THESIS FOR THE DEGREE OF LICENTIATE ENGINEERING

On Deterministic Feature-based Surface Analysis

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Abstract

Manufacturing sector is continuously identifying opportunities to streamline production, reduce waste and improve manufacturing efficiency without compromising product quality. Continuous improvement has been the primary objective to produce acceptable quality products and meet dynamic customer demands by using advanced techniques and methods. Considering the current demands from society on improving the efficiency with sustainable goals, there is considerable interest from researchers and industry to explore the potential, to optimize- and customize manufactured surfaces, as one way of improving the performance of products and processes.

Every manufacturing process generate surfaces which beholds certain signature features. Engineered surfaces consist of both, features that are of interest and features that are irrelevant. These features imparted on the manufactured part vary depending on the process, materials, tooling and manufacturing process variables. Characterization and analysis of deterministic features represented by significant surface parameters helps the understanding of the process and its influence on surface functional properties such as wettability, fluid retention, friction, wear and aesthetic properties such as gloss, matte. In this thesis, a general methodology with a statistical approach is proposed to extract the robust surface parameters that provides deterministic and valuable information on manufactured surfaces.

Surface features produced by turning, injection molding and Fused Deposition Modeling (FDM) are characterized by roughness profile parameters and areal surface parameters defined by ISO standards. Multiple regression statistics is used to resolve surfaces produced with multiple process variables and multiple levels. In addition, other statistical methods used to capture the relevant surface parameters for analysis are also discussed in this thesis. The selected significant parameters discriminate between the samples produced by different process variables and helps to identify the influence of each process variable. The discussed statistical approach provides valuable information on the surface function and further helps to interpret the surfaces for process optimization.

The research methods used in this study are found to be valid and applicable for different manufacturing processes and can be used to support guidelines for the manufacturing industry focusing on process optimization through surface analysis. With recent advancement in manufacturing technologies such as additive manufacturing, new methodologies like the statistical one used in this thesis is essential to explore new and future possibilities related to surface engineering.

Keywords: Characterization, Stylus Profilometer, Coherence Scanning Interferometer, Regression, Manufacturing, Areal surface parameters, Surface profile parameters.

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List of appended papers

The results presented in this thesis are based on the work in the following appended papers:

Paper I: Vijeth V Reddy, Amogh Vedantha Krishna, Fredrik Schultheiss and B-G Rosén, Surface Topography Characterization of Brass Alloys: Lead Brass (Cuzn39pb3) and Lead-free Brass (Cuzn21si3p), Surf. Topogr.: Metrol. Prop. 5 025001, 2017.

Paper II: Vijeth Reddy, Olena Flys, Anish Chaparala, Chihab E Berrimi, Amogh V, BG Rosen, Study on surface texture of Fused Deposition Modeling, Procedia Manufacturing, Volume 25, Pages 389-396, ISSN 2351-9789, 2018.

Paper III: Vijeth V Reddy, Amogh Vedantha Krishna, A Sjögren and B-G Rosén, Controlling the visual appearance and texture of injection molded automotive components. Submitted to Surf. Topogr.: Metrol. Prop.

List of symbols

CSI	Coherence scanning interferometry
GPS	Geometrical product specifications
ISO	International Organization of Standardization
PDF	Probability density functions (PDF)
SEM	Scanning electron microscopy
AM	Additive manufacturing
FDM	Fused Deposition Modeling
ABS	Acrylonitrile Butadiene Styrene
PP	Polypropylene
SI	International System of Units
Sx	Surface parameter
n	Number of surfaces
i	Number of measurements
Sx_m	Mean of surface parameter
Sy	Modeled surface parameter
P	Process variable
k	Number of process variables
$\widehat{Sx}$	Modeled equation
SST	Total sum of squares
SSR	Regression sum of squares
SSE	Sum of squares of residuals
R	Correlation coefficient
R^2	Coefficient of determination
MSR	Mean square regression
MSE	Mean square residual
df	Degrees of freedom
b	Slope of regression line
SE	Standard error
SN_i	Signal-to-noise
Rp	Maximum peak height of the roughness profile.
Rv	Maximum valley depth of the roughness profile.
Rz	Maximum Height of roughness profile.
Rc	Mean height of the roughness profile elements.
Rt	Total height of roughness profile.
Ra	Arithmetic mean deviation of the roughness profile.
Rq	Root-mean-square (RMS) deviation of the roughness profile.
Rsk	Skewness of the roughness profile.
Rku	Kurtosis of the roughness profile.
$Rp1max$	Maximum local profile peak height
$Rv1max$	Maximum local profile valley depth
$Rz1max$	Maximum local height of the profile
RSm	Mean width of the roughness profile elements.

Rdq	Root-mean-square slope of the roughness profile.
Rmr	Relative Material Ratio of the roughness profile.
Rdc	Roughness profile Section Height difference
Rmr (Rz/4)	Automatic relative material ratio of the roughness profile.
RPc	Peak count on the roughness profile.
Sp	Maximum peak height
Spc	Arithmetic mean peak curvature
Spd	Density of peaks
Spk	Reduced peak height (roughness depth of the peaks)
Spq	Root mean square gradient of the scale limited surface
Sq	Root mean square height
Sqnoise	Root mean square height of noise
Sq flat	Root mean square height of measurement on flat
Ssk	Skewness
Std	Texture direction
Str	Texture-aspect ratio
Sv	Maximum pit height
Svk	Reduced valley depth (roughness depth of the valleys)
Svq	Dale root mean square deviation
Sz	Maximum height
t	t-Distribution
Vm(p)	Material volume
Vmc	Core material volume of the scale limited surface
Vmp	Peak material volume of the scale limited surface
Vv(p)	Void volume
Vvc	Core void volume of the scale limited surface
Vvv	Pit void volume of the scale limited surface

Contents

1 INTRODUCTION

This chapter opens with the background to the research field. Following section describes the aim of the thesis, approach, delimitations and thesis disposition.

1.1 BACKGROUND

The term 'quality' has become complex and broad with all-inclusive characteristics that defines or has information on an object. Dr. Joseph Juran [1] defines quality as '*Product's fitness for purpose'* and expands quality into features that meet customer requirements and free from defects or deficiencies. Both aim for higher quality but contradict in the production costs. To ensure robust productivity with good quality, it is important to understand the process and materials behavior upon manufacturing.

With growing competition in the manufacturing sector, focus has increased in producing the parts in a more efficient and controlled approach. In order to control the desired quality, it is important to capture and characterize the output; and maintain control over the quality parameters such as roundness, cylindricity, flatness and also surface deviations. Irrespective of the manufacturing process, solid surfaces contain irregularities or deviations from the prescribed form [2, 3]. Surface metrology helps to capture these surface deviations, also known as surface texture or surface topography, and its relationship with the manufacturing process variables and the function [3, 4].

Achieving reasonable and accurate characterization, evaluation, filtering, classification, monitoring, and prediction of surface topography improves manufacturing precision and assurance for performance of parts [5]. Evaluating manufactured surfaces is challenging, and the methods are still disputable regarding its transcendence. Manufacturing industry currently uses conventional techniques that are still valid but with the growing competition and demand for customized products with higher quality, new methodologies are required to identify solutions for improvement.

For surface texture analysis, statistics is used to resolve the surface features into height, spacing, slope, volume and curvature which are defined by profile parameters in ISO 4287:1997 [6] and areal surface parameters in ISO 25178-2:2012 [7]. These surface parameters help to understand the distribution of features over a manufactured surface. It is not imperative and is often redundant to consider all the surface parameters [8]. For comparing multiple surfaces, it is rather time consuming and inefficient to study all the features that are produced. This propels the need to identify the deterministic features that provides information on distinguishing between the samples and identifying the influence of materials, tool and multiple process variables.

This thesis focuses on identification and analysis of deterministic features from multiple surfaces based on visual and statistical approach. Surfaces produced by subtractive manufacturing, additive manufacturing and injection molding processes are characterized and evaluated. Surface measurements from surface metrology instruments such as stylus profilometer and coherence scanning interferometer are characterized by the surface parameters representing the significant features.

1.2 AIM OF THE THESIS

The overall aim is to develop general methodology to analyze the deterministic features among multiple surfaces applicable to different manufacturing systems. The aim of the thesis is focused on:

- To identify the significant surface parameters and discriminate the surfaces produced by different manufacturing systems and process variables.
- To establish better understanding of the manufacturing process through the characterization of surfaces using significant surface parameters.

- To interpret the surfaces and its function for process optimization.

1.3 RESEARCH QUESTIONS

The thesis is based on the following research questions:

1. Can general surface analysis methods be employed to discriminate surfaces with different manufacturing systems and materials?
2. Does deterministic feature-based surface analysis help to improve the understanding of the manufacturing process?
3. Can the characterized significant surface features interpret optimal surfaces and facilitate process optimization?

1.4 APPROACH

The research approach is built on the surface control loop presented by Stout and Davis, shown in figure 1. Surfaces from turning process, injection molding process and Fused Deposition Modeling (FDM) are captured using optical and tactile methods; Coherence Scanning Interferometry (CSI) for surface area and stylus profilometer for surface profile measurements. Quantifying the features captured help in controlling and improving the efficiency of the process and also the function associated with it. The quantified surface features are parameterized and statistically screened to identify the significant features that vary with respect to the process variables and predict its function.

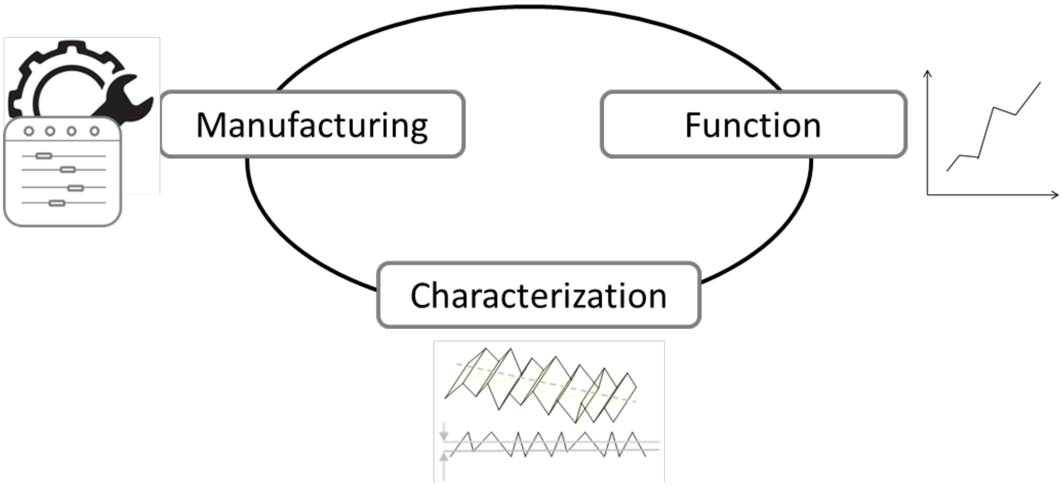


Figure 1: *Relation between manufacturing, characterization and function.* [9]

1.5 DELIMITATIONS

The following are certain limitations within the research approach:

- Surface defects, often associated with random features, are not covered in the thesis.
- Comparison between the surface features from different manufacturing process are not covered in this thesis.
- Scale-limited research: The surface measurements are captured at a particular scale depending on the manufacturing process, surfaces and focus of interest.
- Linear statistical approach is adapted to identify the features that are mostly caused by the controllable variables depending on the manufacturing system under focus.

1.6 THESIS STRUCTURE

Chapter 1 states the aim of the thesis with research approach and limitations.

Chapter 2 describes the manufacturing processes and generated surfaces.

Chapter 3 is an overview of surface metrology and characterization
Chapter 4 describes the research methodology and industrial relevance of the thesis
Chapter 5 discusses the results from the appended papers
Chapter 6 summarizes the conclusions and future work.

The thesis focuses on identifying and analyzing the deterministic surface features using both visual and statistical approach. Surface parameters proposed by the International organization for Standardization are used for quantitative characterization. Random features such as surface defects caused by external noise including mechanical vibrations, environmental conditions and temperature fluctuations are not covered in this thesis. The graphical representation of thesis structure is shown in Figure 2.

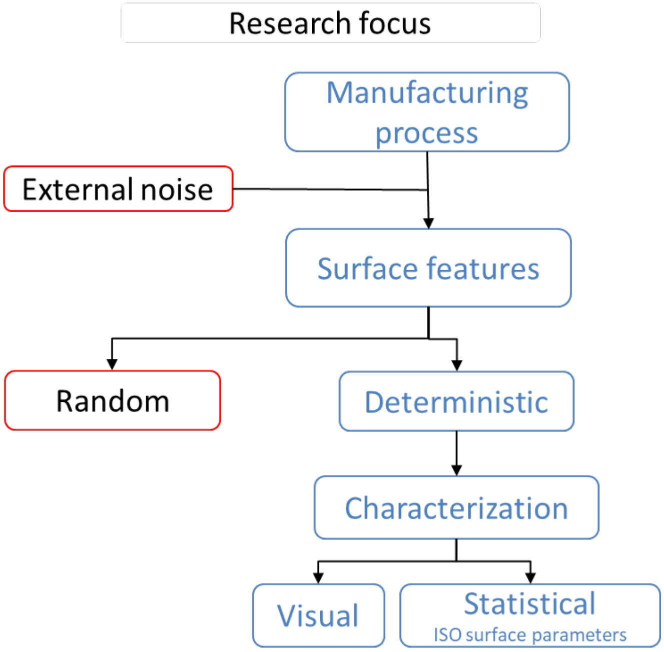


Figure 2: *Thesis structure*

2 MANUFACTURING SYSTEMS

Manufacturing is the process of converting raw materials, components or parts into finished goods based on the requirements creating an economic value. Apart from the factors such as material and design/shape, the economic value depends on the dimensional and surface finish requirements; and operational and cost considerations [10]. Every manufacturing process imparts features on the part surface which includes features put forth by the process and due to errors or vibrations and other external noise. In this chapter, manufacturing systems and the generated surfaces along with critical process variables are discussed.

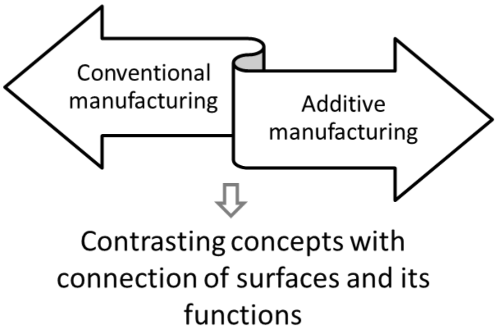


Figure 3: *Connection between different manufacturing systems.*

2.1 CONVENTIONAL MANUFACTURING

In conventional abrasive- and forming manufacturing processes, the workpiece material is removed or plastically deformed towards the desired shape manually or through CNC machine. Depending on the type of material removal, the machining can be classified into traditional and non-traditional operations with traditional operations including turning, milling, drilling, planning, shaping, broaching, gear cutting and boring. The surfaces generated by different operations are unique and are formed by the cutting tool edge and fracture under shear stress [11].

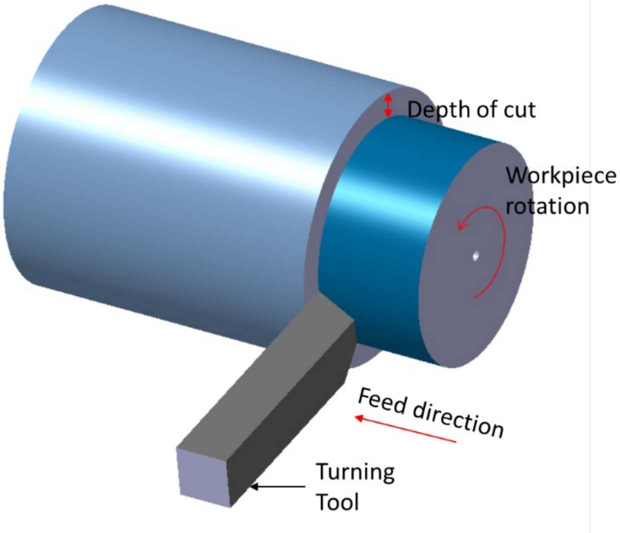


Figure 4: *Turning operation*

Turning process: The cutting tool is traversed into the work piece which is held by the chuck of a lathe and rotated. Turned surface features have dominant lay, as shown in figure 5, generated by single point of the cutting tool moving across the surface during machining. Surfaces generated consists of roughness in macroscopic scale produced by the cutting feed and microscopic range generated by the chip removal [11]. The critical process settings in a turning operation are cutting speed, feed and depth of cut which are adjusted to achieve optimum cutting conditions [11, 12]. The material and geometry of the cutting tool also have significant effect on the turned surfaces [12].

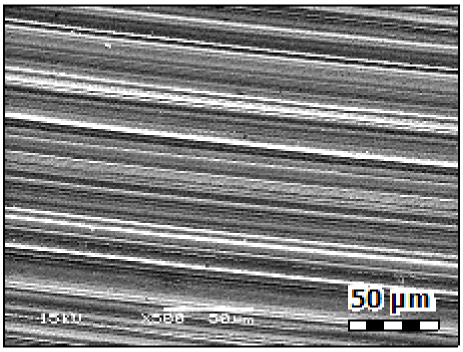


***Figure 5:** SEM image of turned brass sample.*

2.2 INJECTION MOLDING PROCESS

The injection molding process is a manufacturing process which is mostly used to produce plastic parts with complex design and high volume, by thermal softening of thermoplastic or thermosetting materials with aid of heat and pressure [13]. Major advantage in injection molding is mass production of components. Therefore, it is important to maintain the quality to avoid rejection of parts produced in large numbers. Identifying the optimal process parameters is important to maintain high productivity and control the quality. Majority of the automotive interiors are injection molded and the surface topography are investigated to provide better control over appearance and surface functionality.

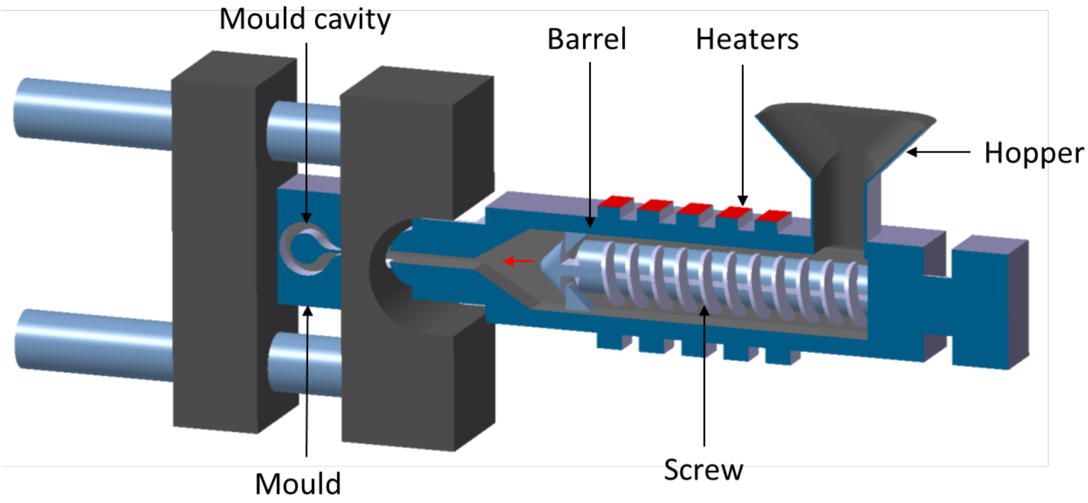


***Figure 6:** Illustration of Injection molding process*

The surfaces on the injection molded parts are replicated from the tool surface, which might have textured or non-textured surfaces. Some of the important variables of injection molding process include condition of resin, mold temperature, tool temperature, melt temperature, injection pressure, holding pressure, injection time, holding time and cooling time [14]. To improve feasibility, function and reduce weight, injection molded thermoplastics are widely used in automotive interiors. Automotive interiors have textured surfaces, as shown in figure 7, controlling the appearance such as gloss/matte and functional properties such as scratch resistance. Several investigations have been conducted to optimize the process and replication of surface features from the mold tool [15, 16, 17, 18]. These studies suggest that by controlling the process variables, it is possible to maintain control over replication of features and its function.

Figure 7: *Injection molded surface*

2.3 ADDITIVE MANUFACTURING

Additive manufacturing (AM), as defined in ISO/ASTM 52900 [19], is a process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies. It involves a sequence of steps and starts from the CAD model converted to STL (Stereolithography) format. The STL file is then sliced into layers depending on set of process variables including layer thickness, print speed, print infill and other set of parameters depending on the type of AM technique used. AM is classified into seven different categories based on the technique and material; Material Extrusion, Material Jetting, Binder Jetting, Vat photo-polymerization, Sheet Lamination, Powder Bed Fusion, Directed Energy Deposition [20].

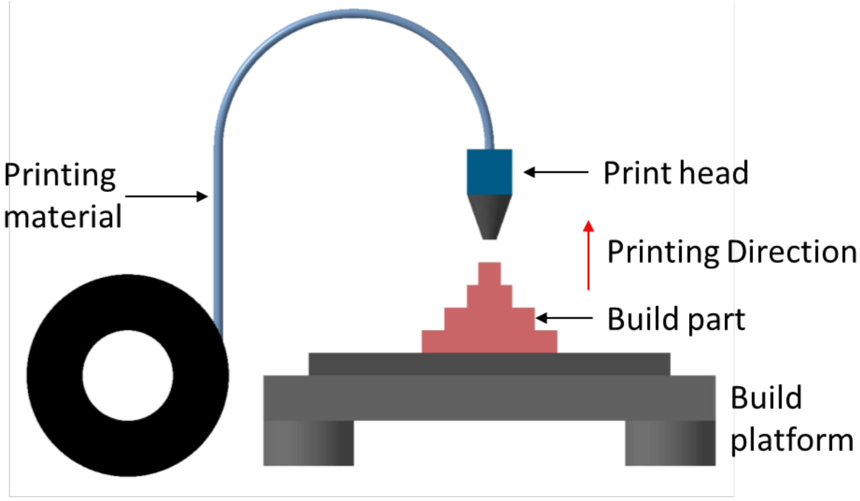


Figure 8: *Additive manufacturing by Fused Deposition Modeling (FDM)*

Fused Deposition Modeling (FDM) is one of the widely adopted additive manufacturing technologies which primarily is used for rapid prototyping with thermoplastics such as Acrylonitrile butadiene styrene (ABS), Polylactic Acid (PLA), Polypropylene (PP) and Thermoplastic Elastomers (TPE). But with the technological advancements, FDM is swiftly moving towards rapid manufacturing exploring new possibilities with respect to part geometries and materials. In FDM, the filament material is melted in the print head, as illustrated in figure 8, and is deposited in layered fashion as in the 3D CAD model [20]. The surface of fused deposition model resembles 'stair stepping' attributed to the layer by layer deposition and raster pattern, shown in figure 9. FDM generates surfaces that are different compared to conventional manufacturing technique and varies with respect to different geometries and process parameters [21]. Most of the studies on FDM have focused on optimizing the process parameters and the key success of additive manufacturing lies in proper selection of process parameters [22]. Some of the process variables include build inclination, layer thickness, print temperature, infill, and print speed [21, 22]

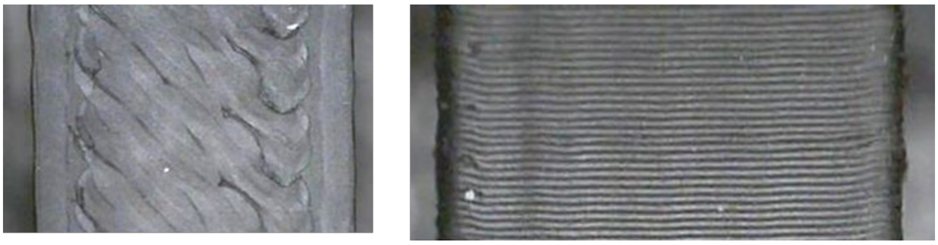


Figure 9: *Raster pattern and stair stepping effect on FDM surfaces*

2.4 SUSTAINABLE MANUFACTURING

With the rise in demand for manufactured products and depleting resources, sustainable manufacturing is more relevant and addressed in recent times. As defined by EPA [23], '*Sustainable manufacturing is the creation of manufactured products through economically-sound processes that minimize negative environmental impacts while conserving energy and natural resources*.' Industries, Innovation and Infrastructure is one of the sustainable development goals propagated by United Nations [24] and recommends on building resilient infrastructure, promoting sustainable industrialization and bolster foster innovation. As cited by UN, '*technological progress is the foundation of efforts to achieve environmental objectives, such as increased resource and energy-efficiency'*. Another sustainable development goal, responsible consumption and production, focuses on ensuring resource efficiency, reduce waste and mainstream sustainability practices across all sectors of the economy [25].

Figure 10: *United Nations sustainable goals* [26]

With Industry 4.0, manufacturing technologies has huge prospects in boosting the man-made capital, in the form of knowledge, especially exploring and understanding the behavior of novel materials with current techniques. This creation in knowledge has paved way to develop customer-specific products, re-manufactured and recycled products. This will have a positive influence on the environmental assimilative capacity, which is described by Hedenus et al., [27], as 'the ability to handle a variety of pollutants and environmental impacts.' The aim for surface topography investigations is well aligned with sustainable objectives, which include identifying optimal process parameters, optimizing process efficiency and part function, thereby driving sustainable manufacturing.

3 SURFACE METROLOGY AND CHARACTERIZATION

Manufacturing sector is continuously working towards achieving the desired quality and function along with improving the manufacturing process efficiency and reducing costs. The quality of a manufactured part can be defined as the specific characteristics that contains or relates information on the function. Functionality of a part or product is directly related to its manufactured part quality and includes surface quality. Surface defects or failure accounts for up to 10% of failing rate for manufactured parts [28]. For any manufacturing systems, identifying the ideal process variables of a process is critical to reduce the defects, boost the efficiency and maximize the function. The influence of process variables on part quality can be determined by two ways; testing its function directly, which in most cases are time-consuming and expensive, or by studying the surfaces generated and interpreting its function. To capture and analyze the information from the manufactured surface, it is important to adopt instrumentation that provides significant results to characterize. Surface metrology is the measurement of deviations from its intended shape and includes roundness, straightness, flatness, cylindricity and also the surface texture left behind by the manufacturing process [3]. Visual comparisons along with standard surface parameters representing the surface texture are widely adopted surface characterization methods in industry.

3.1 SURFACE TEXTURE

Manufactured surface texture consists of roughness, waviness and form [2]. Roughness are the explicitly shaped features from the manufacturing process and the bulk of it are caused and controlled by process variables. Waviness is usually caused by the disturbances during the manufacturing process such as vibrations, temperature variations from surrounding environment. Form is usually the error in form of long waves caused mostly by error in initial setup. Surface topography is known to substantially affect the bulk properties of a material [29]. Therefore, the surface functional properties of a manufactured part can be enhanced by controlling the surface topography generated.

3.2 SURFACE TEXTURE MEASUREMENT

There are several standards specified by International Organization for Standardization, ISO, under the technical committee ISO TC 213 [30] for dimensional and geometrical product specifications and verification. For surface texture measurement, three classification are defined in ISO 25178-6:2010; line-profiling methods, areal topography methods and area-integrating methods [31].

Line profiling methods include measurement of surface deviations in two-dimensional graph or profile represented mathematically as a height function $z(x)$ [31]. Some of the techniques used to capture the surface profile include contact stylus scanning [32], phase-shifting interferometer [33] and the optical differential profiler [34].

Areal-topography methods produces a topographical image of a surface represented mathematically as a height function $z(x , y)$ of two independent variables (x , y) [31]. Some of the techniques used for capturing areal topography include contact stylus scanning [35], coherence scanning interferometry [36], confocal microscopy [37], structured light projection [38], focus variation microscopy [39], angle-resolved scanning electron microscopy (SEM) [40] and atomic force microscopy [41].

Areal integrating methods measures a representative area of a surface and produces numerical results that depend on area-integrated properties of the surface texture [31]. Some of the techniques include angle-resolved scatter [42], parallel-plate capacitance [43], pneumatic flow measurement [44].

Surface measuring instruments used during the course of this research are briefly summarized in the following section:

3.2.1 SCANNING ELECTRON MICROSCOPE

Scanning Electron Microscope, SEM, is an electron microscope where the magnified surfaces are captured using focused beam of electrons. A typical SEM consists of electron gun, two condenser lenses, an objective lens, an electron detection system, set of deflectors and sample holding stage, all of which are operated in vacuum [45]. The electron beam accelerated from the electron gun interacts with the surface of the specimen and generates signals to form the image. SEM images are mostly used for two-dimensional data, but height information can be extracted by stereo photogrammetry which combines SEM images captured at inclined angles [46]. SEM works mostly on surfaces that are conductive; for non-conductive surfaces, coating with conductive material is required.

Visual surface estimations are often subjective and debatable when the surface characteristics are indistinguishable. Hence, contact profilometry and coherence scanning interferometry are used to capture the information in Cartesian coordinates for quantitative characterization.

3.2.2 STYLUS PROFILOMETER

Stylus Profilometer is a contact type measuring device in which the surface profile is captured using the stylus traversed for a predefined length along the surface under investigation [2]. The sampling length of the measurement is defined by ISO 4288 [47] and is based on the average roughness for isotropic surfaces or mean width of roughness elements for anisotropic surfaces/ periodic profiles. The stylus vertical movement following the texture irregularities on the surface while traversed horizontally is detected by a transducer- the probe and corresponding signals are converted to height data. In general, stylus have diamond tip and has radius of curvature ranging from 0.5 to 50µm. The stylus tip is selected depending on the type of surface measured and average roughness. Though the instrument provides traceable-able information with considerable resolution, it requires contact with the surface and is sensitive to soft surfaces.

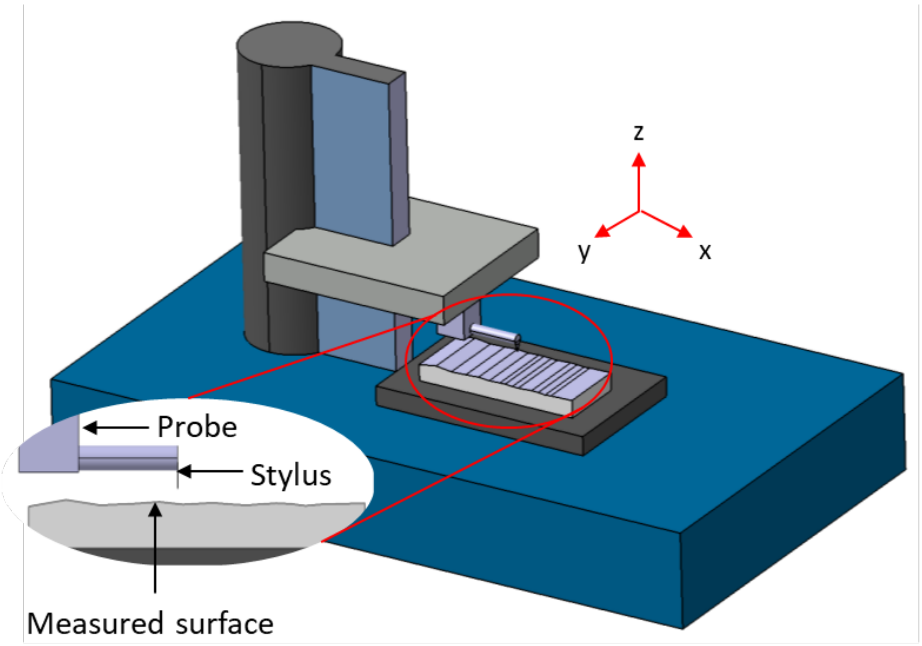


***Figure 11**: Illustration of stylus Profilometer*

3.2.3 COHERENCE SCANNING INTERFEROMETER

Coherence Scanning Interferometer is a non-contact optical measurement instrument to capture areal surfaces. It works on the interferometric technique with electronic data acquisition that provide a signal for each image pixel as a function of scan position [48]. The light from the source is split into two paths, one to the reference surface and the other to the surface to be measured. The reflected beams from the measured surface and the reference recombine and the detector measures the resultant light intensity consisting of multiple points with differences in path lengths [48].

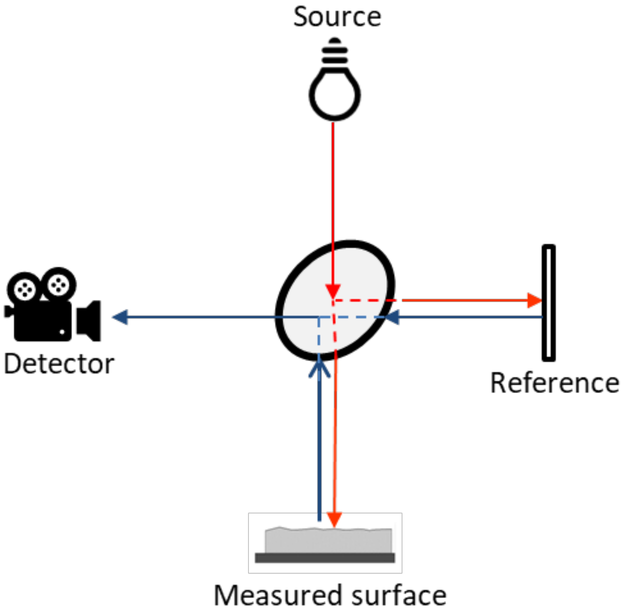


Figure 12: *Illustration of working principle of coherence scanning interferometer*

3.3 SURFACE IMAGING AND ANALYSIS

Surfaces captured using measurement instrument are input to the surface imaging software tool, Digital Surf's Mountains Map. The raw image captured from the instrument contains different levels of noise; from instrument and environment conditions [2, 49]. It is important to remove the noise to capture the relevant and useful information. Filters are applied to remove the irrelevant features and noise [50].

3.4 RELOCATION

In case of high intra-surface variation, it is efficient to relocate the surfaces and reduce the time for capturing and analysis. Relocation refers to capturing exact profile/area transcribed by the tool on samples with a series of surfaces generated in a manufacturing sequence or during its function [51]. Relocated surfaces provide more accurate information on the influence of different process variables on the feature generated on the samples.

3.5 SURFACE CHARACTERIZATION

The surface profile or areal surfaces captured provides qualitative information on the influence of process and its variables. Quantification of these surface data is important to understand the distribution of the features. ISO has indexed standards to define and characterize the features based on the type, region, volume of the features captured. Surface texture captured as profiles are characterized by profile parameters indexed by ISO 4287:1997 [6] and areal surfaces captured are characterized by ISO 25178-2:2012 [7].

3.5.1 ROUGHNESS PROFILE PARAMETERS

Characterization using profile parameters were standardized in 1990s and has been extensively used even today. The Primary Profile is generated from the raw profile captured from stylus profilometer. The nominal form of the raw profile is subtracted to suppress short wave lengths using a λs filter according to the ISO 3274 standard [52]. The Roughness Profile is generated by applying a high pass Gaussian filter according to the ISO 11562:1996 [53] standard and ISO 16610-21 [50] standard. Profile parameters are divided into three groups depending on their type of profile. P parameters are calculated on the Primary Profile, R parameters are calculated on the roughness profile and W parameters are calculated on the waviness profile [54]. The parameters, based on their height, spacing, and distribution, are categorized into amplitude, spacing parameters, material ratio parameters and peak parameters.
The roughness profile parameters are listed in Table 1:

Table 1: *Surface profile parameters [6]*

Family	Abbreviation	Surface profile parameter	Unit
Amplitude parameters	Rp	Maximum peak height of the roughness profile.	µm
	Rv	Maximum valley depth of the roughness profile.	µm
	Rz	Maximum Height of roughness profile.	µm
	Rc	Mean height of the roughness profile elements.	µm
	Rt	Total height of roughness profile.	µm
	Ra	Arithmetic mean deviation of the roughness profile.	µm
	Rq	Root-mean-square (RMS) deviation of the roughness profile.	µm
	Rsk	Skewness of the roughness profile.	
	Rku	Kurtosis of the roughness profile.	
	Rp1max	Maximum local profile peak height	µm
	Rv1max	Maximum local profile valley depth	µm
	Rz1max	Maximum local height of the profile	µm
Spacing parameters	RSm	Mean width of the roughness profile elements.	mm
	Rdq	Root-mean-square slope of the roughness profile.	°
Material ratio parameters	Rmr	Relative Material Ratio of the roughness profile.	%
	Rdc	Roughness profile Section Height difference	µm
	Rmr (Rz/4)	Automatic relative material ratio of the roughness profile.	%
Peak parameters	RPc	Peak count on the roughness profile.	1/cm

3.5.2 AREAL SURFACE PARAMETERS

Areal surface texture provides three-dimensional information on the manufactured surface and is better than profile measurements [8]. The areal surface parameters, based on their distribution, region, type, feature and distribution, are categorized as amplitude parameters, spatial parameters, hybrid parameters, areal functional parameters, areal feature parameters. The areal surface parameters are defined in ISO 25178-2:2012 and the parameters start with letter S or V followed with one or more subscripts [55] as listed in Table 2.

***Table 2**: Areal surface parameters [7]*

Family	Abbreviation	Surface profile parameter	Unit
Height Parameters	Sq	µm	Root-mean-square height
	Ssk		Skewness
	Sku		Kurtosis
	Sp	µm	Maximum peak height
	Sv	µm	Maximum pit height
	Sz	µm	Maximum height
	Sa	µm	Arithmetic mean height
Functional Parameters	Smr	%	Areal material ratio
	Smc	µm	Inverse areal material ratio
	Sxp	µm	Extreme peak height
Spatial Parameters	Sal	µm	Autocorrelation length
	Str		Texture-aspect ratio
	Std	°	Texture direction
Hybrid Parameters	Sdq		Root-mean-square gradient
	Sdr	%	Developed interfacial area ratio
Functional Parameters (Volume)	Vm	$\mu m^3/\mu m^2$	Material volume
	Vv	$\mu m^3/\mu m^2$	Void volume
	Vmp	$\mu m^3/\mu m^2$	Peak material volume
	Vmc	$\mu m^3/\mu m^2$	Core material volume
	Vvc	$\mu m^3/\mu m^2$	Core void volume
	Vvv	$\mu m^3/\mu m^2$	Pit void volume
Feature Parameters	Spd	$1/\mu m^2$	Density of peaks
	Spc	1/µm	Arithmetic mean peak curvature
	S10z	µm	Ten point height
	S5p	µm	Five point peak height
	S5v	µm	Five point pit height
	Sda	μm^2	Mean dale area
	Sha	μm^2	Mean hill area
	Sdv	μm^3	Mean dale volume
	Shv	μm^3	Mean hill volume
Functional Parameters (Stratified surfaces)	Sk	µm	Core roughness depth
	Spk	µm	Reduced summit height
	Svk	µm	Reduced valley depth
	Smr1	%	Upper bearing area
	Smr2	%	Lower bearing area
	Spq		Plateau root-mean-square roughness
	Svq		Valley root-mean-square roughness
	Smq		Material ratio at plateau-to-valley transition

It is well known that manufacturing process produces surfaces which depend on the material, process settings and other external conditions. To completely understand the physics behind manufacturing of these surfaces in micro and nano scale, it is important to characterize and analyze significant surface features represented by the surface parameters. Sa, arithmetic mean height or Ra, average roughness are most commonly used surface parameters for characterization of surfaces. But it is only based on the mean values of the surface height or amplitude variation and does not provide complete information on special properties like wavelengths or features like valleys or pores in the surface. Also, it is mostly redundant to use all the surface parameters to evaluate the surfaces produced. So, a set of significant and relevant parameters might provide the necessary information on the manufactured surface to improve its surface function. In this thesis, a methodology is proposed to choose these significant surface parameters.

4 RESEARCH METHODOLOGY

Manufacturing industry has been increasingly focusing on improving the efficiency of manufacturing and to produce the best quality product. Product quality has different aspects; including functional, visual, cost, features, reliability, repeatability and defect-free. Improving manufacturing efficiency controls the cost and by conformance to standards, other aspects are covered. Identifying the process variables that have a higher influence on the produced quality helps in improving the efficiency of production.

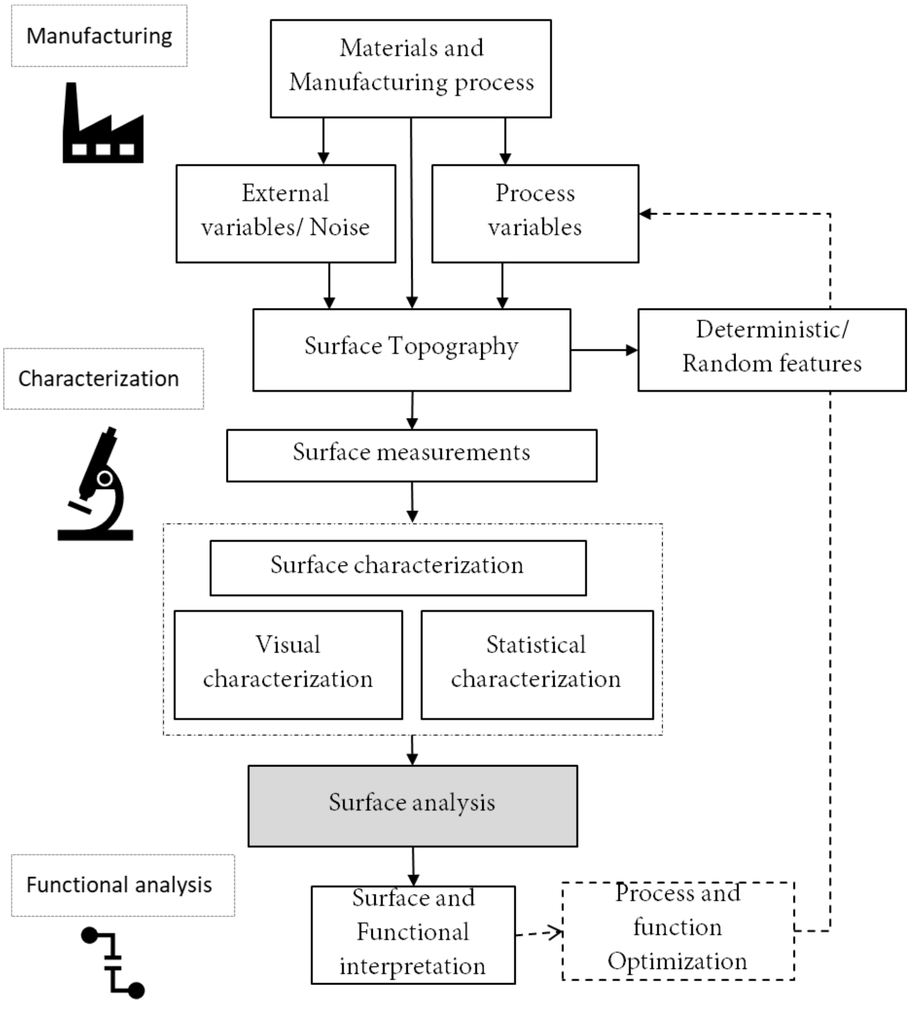


***Figure 13**: Research workflow*

4.1 SURFACE ANALYSIS

The research workflow, shown in figure 13, include numerical characterization of manufactured surfaces produced under different process variables. The surface parameters are the dependent variables which vary with respect to the independent variables (e.g. sampling position, sampling size and resolution, work piece geometry variation, tooling and cutting data). The study includes identifying the relationship between the independent variables and the surface texture. The research focus is to identify a set of robust surface parameters that are capable to describe significant features of the surface texture. Further, comparisons are drawn between the obtained results. interpreting the surface and functional characteristics of the samples.

Depending on the number of process variables, different statistical methods are employed for surface analysis. Average and standard deviation method, correlation coefficient, ANOVA and multiple regression analysis are some of the statistical methods used to extract these robust parameters. These methods are briefly summarized in this section.

4.1.1 CORRELATION COEFFICIENT AND VARIABILITY

Correlation coefficient, R, is a measure of linear association between two variables [56]. It is used to verify whether the relationship exists between the areal surface parameters. Variability is the ratio of standard deviation-to-average. The variability of surface parameter along with the strength of correlation coefficient between the surface parameters helps to shortlist useful group of parameters that are interchangeable. The following conditions are considered in selecting the significant surface parameter [57]:

- Surface parameter having strong correlations with other parameters and lower variability are considered as significant for the study.
- Surface parameter having weak correlations with other parameters and lower variability are considered as significant since they describe a unique property of the surface.
- Surface parameter having strong correlations with other parameters, but higher variability is not considered for the study. They are interchanged with surface parameter with strong correlations within the same category as it is redundant to include both for analysis.
- Surface parameter with lower correlation coefficient and higher variability are not considered in the study.

This method is quite complex for comparing multiple surfaces as the correlation coefficient differs for different surfaces.

4.1.2 AVERAGE AND STANDARD DEVIATION METHOD

In average and standard deviation method, the variation of each surface parameter is analyzed on basis of standard deviation and confidence interval. The surface parameter with the highest significance value, calculated by normalizing with the average values are considered as significant for the study [58]. As illustrated in figure 14, the overlap in the gaussian bell curve of surface parameters, decides whether the surface parameter is significant to discriminate two surfaces. In case of no surface parameter without overlap in the curve, the parameter with the lowest overlap is considered significant for discrimination.

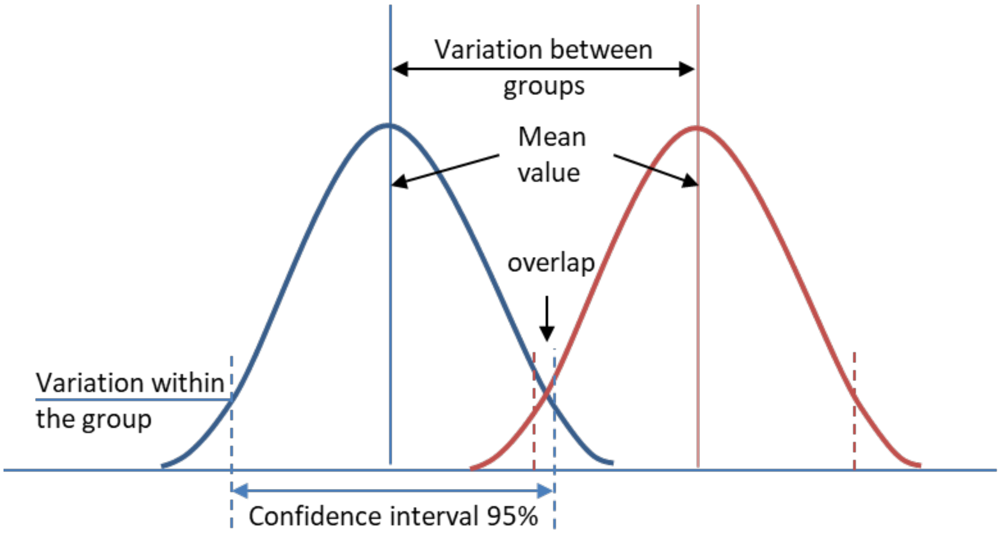


Figure 14: *Gaussian Bell curve illustrating variation within and between groups for two set of surface parameter values*

4.1.3 ANALYSIS OF VARIANCE

ANOVA or analysis of variance is the most commonly used statistical methods in medical research. ANOVA explains how the difference in means can be explained by comparing the variances [59]. ANOVA provides statistical analysis explaining the variation in the surface parameters for multiple surface measurements. ANOVA helps to evaluate the influence of one or more independent variable with multiple levels on surface parameters.

4.1.4 MULTIPLE REGRESSION ANALYSIS

Multiple regression analysis is an extension to ANOVA wherein multiple surfaces can be compared and analyzed. In general, the purpose of the regression analysis is to identify the correlations between the dependent and independent variables and to predict dependent or the response variables on basis of independent or explanatory variables [60]. For surface topography characterization and analysis, multiple regression helps to identify the relationship between the process variables and the surface parameters and helps to identify the influence of the different process variables.

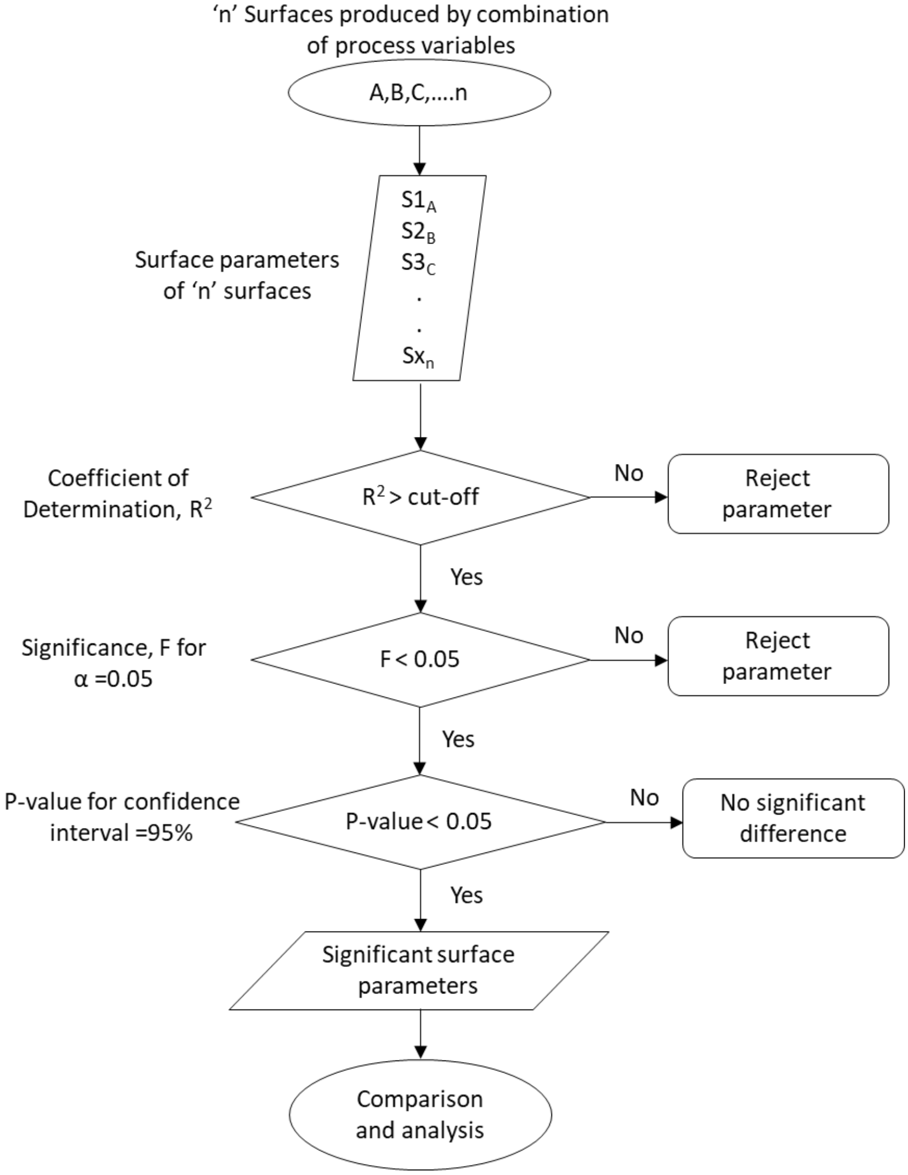


Figure 15: *Research Methodology*

A methodology is designed, as shown in figure 15, to avail this statistical approach for comparing multiple surfaces.
Consider ‘n’ surfaces produced by a combination of manufacturing process variables (A, B, C, ...n). The surface parameter readings of these ‘n’ surfaces is denoted as:

$S1$: $S1_A$, $S1_B$, $S1_C$, ... $S1_n$

$S2$: $S2_A$, $S2_B$, $S2_C$, ... $S2_n$

$S3$: $S3_A$, $S3_B$, $S3_C$, ... $S3_n$

……

Sx: Sx_A, Sx_B, Sx_C, ... Sx_n

In the following sections, three major parts are addressed; correlations using R^2, randomness of the data using F-statistic and the influence of the variables using T-statistic.

Coefficient of determination, R^2: provides information on the proportion of variance of the dependent variables with respect to the independent variables. In general, R^2 demonstrates the overall regression accuracy. With respect to surface study, R^2 helps to identify the variability of surface topographical features with respect to the independent variable.

If, Sx_m is the mean of the surface measurements, Sx_A, Sx_B, Sx_C, ... Sx_n,

$$Sx_m = \frac{1}{n}\sum_{i=A}^{n} Sx_i$$

Total sum of squares, $SST = \sum_i (Sx_i - Sx_m)^2$

Regression sum of squares, $SSR = \sum_i (Sy_i - Sx_m)^2$

Where, $Sy_A \ldots Sy_n$ is the modeled value for surface parameter readings $S1_A$, $S1_B$, $S1_C$, ... $S1_n$.

Sum of squares of residuals, $SSE = \sum_i (Sx_i - Sy_i)^2$

Coefficient of determination, $R^2 = \frac{SSR}{SST}$

$Adjusted\ R^2 = R^2 - (1 - R^2) * \frac{(k-1)}{(n-k)}$, where k is the number of process variables.

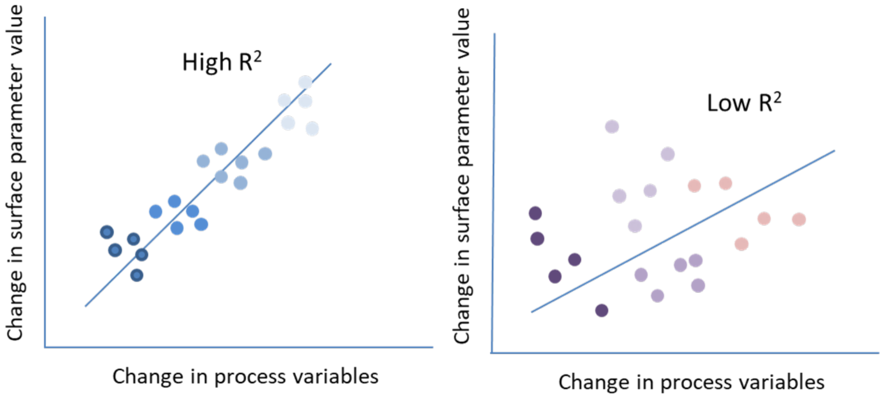


Figure 16: *Illustration of measurements with high and low R^2*

Higher the R^2, the higher will be the variability explained in the surface parameter values, as demonstrated in the figure 16. The surface parameters with higher R^2 display proximity to the regression line.

Significance F: F-Statistic provides information on the randomness of the data. Probability of the measurements with respect to the process variables is not random, if the p-value associated with the F-test is less than α (0.05).

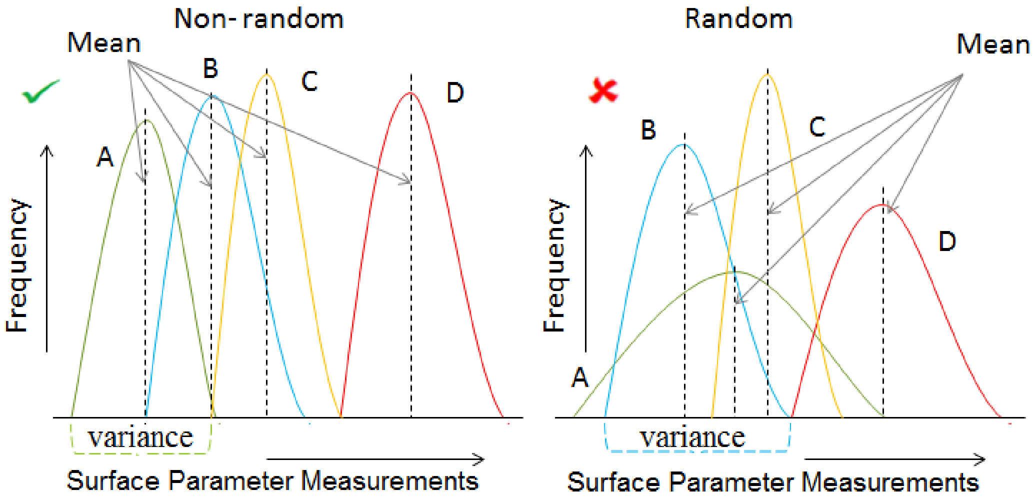


Figure 17*: Illustration of measurements with non-random and random data*

Figure 17 illustrates example for bell shaped normal distributions of non-random and random measurements. For a significant data set, the frequency of the probability density function is higher and has lower variance. For non-random set of measurements, the mode in a bell-shaped normal distribution curve maintains proximity in the range of frequency across all the samples, irrespective of its mean values.

$F\ statistic,\ F^* = \frac{MSR}{MSE},$

Where,

Mean Square Regression, $MSR = \frac{SSR}{df_{SSR}}$

Mean Square Residual, $MSE = \frac{SSE}{df_{SSE}}$

Degrees of freedom, df,

$df_{SST} = Total\ number\ of observations - 1$

$df_{SSR} = number\ of\ variables - 1$

$df_{SSE} = df_{SST} - df_{SSR}$

Considering the threshold for randomness or the significance level α=0.05,

Significance F = F* distribution with respect to df_{SSR} and df_{SSE} in the F distribution table.

Statistical variables are illustrated in figure 18.

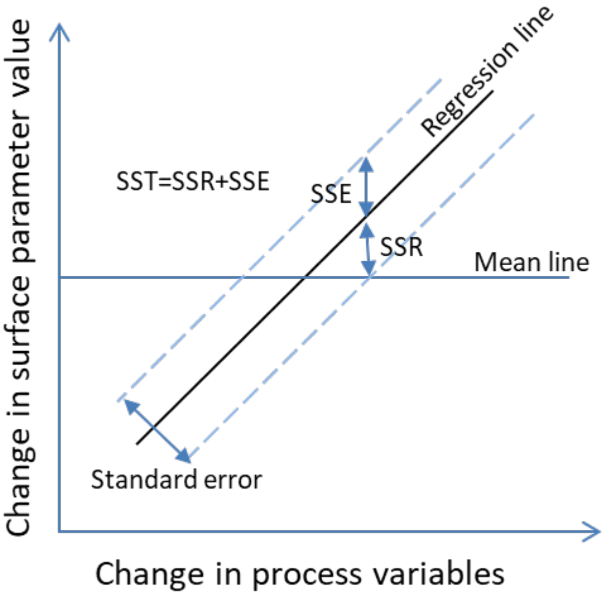


Figure 18: *Illustration of statistical variables*

p-value- helps to determine whether the populations are statistically different and the influence of process variables on surface parameters.

$t - statistic = \frac{b}{SE}$, Where b is the slope of the regression line.

$$Standard\ error, SE = \sqrt{\frac{\sum_i \frac{(Sx_i\_Sy_i)^2}{n-2}}{\sum_i (P_i - Pm)^2}}$$

Where, P_i is the value of the process variable for observation 'i' and Pm is the mean of that particular process variable.
For x^2 at 95% confidence interval, p-value is approximated from the t-statistic distribution table. The influence of the process variables is determined based on this p-values. surface parameter with p-value less than 0.05 is considered to be influenced by that particular process variables.

Regression coefficients: Using the regression coefficients, surfaces can be modelled or predicted which helps to improve manufacturing precision and performance of parts. From the regression analysis, the following equation is generated:

$$\widehat{S_x} = b_0 + b_1 A + b_2 B + b_3 C + \cdots + b_n n$$

Where, $\widehat{S_x}$ is the predicted surface parameter value; A,B, C,…,n are the process variables; b_0 is the value of surface parameter when all the process variables are zero; $b_1, b_2, \ldots, b_n$ are the predicted coefficients calculated using the equation.

$$b_i = \frac{\sum (A_i - A_m)(S_{x_i} - S_{xm})}{(A_i - A_m)^2}$$

Where, A_i is the process variable for i^{th} observation; A_m is the mean value of the process variable A; S_{x_i} is the 'x' surface parameter; S_{xm} is the mean surface parameter.

4.2 ASSUMPTIONS AND LIMITATIONS

The surfaces generated are a result of combined influence of many factors and the surface parameters represent the generated surface features. For surface analysis, the number of process variables considered for an investigation is limited and correlations with the surface parameters vary. The necessity for assumptions in any statistical analysis is primarily due to the data used and the purpose of the study. Accordingly, multiple regression statistics for surface analysis has certain assumptions and limitations which are discussed in this section:

- The relationship between the process variables and surface parameters are linear.

Linear or Non-linear? The spread of the residual plots provides information whether a linear regression or non-linear regression is suitable for analysis. Random distribution shows that the linear regression is suitable for a particular set of measurements. Non-random distribution or a trend in the residual plots shows a non-linear regression is better suited for the analysis.

- Threshold for coefficient of determination, R^2.

Why Threshold for coefficient of determination, R^2? The output from regression analysis provides coefficient of determination for all surface parameters. In order to select robust set of parameters that significantly explain the variation in the data, a limit or a threshold is applied. Thresholding helps to identify the surface parameter or set of surface parameters that have higher correlations and explain the property of the surface significantly.

- Inclusion of both categorical and non-categorical data.

How to include categorical variable? Categorical data can be included using dummy variable which are the dichotomous variable coded to indicate the presence or absence of something. Categorical variables with two levels are coded 0 and 1.

- Model appropriateness is based on R^2 and adjusted R^2.

Linear/Polynomial or Quadratic? The coefficient of determination, R^2, considers that every process variable explains the variation in surface parameters. The adjusted R^2 provides information on the variation in percentage explained by process variables that actually affect the dependent variable. If the difference between the R^2 and adjusted R^2 is high, the inclusion of additional process variables in form of interaction effects or quadratic effects helps to improve the model accuracy.

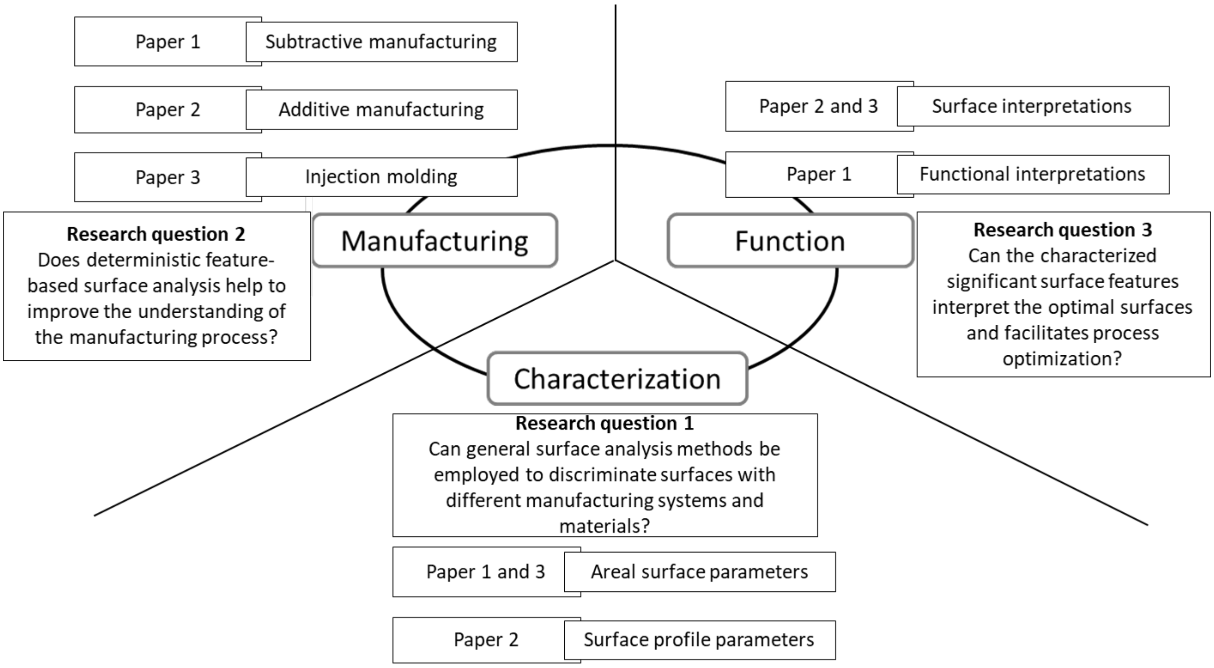
- Measurements from multiple surfaces have unequal variance.

Homoscedasticity or Heteroscedasticity? In general, residual plots are also considered to confirm whether the data is significant. Data showing homoscedasticity do not display a trend in the residual plots. Homoscedasticity refers to dependent variable having same variance in their errors, regardless of the process variables. For surface analysis, the assumption of equal variance is invalid and not considered, since the surface parameters have wide range of variance. The variance in surface topographical features and its distribution is often unequal and hence the surface features are heteroscedastic.

Further, the output of regression analysis can be affected by outliers in the data, multicollinearity and overfitting. Outliers in the data can inflate the regression results, especially linear regression. The inclusion of more data can overfit the model and show inaccurate output results. Regression analysis, irrespective of assumptions and limitations, with measurement data under scrutiny has the potential to detect the deterministic trend in the data and provide valuable output.

5 RESEARCH RESULTS AND DISCUSSIONS

The research results are presented with respect to the methodology reasoning on surface characterization and analysis. Selection of significant surface parameters that represent the deterministic features is adapted for different manufacturing systems and presented in the research papers. The results from the papers contemplates and answers the research questions using the proposed methodology.



Research question 2
Does deterministic feature-based surface analysis help to improve the understanding of the manufacturing process?

Research question 3
Can the characterized significant surface features interpret the optimal surfaces and facilitates process optimization?

Research question 1
Can general surface analysis methods be employed to discriminate surfaces with different manufacturing systems and materials?

***Figure 19**: Classifying thesis structure, research questions and research papers*

The application and analysis based on the deterministic features is briefly summarized in this section in three parts as shown in figure 19.

- Selecting significant surface parameters to identify the significant features to differentiate the study surfaces.
- Using the significant surface parameters to understand the principle of the manufacturing process and influence of process parameters.
- Surface evaluations for process optimization and interpreting its functional behavior.

5.1 PAPER 1: SURFACE TOPOGRAPHY CHARACTERIZATION OF BRASS ALLOYS: LEAD BRASS ($CuZn_{39}Pb_3$) and LEAD-FREE BRASS ($CuZn_{21}Si_3P$)

Considering the dangerous consequences of lead usage in brass products, it is important to identify/ develop a contemporary manufacturing technique to increase the functionality, efficiency and to economically produce the unleaded brass components. The project aims to maintain control on the surface integrity of unleaded brass, substituting lead with silicon. Investigations include turned lead brass and unleaded brass samples, shown in figure 20, captured using coherence scanning interferometer, CSI, characterized by areal surface parameters. The study helps to analyze the influence of the feed rate, material and tool coating on the surface topography of the lead- and unleaded brass through the selection of significant surface parameters.

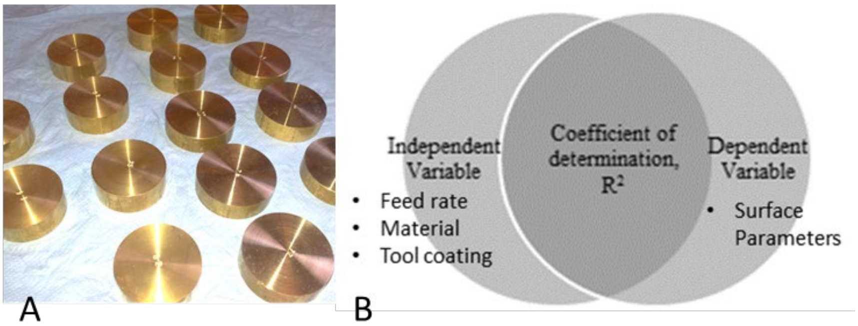


Figure 20: *A. Turned brass samples.*
B. Coefficient of determination. R2, Independent and dependent variables in Paper 1

Areal surface parameters, Sa, Sxp, Sdr, Sdq, Smc, Vmc and Vv are found to be significant for analysis. The surface amplitudes are higher in lead brass compared to the unleaded brass after machining, as shown in figure 21. Unleaded brass has lower surface parametric value compared to the lead brass, shown in figure 22. Tool coating is found to increase all significant surface parameter values except Smc and Vv. The increase in feed rates has increasing effect on most of the samples surface topography.

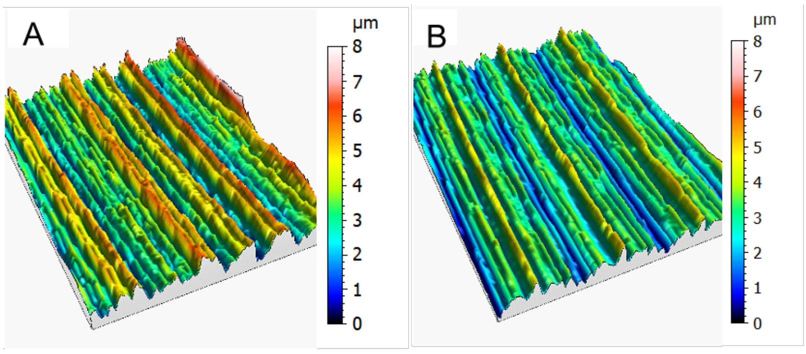


Figure 21: *Turned Lead brass and unleaded brass surfaces*

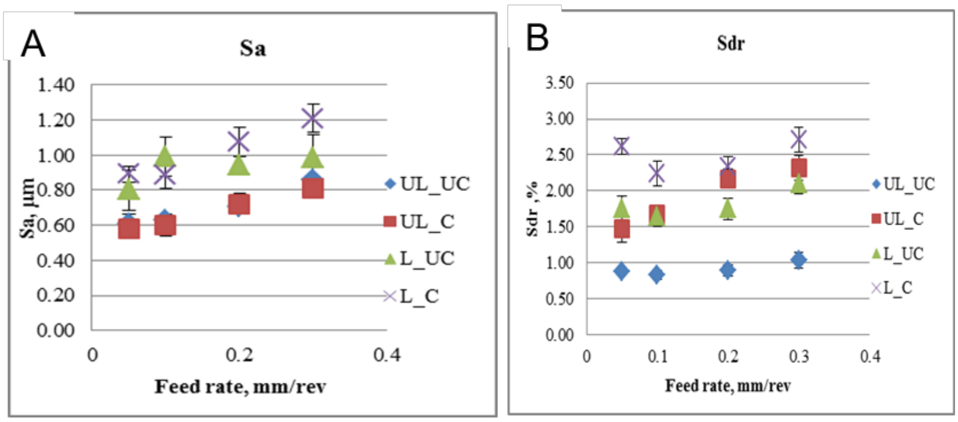


Figure 22: *Mean values of significant surface parameters, Sa-Arithmetic mean height and Sdr- Developed Interfacial area ratio. UL_UC: unleaded brass machined using uncoated tool. UL_C: unleaded brass machined using coated tool. L_UC: lead brass machined using uncoated tool. L_C: lead brass machined using coated tool.*

With lead brass, the lead content provides favorable condition during manufacturing and the surface topography is found to have good fluid retention based on higher Smc and Vv. Hence, brass samples with lead content exhibit favorable condition during manufacturing process.

Higher surface parameter values of the brass samples with lead content makes it vulnerable to corrosion and fatigue. Therefore, the unleaded brass may exhibit better surface functional behavior. From the study results, it is clear that it is possible to control the functional behavior by interpreting the variation of the surface parameters with respect to process variables.

As shown in table 3, the probabilistic variation is drawn from the regression output. Significant parameter values are found to be higher for lead brass and the differences are higher in surface parameters, Smc, Vv, Vmc, Sdc and Sa. The influence of coatings is found to be higher on hybrid parameters, Sdq and Sdr but is insignificant for parameters, Smc and Vv. Feed rates have slightly higher influence on parameters Smc, Vv and Vmc.

Table 3: *Illustrating the probabilistic variation and the difference in influence of the significant parameters from paper 1*

Probabilistic variation ⇩ *: Lower* ⇧ *: higher ; Difference:* ● *: high* ○ *: low.* **/**: *No significant impact*

Significant Surface parameter	**Independent variables**							**Comments**
	Unleaded brass		**Lead brass**	**Uncoated tool**		**Coated tool**	**Feed rates**	**Higher the parameter value,**
Smc (p = 10%)	⇩	●	⇧	⇩	/	⇧	●	Surface exhibits an increase in the fluid retention and debris entrapment
Vv (p = 10%)	⇩	●	⇧	⇩	/	⇧	●	
Sdq	⇩	○	⇧	⇩	●	⇧	○	Better wettability and sealing properties
Sdr	⇩	○	⇧	⇩	●	⇧	○	
Vmc (p = 10%, q = 80%)	⇩	●	⇧	⇩	○	⇧	●	Higher the load withstanding capacity in the material ratio 'p' and 'q'.
Sdc (p = 50%, q = 97.5%)	⇩	●	⇧	⇩	○	⇧	○	
Sa	⇩	●	⇧	⇩	○	⇧	●	Higher the roughness, higher asperities and decrease in wear resistance

5.2 PAPER 2: STUDY ON SURFACE TEXTURE OF FUSED DEPOSITION MODELING

In this study, Truncheon test artefacts, shown in figure 23, are 3D printed by Fused Deposition Process (FDM) at different inclination, layer thickness, material infill and print quality; and its influence on the surface texture are investigated. Taguchi's orthogonal array design of experiments are used to minimize the experiments and simplify the study. Surface profile measurements are captured using stylus profilometer.

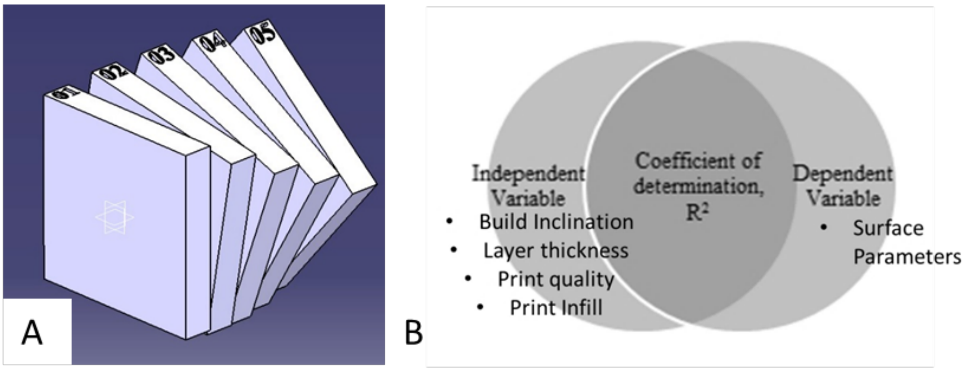


Figure 23: *A) Truncheon artefact. B) Coefficient of determination. R2, Independent and dependent variables in Paper 1*

The surface profile parameters are subjected to regression to identify and analyze the influence of critical process variables and its interactions on the surface texture. The influence of the process variables is quantified using signal-to-noise ratio (SNi), shown in equation 1, on significant roughness parameters. It helps to identify the process variable and the surface feature that vary significantly between the sample surfaces.

$$SN_i = 10\log\left(\frac{mean_i^{2}}{variance_i^{2}}\right) \text{...} \ \text{equation 1}$$

It is observed that the surfaces produced by FDM process vary with respect to different layer thickness and build inclination. Surface roughness parameters, Rp, Rv, Rz, Ra, RSm, Rdc and RPc are considered significant for the study with its variation explained by the process variables. Profile roughness parameters, Ra, Rz, Rp and RSm decrease and peak count parameter, RPc, increase, as build inclination increases. Roughness parameters, Ra, Rz, Rp and RSm of the surface profiles increase and RPc decrease, as layer height increases. Except the peak count parameter, RPc, the influence of material infill and print quality is found to be insignificant on the roughness parameters. The influence of build inclination on Rv and RSm is found to be insignificant but interaction effect of layer thickness and build inclination on Rv and RSm is found to be significant.

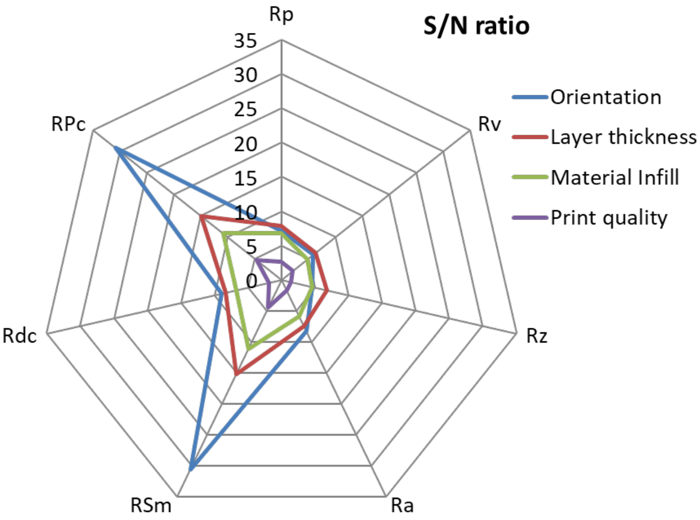


Figure 24: *Signal-to-noise ratio of significant surface parameters influenced by FDM process variables*

As shown in figure 25, the experimental values and the modeled values of Rp, Rv, Rz, Ra, RSm are plotted with respect to the build inclination. These parameters decrease with increase in build inclination and increases with increase in layer thickness. The experimental values and modeled values of RPc increases with increase in build inclination and decreases with increase in layer thickness.

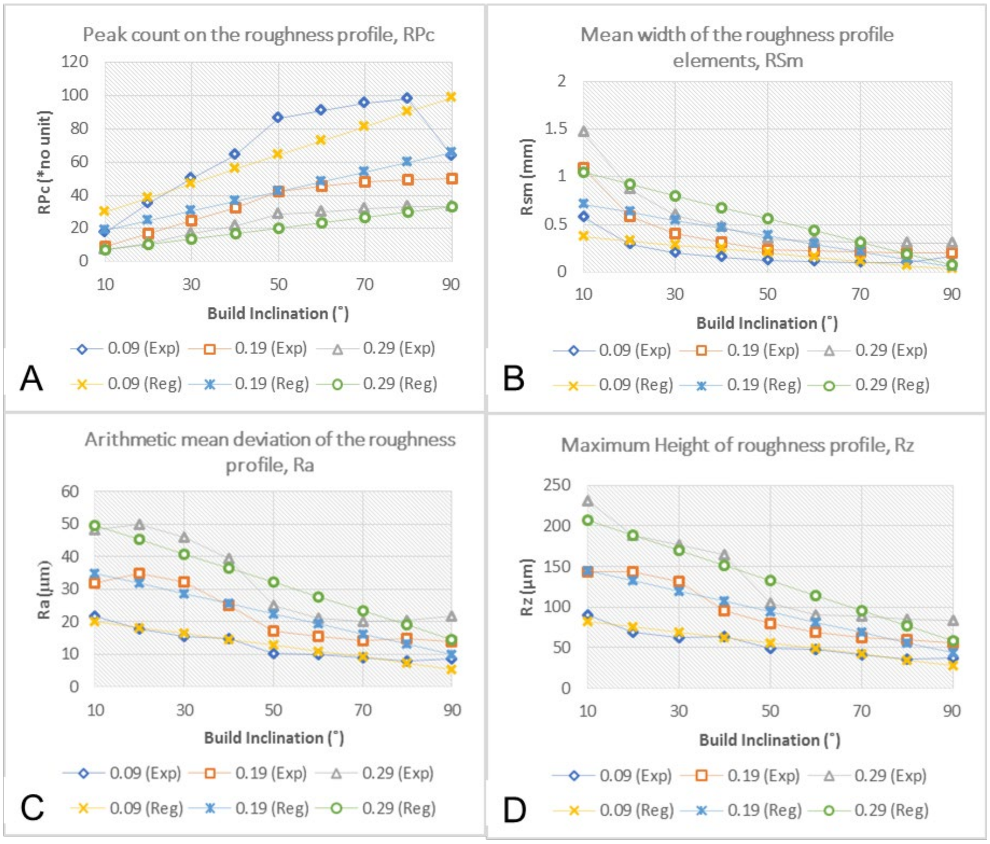


***Figure 25:** Mean values and predicted values of significant surface parameters*

5.3 PAPER 3: CONTROLLING THE VISUAL APPEARANCE AND TEXTURE OF INJECTION MOLDED AUTOMOTIVE COMPONENTS

In this study, investigations are conducted on injection molded Acrylonitrile Butadiene Styrene (ABS) and Polypropylene (PP) samples; and to interpret the relation of surface texture and process variables. The influence of materials and manufacturing process variables on the replicated surface topography of injection molded plastics are examined. The evaluations are conducted on the surface topography captured using Coherence Scanning Interferometry (CSI) and characterized by areal surface parameters. The study aims to generate an understanding of the material's capability to replicate the surface features from the mold die and provide the process designers with knowledge to better control the function through surface texture.

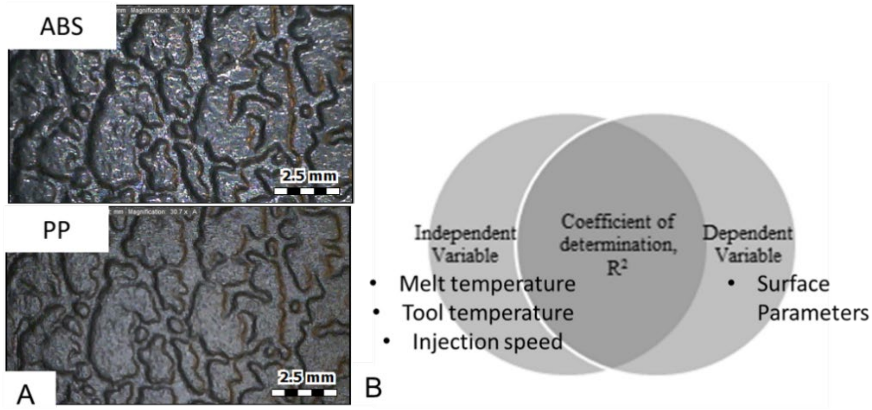


***Figure 26:** A) Injection molded surfaces.*
B) Coefficient of determination. R2, Independent and dependent variables in Paper 1

Injection molded surfaces exhibit similar features in replication of surface topography between the material ABS and PP at macro scale, shown in figure 26. But as observed from the surface images, shown in figure 27, the complexity (high frequency components) in the surface increases as the injection speed and tool temperature increases for both ABS and PP. The effect of tool temperature and injection speed on all surface parameter is found to be statistically significant except for the effect of injection speed on surface parameter, inverse material area ratio, Smc, and Void volume, Vv. The effect of melt temperature is insignificant on most of the surface parameters including the shortlisted significant surface parameters.

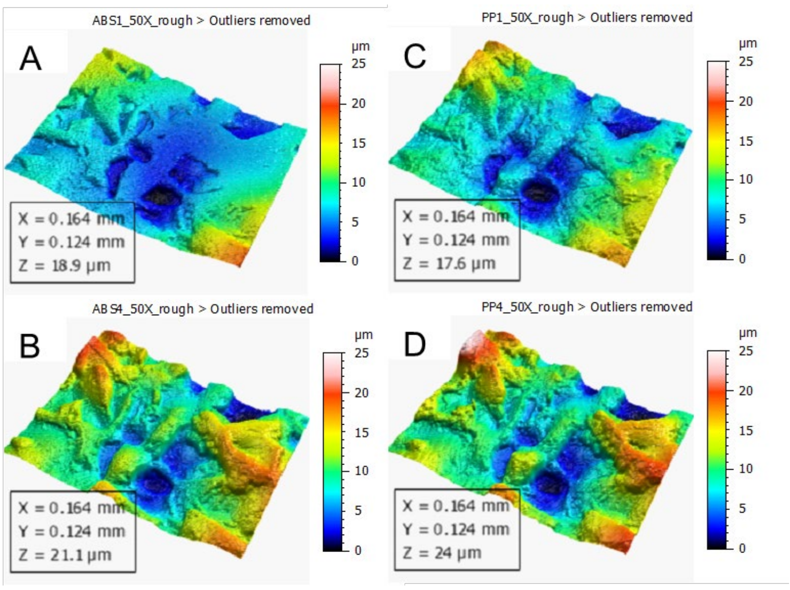


***Figure 27:** Molded plastic sample's surfaces of A) ABS and C) PP manufactured at lower injection speed and tool temperature. B) ABS and D) PP manufactured at higher injection speed and tool temperature*

From the statistical study of surface measurements, the following conclusions are deduced: Process variables of injection molding, tool temperature and injection speed have significant influence on replication of surface features. Higher the tool temperature and injecting speed, higher the values of significant parameter readings. The material depending on the melt flow properties influences the replication of surface features which is noticed on the sample's surface topography manufactured with high and low process settings. The influence of melt temperature is found to be insignificant on the surface measurements.

6 CONCLUSIONS AND FUTURE WORK

Surface investigations primarily aims to optimize the process and improve its surface function. Lack of standards on analysis has left the manufacturing sector to rely on well-established but archaic methods. The methods discussed in this thesis helps to improve this understanding and knowledge on the use of statistical methods for surface analysis. Certain value of a surface parameter, Sa or Ra and its increments or decrements do not provide adequate information to optimize the process and function. Valuable data on statistical distribution of significant features defined by the surface parameters are identified.

Research question 1: Can general surface analysis methods be employed to discriminate surfaces with different manufacturing systems and materials?
From the results of Paper 1, 2 and 3, the statistical approach discussed in the thesis is found to be effective in differentiating the study surfaces. Though the assumptions are debatable and chosen based on the type of surface. The methodology is observed to be valid and efficient for analyzing surfaces manufactured with different techniques, materials and is useful to different applications.

Research question 2: Does deterministic feature-based surface analysis help to improve the understanding of the manufacturing process?
Surface topography does certainly help in understanding the principle of a manufacturing process. To unravel the physical phenomenon and interpret the underlying mechanism it is important to identify the deterministic features caused by the variation in the process variables. From the research results, the significant surface parameters representing the deterministic features helps to evaluate the influence of the process and process variables.

Research question 3: Can the characterized significant surface features interpret the optimal surfaces and facilitate process optimization?
Predicting the surface functional behavior or interpreting the ideal surface topography is important for process optimization. The variation of highly correlated surface parameters provides comprehensive information on the surface functional behavior and using the regression coefficients, the surface pattern can be interpreted for a range of process variables.

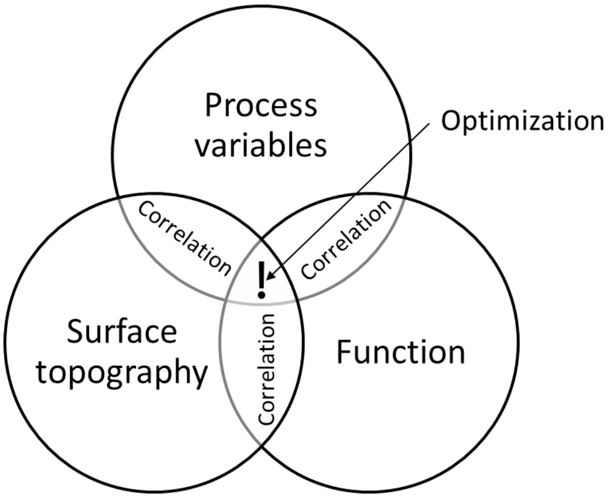


Figure 28: *Process optimization cycle*

Future work: Troubleshooting problems during manufacturing, especially issues pertaining to surfaces are mostly handled offline. With AI based automation forcing its way towards quality control in manufacturing sector, novel methods are required to characterize and analyze the data generated. As the techniques to capture surfaces is sophisticated and the application of standards for characterization is debatable, it is important to analyze the captured information effectively to improve the understanding and explore the capability. As illustrated in figure 28, overall process optimization is achieved by identifying the correlations between the process, surfaces and function. The current thesis covers manufacturing process and surface topography investigations. Future investigations will be focused on surface function and its correlation with the process and surfaces.

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