998).

For the creep grinding the roughness equation is defined as:

\[ R_z = K \times |q|^{\frac{-2}{3}} \]  \hspace{1cm} (3.17)

For the reciprocal grinding the roughness equation is taken as:

\[ R_z = K \times (1 + \frac{1}{|q|})^{\frac{-2}{5}} \]  \hspace{1cm} (3.18)
There is a relation between the surface metrology and manufacturing. As per the words from (David, 2002) it is correct that no metrology is required if the manufacturer understood the function and if the process is controlled. The main problem with the current measuring system is that it is not possible to find the real time measurement, that is at the same time the manufacturing occurs.

Grinding is the machining process which has a tool of abrasive material. The cutting elements are made of abrasive material grains which is also known as grit. A proper bonding material is used in the tool for making the grits together and to maintain a proper shape for the tool. The major advantage due to grinding process is that it is possible to attain dimensional accuracy, surface finish, locational accuracy and possible to machine over material having different hardness properties. Abrasive grinding wheel are of two types based on the structure. The grinding wheels of tightly packed abrasive are known as closed structured and of less tightly packed are known as open structured. Soft wheels are for machining the hard materials and hard wheels are used for soft material machining (Gupta, 2009). Grinding wheel abrasive grain size has a relationship with surface roughness. If the grinding wheel abrasive grain size is large it means that the distance between the grains will be more and the chip cross-section removed also will be larger. The surface roughness will increase when the grinding wheel abrasive grain size increases (Halil, et al., 2010).

3.5. **Surface roughness inspection techniques**

The surface finish is controlled based on two principles. The first one is to reduce friction and the second is to control wear. In the case of a film of lubricant, the surface irregularities of the two moving parts must be in a limit. If it is over the limit the oil film will penetrate under the severe operating condition and will not be able to maintain in between the two-moving part (John, 2008).

The surface roughness varies by the influence of different factors. The surface finish inspection in a right way will help to identify if some of the factors goes wrong from the specified limit. The factors that influence surface finish are machining variables (cutting speed, feed rate, depth of cut), tool geometry (nose radius, rake angle, side cutting edge angle, cutting edge), tool vs machining process, tool machining vs workpiece, auxiliary tool (clamping system which controls vibration etc.), lubrication/ coolant and vibration between workpiece machine and cutting tool (Krizbergs & Kromanis, 2006). The tool feed and corner radiuses are closely related to roughness. I.e. feed (f) is directly proportional to roughness and corner radius (r) is inversely proportional to roughness of surface.

As per the theoretical expression, The maximum roughness depth, (Krizbergs & Kromanis, 2006)

\[
R_{\text{max}} = \frac{0.321f^2}{r} \tag{3.19}
\]
As a reverse process it is possible to analyses the reason behind the surface roughness, in every quality control system this is the way of inspecting the workpiece and finding the problem.

3.5.1. Visual Inspection of ground surface

The various types of surface flaws such as corrosion, contamination, surface finish and surface discontinuities can be examined by visual inspection (Campbell, 2013). When a light is exposed in to plane mirror it will be reflected in to the human eye and this will help people to see the virtual image of an object on a mirror. Using the same principle, the visual inspection is taken place by considering the ground surface as a plane mirror and the camera as the human eye. According to the different ground surface finish, the intensity and precision of reflected light will change (HUAIAN, et al., 2016). For more details see Appendix I.

3.5.2. Coherent scanning interferometry (CSI)

Complex surfaces with respect to roughness, structure, discontinuities or steps like transparent films cannot be measured using normal interferometers because these instruments need opaque surface. CSI fill this gap. In addition, it also subdues the false interference from scattered light by autofocusing to right level at every point (Kanik, 2013). When a LED (light emitting diode) or similar low coherent source is used in interference microscope it becomes a low-coherence interferometer which is also known as CSI. The focus of an interference microscope is scanned vertically across the surface and a surface where focus is superimposed get a fringe pattern. This pattern is recorded in a video. Fringes are confined near the surface due to the low coherent light source. Each pixel of the surface topology for the surface is found by the fringe intensity function closest to the surface (Kanik, 2013).

3.6. Coherent wave scattering (CWS)

CWS is an laser measurement instrument using coherent wave scattering principle which was developed by QISAB. The basic theories used in QISAB CWS 640 are the Huygens principle and antenna theory.

3.6.1. The Huygens principle

In 1670 Christian Huygens stated a wave theory of light which helps to study the various optical phenomena. Huygens principle says the way of light is traveling around a sharp edge. “According to Huygens principle for the projection of light, every point illuminated by an incident primary wave front becomes the origin of the secondary wave front” (Liu, 2007). Usually the light source geometry determines the shape of the wave front. Wave front is the imaginary surface on which a constant phase is attained by an optical wave. For a point source the wave fronts are in spherical in shape and radially the waves are propagated.
The propagated wave directions will be always perpendicular to the imaginary surface (wave front) at each point. (Liu, 2007)

### 3.6.2. Light Scattering Theory

The light scattering on a surface is mainly varies based on the surface structure of the rough surface, incident angle and the incident wave length (Schröder, et al., 2011). The light scattering is the redirection of the incident rays that is the electromagnetic waves when it meets an objective or a scattering particle. The light scattering process is a complex interaction between the incident electromagnetic wave and the molecular of the scattering object (Wriedt, 2012). The scattering takes place when a light incident hit a rough surface and the direction of the incident wave change. If the surface irregularities of a rough surface such as height and correlation length are much smaller than the wave length the surface is microscopically rough, This surface will be considered as layers of effective medium and will affects the polarization of the incident light (Lianhua, et al., 2017). The property of light wave when oscillating in more than one direction is called polarization. Unpolarized light are those which can vibrate in more than one plane, the method of converting unpolarized light into polarized light is known as polarization of light (Guibo, 2017).

The Rayleigh scattering theory states about the scattering of light without change in wave length. So it is considered as an elastic scattering because the photon energy of light is not changed when it scatters. In this case the dimension of the obstacle will be much smaller than the wave length of the light. There is no size limitation for the theory of Mie scattering. That is why this theory is mailed used for explaining the spherical element scattering systems (David, 2009).

Theoretically, when an electromagnetic wave gets in contact with an isolated element; the electron orbits within the isolated element, which will be disturbed periodically in a same frequency ($V_0$) of the incident wave electric field. Inside the element molecules the period separation of charge will happen due to the element electron cloud oscillation which is called an induced dipole moment. The induced dipole moment oscillating is a source of the electromagnetic (EM) wave, by this manned the scattering happens as shown in Figure 3.17 (David, 2009).

![Figure 3.17 Light scattering by an incident dipolar moment](image)

*(David, 2009)*
3.6.3. Working principle

The laser beam from the light goes through the optic fiber to the beam splitter. The beam splitter is used to make the light source parallel to reflect light from the sample as well as the reflected light to pass through to the CCD. The beam gets deflected from the beam splitter as seen in the figure 3.1 then passes through a objective and the filter to filter out external light disturbances before it hits the sample. The reflected light from the sample passes through a filter and then through the beam splitter again to the CCD camera. The peak of the surface is being calculated from the amount of light scattered. This is directly proportional to the true surface rms value and is noted as Rq_eq equivalent to Rq(rms) in ISO 25178. The phase error introduced by the height of the wave is:

\[ \Theta = 2\pi a \frac{2d}{\lambda} \]  
(3.20)

Where d is the height;

Factor 2 because reflection (trough);

\( \lambda \) is the wave length;

a is a constant depending on the surface size and directivity.

The standard deviation of the phase error is;

\[ \rho = \text{stddev}(\theta) = 4\pi a \frac{\sigma}{\lambda} \]  
(3.21)

Where \( \sigma = \text{stddev}(d) = R_q \)  
(3.22)

The main lobe efficiency is the power in the main lobe over the total power, that is,
\[ \varepsilon_{MB} = C \cdot e^{-\frac{\rho^2}{2}} \]  

(3.23)

The scattered Amplitude is calculated in voltage

\[ V_{scatter} = V_0(1 - \varepsilon_{MB}) \]  

(3.24)

Or

\[ V_{scatter} = V_0(1 - C \cdot e^{-0.5 \left( \frac{4\pi \sigma}{\lambda} \right)^2}) \]

3.7. CWS parameters

There are 7 parameters in CWS which will be discussed bellow
3.7.1. $R_q_{eq}(nm)$

$R_q$ the root mean square value of the surface as per ISO 4287:1997 and $R_{q\,eq}$ the parameter that measures roughness in CWS, which are quite similar. Both the parameter shows the roughness of the surface. The main difference is that $R_q$ in ISO standard measures the roughness in single direction which it’s been used to measured were as $R_{q\,eq}$ considers all the direction and takes the highest roughness value (worst surface direction), Range from 10nm to 500 nm.

3.7.2. $R_{int} (db)$

The roughness value above 500 nm is given in $R_{int}$. For a very rough surface most of the light will be scattered and very less light reflects. So, there will be many dark spots.

$$R_{int} = \frac{\text{Intensity of light reflected back}}{\text{no of black spots}}$$

(3.25)

Here the value is in dB. Since low dB shows higher scattering of light means higher surface roughness.

3.7.3. Structure (dB)

Structure is similar to the parameter Str (Texture aspect ratio) which has been discussed in theory 3.2.5 as per the ISO 25178. Shows how coherent, sharp and near the structure are. It shows what $R_{q\,eq}$ can’t show. It can be scratches but large numbers in certain direction. There will be random structures which are less in number. So here this parameter shows the strength of the structure in same direction compared to the random structures. The values are measured in dB. The higher the dB values the more structure are present.

Decibel is a term which is adopted from the electronics and communication engineering It is associated with noise measurement which is mainly used in sound pressure and for light intensity too. In basic decibel is the logarithmic way of describing a ratio. It is also an expression of change in value (Jeff, 2002). The basic equation for dB equivalents is $10 \log_{10} x$. Where power ratio is $x$ and amplitude ratio is $\sqrt{x}$ (Francis T, 1997). Here the power ratio $x$ is the amount scattered light intensity to the total light intensity.

$$x = \frac{\text{intensity of scattered light}}{\text{total intensity of incidenting light}}$$

(3.26)

3.7.4. Structure angle

To which angle the structure are strongly aligned is shown here which is similar to Std (texture direction) in ISO 25178. Range from $\pm 0$ to $90^\circ$
3.7.5. Asymmetry

The direction perpendicular to the worst surface direction from where $R_{q_{eq}}$ is calculated is known as the best surface direction.

\[
\text{Asymmetry} = \frac{R_{q \text{ in the best surface direction}}}{R_{q \text{ in the worst surface direction}}} \quad (3.27)
\]

Range 0 to 1 where 0 shows that all the structure is aligned in one direction whereas close to 1 shows the structure is aligned in different directions.

If the asymmetry is small and $R_{q_{eq}}$ is large the surface must be polished in the best surface direction to get a smooth surface.

3.7.6. Asymmetry angle

The angle at which the most surface direction aligned is the asymmetry angle ranges from ±0 to 90°

3.7.7. Intensity

Shows the total light scattered back from the surface overexposed > 55dB

3.7.8. The surface parameters which are applicable in the Automotive Industry.

The CWS parameters, which are applicable to the automotive industry, are the Surface roughness, Asymmetry, Asymmetry angle, Structure, Structure angle and Gloss. Surface roughness is calculated by using the scattered light, those are the light which are no came back to the camera while inspecting a test piece. In here Scattered light is directly proportional to the peak portions on the surface of a test piece. That is by using the scattered light an equivalent value to the $R_{q}$ is derived. (Bååth, 2015) $V_{scatter}$ is been determined from the light been reflected to the CCD. Therefor by substituting the value for $V_{scatter}$ the standard deviation of d can be found ($\sigma$), which equivalent to $R_{q}$. Thereby the standard deviation of the surface is being found out.

3.7.9. Merits due to the new technology

QISAB had created an evolution in the roughness measurement method by taking out the surface parameters testing system into the production line that is inside the industrial process. When an operator of the surface testing machine tested the part there will be some human error, by the QISAB CWS 640 the manual inspection moment can be replaced. The automated inspection system of the CWS 640 will help the industry to schedule the replacement and maintenance of tool than using the tool till the life of its which makes not possible to repair and makes high maintenance cost. In the production line this system is capable of measuring roughness, surface error, asymmetry and asymmetry angle and structure and
structure angle even if the surface is glossy too. By using CWS 640 in a production line 4*4 mm of the product surface can be measured in 1 millisecond and the analyzing time for the instrument is 0.2 sec (Bååth & Rosén, 2018).
4. RESULTS

By analyzing the existing surface parameters with respect to the manufacturing process it is necessary to have a continuous monitoring on the surface structure of the product while manufacturing. Different instruments measure using different techniques, at the end they all measure surface irregularities. Stylus is the only instrument which gets the exact standard Ra value because Ra is standardized based on stylus, but it leaves a mark on the surface changing its properties. While using the non-contact measuring instruments as shown in Appendix II does not get the exact Ra value because it is nearly impossible to gather all the reflected light values. The surface roughness has an important role in predicting the service life and the reliability of the mechanical product.

The surface texture direction of a part and the roughness makes a major impact on the size and shape of the virtual image created by a single point light source. The detailed study about the reflection of light on different types of surface is mentioned as a literature review in Appendix I.

4.1. Comparing CWS, visual inspection and White light interferometer

The sample was ground and polished in 11 different steps as in figure 4.1 to achieve a mirror like finish. The initial step was achieved using flat grinding. From step 1 to 3 the surface has been hand polished using polishing stone Falcon SE 320, 400 and 600 respectively. 4, 5 & 6 steps are being hand polished using sand paper 400, 600 & 800 respectively. From 7 to 9 hand held unit with linear motion is used with brass, wood and wood with diamond paste. For step 10 rotational hand-held unit with hard felt in diamond paste is used. For final step hand polish using cotton wool and diamond paste is used.

While considering the Sq and Sa valued from the White light interferometer initial, step 2, step 5, step 7 and step 11 have large difference with their reading as seen in table 4.1. From step 8 and above as can be seen from Figure 4.2 these areas were over exposed since they are out of the scope of the CWS machine as minimum value that can be measured using CWS is 10 nm, so they were excluded for comparison using visual inspection, white light interferometer and CWS.
Table 4.1 values from white light interferometer

<table>
<thead>
<tr>
<th>Mean values (15 measurements interferometer 10x)</th>
<th>Sq</th>
<th>Sa</th>
</tr>
</thead>
<tbody>
<tr>
<td>K E019 initial</td>
<td>613</td>
<td>497</td>
</tr>
<tr>
<td>K E019 Step1</td>
<td>505</td>
<td>382</td>
</tr>
<tr>
<td>K E019 Step2</td>
<td>273</td>
<td>207</td>
</tr>
<tr>
<td>K E019 Step3</td>
<td>275</td>
<td>202</td>
</tr>
<tr>
<td>K E019 Step4</td>
<td>176</td>
<td>131</td>
</tr>
<tr>
<td>K E019 Step5</td>
<td>126</td>
<td>98</td>
</tr>
<tr>
<td>K E019 Step6 EX</td>
<td>124</td>
<td>96</td>
</tr>
<tr>
<td>K E019 Step7 Phase</td>
<td>17</td>
<td>13</td>
</tr>
<tr>
<td>K E019 Step8</td>
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<td>K E019 Step9</td>
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<td>6</td>
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<tr>
<td>K E019 Step10</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>K E019 Step11</td>
<td>7</td>
<td>5</td>
</tr>
</tbody>
</table>

Figure 4.1 Sample workpiece

Figure 4.2 CWS intensity
4.1.1. Visual Inspection

Initially the sample looks smooth and there was no specific structure orientation which was seen. Light reflection is least here. Here it looks more like white noise which are disturbance with no specific properties in any specific direction. In stage 2 the structure line was visible mostly in horizontal even though there are few random structures. Light reflection is more than the stages before. In stage 5 the structure was still strongly aligned in horizontal direction, but the structures looked far more apart from each other. The reflective property has improved from previous stages. In stage 7 the structures have now changed the direction to more perpendicular with a site tilt to right. This was due to the change in direction of polishing to reduce the roughness value. Light reflection has really improved, and the reflected image was almost clear as mirror which slightly visible structure.

4.1.2. White light interferometer (WLI)

White light interferometers measured a 617 µm by 817 µm point as in Figure 4.1. Comparing the whole work piece this is very small area. Even though we can’t compare measurement values from WLI with the CWS directly as both of the
instruments measurement vary a lot in the areal size as CWS measure the whole surface 10 cm by 10 cm. Still tried to see how their parameters correlate.

*Table 4.2 Selected steps White light interferometer readings*

<table>
<thead>
<tr>
<th>Mean values (15 measurements interferometer 10x)</th>
<th>Sq (nm)</th>
<th>Sa (nm)</th>
<th>Ssk</th>
<th>Sku</th>
<th>Grain size (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>K E019 initial</td>
<td>613</td>
<td>497</td>
<td>-0.321</td>
<td>2.71</td>
<td>260</td>
</tr>
<tr>
<td>K E019 Step2</td>
<td>273</td>
<td>207</td>
<td>-0.561</td>
<td>4.99</td>
<td>22</td>
</tr>
<tr>
<td>K E019 Step5</td>
<td>126</td>
<td>98</td>
<td>-0.224</td>
<td>3.62</td>
<td>27</td>
</tr>
<tr>
<td>K E019 Step7 Phase shift</td>
<td>17</td>
<td>13</td>
<td>-0.466</td>
<td>4.15</td>
<td>9</td>
</tr>
</tbody>
</table>

From Table 4.2 it’s clear that the roughness $S_q$ and $S_a$ was reduced in each stage. When looking the table 4.2 it can be seen that in step 2 $S_{sk}$ have changed from -0.321 to -0.561. $S_{sk}$ shows the symmetricity of the peak and valley. So increase in value negatively means that the heights of valleys are more than peak. Which in turn mean that the peaks heights are been reduced. This can be supported from the visual inspection done before as the surface looks smoother than the initial stage. Similarly, $S_{ku}$ have increased from 2.72 to 4.99 which show that there were many high peaks present in the profile. When visually inspected it was clearly seen that there were visible structures than before which in turn means more peaks. In next stage the $S_{sk}$ increases and $S_{ku}$ degreases as the surface become smoother. In stage 7 the direction of the structure was changed as seen in Figure 4.3. There was an increased negative value of $S_{sk}$ and positive value of $S_{ku}$ here as more structure is visible compared to the previous stage.

![Image from MountainsMap with the WLI values](image)

*Figure 4.4 Image from MountainsMap with the WLI values.*
From the Figure 4.4 achieved from Mountains Map it was clear that the roughness was reduced along the stages and the structure was aligned along horizontal direction until step 7 from where the direction of structure was changed to vertical.

4.1.3. CWS (coherent wave scattering)

In Figure 4.5 & Figure 4.6 shows the asymmetry and asymmetry angle respectively. Here the values are ranged from 0.7 to 1. Higher asymmetry value means the structure is aligned more in the best direction than is the worst direction as mention in section 4.4.5. Initial stage the values range from approximately 0.85 to 1. From visual inspection it seemed that there was no specific direction for surface was clear. Comparing to the stage 2 and 5 initial stage seems to have a lower value of asymmetry in turn mean that the later 2 stages, structure is more aligned to the best direction which is horizontal in this case. Asymmetry angle shows zero as most of the structure are aligned in same direction which was clearly seen during visual inspection as well as in WLI. In stage 7 the directions of the structure have changed more in perpendicular direction there by reducing the asymmetry value. When the asymmetry angle is checked here can see a tilt of almost 90° which is been confirmed in the above two techniques.

Figure 4.5 Asymmetry from CWS

Figure 4.6 Asymmetry angle in deg from CWS
Figure 4.7 and Figure 4.8 shows the structure and structure angle which been explained in section 4.4.3 and 4.4.4. In all the stages it shows similar structure value with few up and downs. So according to CWS principle it means that almost all the stages have similar structure intensity just that in stage 7 there is a shift in structure angle which was able to be seen in the structure angle parameter in CWS. During visual inspection deep scratches or grooves were not visible unlike the normal structure orientation.
From Figure 4.9 & Figure 4.10 the roughness parameters $R_{q\text{-eq}}$ and $R_{\text{int}}$ can be seen. Since initial stage have a roughness above 500 nm $R_{\text{int}}$ is used instead of $R_{q\text{-eq}}$. The $R_{\text{int}}$ value for initial is showing low dB which says that the roughness is high according to section 4.4.2. Stage 2, 5 and 7 roughness value can be seen in $R_{q\text{-eq}}$.

4.1.4. Discussion

In this thesis the history, background of surface inspection, basic parameters and the CWS parameters has been described. Then the thesis came to a point to end the qualitative study. It was necessary to have a quantitative study of CWS and a similar type of optical instrument. The works then continued with the quantitative study by comparing a sample work piece with visual inspection, WLI and the CWS measurements.

The basic surface texture parameters are form, waviness and roughness and graphically it is explained in figure.3.5. Roughness is manufacturer fingerprint, or the process mark due to machining process and structure of material. Due to the instability in the machining process waviness are created at it is having longer wavelength deformation on the surface than roughness. Excluding the roughness and waviness the general shape of the surface is known as form.

4.1.5. $R_{q\text{v/s}} R_{q\text{-eq}}$ (CWS)

As described in the theory 3.2.1 in $R_q$ is the root mean square parameter which is also known as rms. $R_q$ is standardized based on the tactile measurement method which is the standard deviation of height. $R_q$ equivalent is a similar parameter which takes the height in all direction. Result from quantitate and qualitative study states that both the standardized $R_q$ and the CWS $R_{q\text{-eq}}$ gives the similar result.

4.1.6. Visual, Stylus and white light interferometer v/s CWS

Visual inspection is one of the initial and traditional surfaces analyzing method and it fully manual too. As explained the chapter 3.5.2, when a light is exposed in perpendicular to the ground surface and a camera the human eye can sense and visually identify how the surface is formed. The form, waviness and surface roughness can be easily sensed using this method. For an experienced visual inspector, it is easy to identify the defects and how much rougher the surface is machined. From figure 4.3 and theory 4.6.3 it is clear that the readings from the CWS the structural deformation and roughness values can be identified visually in the software which we may and may not identify using the visual inspection.

Tactile is a contact measurement system which is wildly used in the automotive manufacturing industry from the earlier times. The detailed explanation and methods had been explained in the introduction part. The main drawback of this measurement method is that it leaves a fingerprint of stylus probe after each measurement which can change the surface roughness after each measurement of the surface. The roughness average is standardized as per ISO according to the
tactile instruments. Tactile instrument probe should be placed perpendicular to the machined direction and the probe should be placed in parallel to the surface. It is not possible to measure the complex structured surface due to this limitation of tactile instruments. Most of the roughness 2D parameters are standardized mainly for tactile measurement method. CWS parameters are basically derived from noncontact measurement method so it is not directly related to the tactile measurements but as looking theoretically the parameters are related to each other. CWS takes the reading of the whole surface by inspecting each 4*4 mm area in over lapped manner.

White light interferometry is also known as coherent scattering interferometry which is a non-conduct optical measurement method. The working principle of White light interferometry is explained in the theory 3.5.3. Using these methods, it is not possible to take the entire surface measurement that is it is possible to take only selected minor areas. It might be time consuming if the white light interferometer is used to take the entire surface roughness measurement. In reality it is not possible to compare the whole surface measurement with a particular section. For a general example when we consider a football ground as the whole surface and the goal post area as a small section of the surface, the reading taken from the whole football ground and a small area will be distinct. This logic should be considered for this comparison too.

4.1.7. CWS vs ISO

The CWS is an ideal measurement method for surface texture. As per the theoretical study regarding the standardized parameters 3.2.1, the texture direction which is explained in the section 3.2.2 and texture aspect ratio which is explained in 3.2.4 which comes under the ISO 25178. These standardized parameters are compared and discussed with the similar parameters of CWS in 4.5.

4.6.4 Future scope of CWS 640

In the fast-growing industrial world, time is an important concern. The existing instruments available in the market for surface inspection will take more time and human effort, using CWS the inline inspection of surface measurements can be taken for the products manufactured by the companies. Thereby the time can be easily saved and the wastage can easily reduce. The other instruments such as white light interferometer will only take micron level measurements from small areas. It will take more time for these instruments to measure the whole surface. Due to these advantages CWS will be the advanced surface measurement method for surface roughness.
5. CONCLUSIONS

This thesis was about to compare the CWS parameters with the existing standardized parameters and the instruments currently used in the automotive industry. The thesis was a great success to fulfill the research questions that had been assigned initially and hence the goal of the thesis has been attained.

The surface characteristics are basically of form, waviness and roughness, form is the basic shape of material, waviness is the major roughness which happens like a wave due to the machining problems such as alignments etc. and roughness is the minor unevenness formed on surface. The roughness is divided into different parameters and based on this parameters the manufacturing process are controlled which is explained in 3.3.

There are number of surface parameters in the industrial world, of them the important parameters used in automotive industry are roughness average, root mean square of roughness, space parameters, skewness, kurtosis, areal roughness average, areal root mean square, texture aspect ratio and texture direction. Of them roughness average is wildly used in the industries, but it will not make sense for inspection to understand the surface. The other parameters such as root mean square texture aspect ratio and texture direction are directly related to the CWS root mean square equal, structure and structure angle.

The basic reason for the thesis was to relate the CWS parameters with the standardized ISO parameters. The ISO 25178 is a series having geometrical product specification standards on surface texture. Some of the parameters which are standardized in ISO 25178 are related directly with the CWS parameters.

Usefully standardized surface parameters and related CWS parameters
Structure of the CWS is directly related with the texture aspect ratio ($S_t$)
The common surface parameter which is the root mean square of roughness ($R_q$) is similar to the root mean square of roughness equal ($R_q_{eq}$) and $R_{int}$ of CWS. $R_{int}$ is the root mean square of roughness above 500nm.
The standardized surface texture direction ($S_{td}$) is directly related to the structure angle.

The experimental comparison of CWS with visual inspection and white light interferometer had come to a conclusion that the above parametric relations are correct. It is found out that the roughness that can be visually identified and the micro roughness which not possible to inspect can be easily found and inspected out by the CWS. So in the production line it can be implemented instead of the visual inspection with the similar time accuracy and improved performance.
The readings taken using the white light interferometer are from a very small region. It will not make sense while comparing these smaller regions roughens with the whole measurement, but the comparison shows the similarity and more accuracy of the readings in different areas visually by the CWS. The future of the CWS is to become the next generation roughness measurement instrument due to the visualizing ability and faster measurement.
5.1. **CRITICAL REVIEW**

The aim of this thesis was to find the relation between the CWS parameter and the existing surface parameters used in the industry. Initially conducted a qualitative study by researching on similar papers published, reading books, and related ISO standards and tried to understand the existing parameters of surface. Then tried to understand the CWS in similar manner. Afterwards realized that with just qualitative study the result can’t be achieved, thereby decided to do quantitative study with the support of qualitative study results. This lead to the extension of thesis as more time was required to do this. With the help of quantitative study required result was achieved.

If the group members get another chance to do this thesis they would like to first plan well the tasks to be done so that the thesis would have finished in the right time. Here they started by researching other instruments then analyzes the CWS then again checked with other instruments to compare the parameters. This process was time consuming. Instead if the thesis could have started by understanding the CWS and working principle, the comparison with another instrument would have been easier. Because during researching about the other instruments and parameters, they could have been compared with CWS at the same time.
6. REFERENCES


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Grain Size and Grinding Parameters on Surface Roughness and Grinding Forces when Grinding, 24 5, pp. 447-454.


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7. APPENDIX I: Based on a color distribution statistical matrix

The properties of mechanical parts such as fit, wear resistance, fatigue strength, contact stiffness, vibration, noise is closely associated to surface roughness. It also makes a significant impact on the service life and reliability of mechanical products (Liu, et al., 2016). The general classification of roughness measurement methods are of two types, contact measurement methods and non-contact measurement methods. The methods involving a stylus have high requirements for the environment which are not easy to use and not possible to use for online measurements is contact method. (B.Y, et al., 2004). The various optical measurement methods, ultrasonic methods, scanning tunneling microscopy (STM), and measurement methods based on machine vision technology are the non-contact measurement methods. (T.V., et al., 1993) (B & B, 2008) The high requirement of environment, expensive equipment’s and limited size in measurement makes limited in application of the optical, ultrasonic and STM measurement methods in engineering fields. The light source type design, image preprocessing algorithms, roughness evaluation algorithms and indices, prediction model algorithms, anti-interference ability, and other methods for measuring different processed surfaces are mainly involved in research in the field of machine vision-based measurement technologies (D.M, et al., 1998) (T & M, 2013). Recently the turned specimens have been attained online measurements of the surface (B.M & M.M, 2015). The extraction of the geometric features of the specimen surface is respectable when the machining process has a strong pattern (Shahabi & Ratnam, 2010). If there is a large degree of randomness in the machining process such as grinding, milling, and lapping of a specimen the geometric feature extraction is not relevant.

Basic analysis of the mechanism of imaging of rough surfaces:

“The law of reflection of light states that when light illuminates a target object, the light is reflected by a plane mirror, which formerly reflects the light to the eyes of a person. Thus, the person sees the virtual image of the target object in the plane mirror.” Here the plane mirror is the ground surface, and the eyes of a person is a camera. The light emitted from target object A is first reflected by the ground specimen block will reflects the light which is emitted from the target object and the camera lens will focus this light. Consequently, the virtual image of the target object will be captured by the imaging sensor of the camera. The lens of a camera is a composite lens which includes several lenses. While considering a single thin lens the overall image property of these lens will be significantly like a single thin lens.

The image equation is \[
\frac{1}{f} = \frac{1}{i} + \frac{1}{o}
\]
Where, $f$ is the lens focal length; $i$ is the image distance, that is the distance between the imaging plane and the lens; and $o$ is the object distance, that is the distance between the object and the lens. (Liu, et al., 2016)

In the figure (no) point light source is the target object. In the form of spherical wave part, the point A emits light in all directions that reaches the reflecting surface. The geometrical image will be formed in the point A10 by the concentration of the any two rays which is already passed through point A' in fig (no) a and reflected by the mirror due to the paraxial approximation. A clear point can be captured by adjusting i, the imaging sensor of the camera, A1” stays fixed that is the $f$ and $o$ will be fixed when camera is fixed. Due to the rough surface reflection the lights emitted from point A are scattered in all directions by this way the ground specimen surface will be reflected. There are three situations of which some of the reflected light will not arrive in the view range of the camera Fig (no) (b-d). First situation is when $f$ and $o$ are fixed and focus is done by the specific value $i$ so every reflected rays will not delivers a clear form of image on the camera sensor and by these the roughness will not be fully reflected figure no (b). Second is at point A with a reduced brightness multiple virtual image will be formed due to diffuse reflection, that is one object will have multiple images, A1 and A2. Third situation is the due to the lens of the camera the reflected light will not be focused on the image sensor of the camera fig no (c, d). In Fig (no) (c) Before the image plane the reflected light is focused and in figure no (d)behind the image plane the reflected light is focused. Both situations magnified point is formed as blurry. From the image plane additional focal point is of blurrier image (Sutton, et al., 2009). By the increase of the ground surface roughness at the point A the magnified degree will be greater (Huaian, et al., 2016).

Figure no Imaging by different reflecting surfaces (Liu, et al., 2016).
The surface texture direction of the part and the roughness make a major impact on the size and shape of the virtual image created by a single point light source for a ground specimen block.

The virtual image of the light source will diffuse to two sides (left and right) and the light source is will be aligned horizontally if the texture direction of part is placed perpendicular and camera location is fixed. As proved by the Fig 1 (b-d) The light source will be aligned vertically, the light source will be diffuse to tope and bottom of the virtual image as in the (Figure2 (b)).

Fig: The effect of texture direction of a ground specimen on the alignment of light source (Liu, et al., 2016).

As per the image principle the brightness of a point light source will not influence the size of the virtual image and on the plain mirror the virtual image formed will be on a point. Same as the size and shape of the virtual image will only be affected by the roughness of the ground specimen block, where the texture direction of ground specimen block, location of camera and light source are fixed.
8. APPENDIX II Surface measurement instruments

Surface measuring instruments

Contact
- stylus

Non-contact
Non-optical
- Scanning Electron microscope (SEM)
- X-ray topography

optical
- Focus variation (FV)
- Confocal scanning microscopy (CSM)
- Phase shifting interferometry (PSI)
- Wave scanning interferometry (WSI)
- Coherence scanning interferometry (CSI)

Scanning Electron microscope (SEM)

A focused beam of electrons are used to scan the surface of a sample in Scanning electron microscope. Sample surface topology and composition are achieved from various signal produced after the elections interact with atoms of the sample. Resolution up to 1nm can be achieved in SEM.

X-ray topography

Depending on the surface structure different diffraction patterns are formed when a collimated beam of x-ray hits on the surface. From these pattern computes the surface topography. This technique is new and the main advantage is high resolution 3d Images

Focus variation Instrument (FV)

Focus variation is a method that allows the measurement of areal surface topography using optics with limited depths of field and vertical scanning. Compared to other methods, focus variation is very new in the field of measuring surface texture although its principle was first published in 1924 (von Helmholtz 1924). In the following sections, focus variation is described in detail

Focal variation is a method that permits the estimation of areal surface topography utilizing optics with constrained depth of field and vertical filtering. Contrasted with different methods, focus variation is new in the field of estimating surface
texture in spite of the fact that its principle was first distributed in 1924 (von Helmholtz 1924). In the accompanying areas, focus variation is depicted in detail. On the sample, the optical element is positioned to search the right focus and by analyzing the variation in focal position the depth is been measured. (Scherer et al. 2007, ISO/WD 25178-606 2011). Depth (sample value) is associated to the focal point at a certain distance. To generate the depth map of sample, laterally many positions are processed this way.

Confocal scanning microscope (CSM)

Surface distance is obtained in confocal scanning microscope is by chromatic decoding and dispersion by confocal setting surrounded by single point optical sensors. Surface texture, roundness or coordinates are been measures using these sensors. Calculation of thickness is possible by this method as it can measure transparent material as well as detect several interfaces between materials. Confocal microscopes have metrological characters similar to stylus so this instrument is used as substitute to stylus in non-contact method.

Lateral scanning system and a confocal probe are used in confocal scanning microscope. With the associated light density sensed by the confocal probe at each point the height of profile is been extracted. Line, areal or any geometrical configuration profiles is been measured using lateral scanning system in different axis by linear or rotation stages. The technique is very similar to stylus profilometer thereby showcasing the same advantages like setup length of scanning profile and measuring circular profiles. Confocal scanning is insensitive to unexpected refection from surface or ambient light. Compared to FV confocal microscope doesn’t require vertical scanning to extract the surface height. This instrument comes under the classification ISO 25178-6 2010.

Phase shifting Interferometry (PSI)

By phase shifting interferometry through controlled phase shift interference digitalized data is attained to find the characteristics of an areal surface. 3D images are achieved by this method with repeatability of less than 1nm height measurement.

Phase changes between a sequence of images which are precisely controlled are acquired by PSI. When few fringes are visible on the surface the camera captures images manifesting a shift in position of fringe by shifting the optical path the reference arm with respect to test arm bu a known distance. Phases are shifted to see the change in pattern of fringe and by comparing these, the surface characteristics are achieved. This method is limited to smooth surfaces.

Wave scanning Interferometry (WSI)
Here over time many 2D images are recorded for the changed wave number of the light source in sequences. Here sample need not be mechanically moved for scanning. Bandwidth of the source determines the height resolution here.

CCD(Charged couple device) detector records pattern of wavelength interference from the sample which has been illuminated using tunable laser source with multiple wavelengths combined with a reference mirror. Inverse of wave or change of phase corresponding to wave number is measured to calculate each pixel of the surface height. By increasing the bandwidth the accuracy can be improved. There are not many choices for a laser source that produce uniform wavelength over a long period of time.

Coherent scanning interferometry (CSI)

Complex surfaces with respect to roughness, structure, discontinuities or steps like transparent films can’t be measured using normal interferometer. CSI fills this gap. In addition it also subdues the false interference from scattered light by autofocusing to right level at every point.

When led or similar low coherent source is used in interference microscope it becomes a low-coherence interferometer which is also known as CSI. Focus of interference microscope is scanned vertically across the surface and surfaces were focus is superimposed get a fringe pattern. This pattern is recorded in a video. Fringes are confined near the surface due to low coherent light source. Each pixel of the surface topology for surface is been found by fringe intensity function closest to a surface.
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