Robotic mirror finishing KPV (key process variable) optimization in the aerospace industry

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**NANYANG
TECHNOLOGICAL
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**ROBOTIC MIRROR FINISHING KPV (KEY PROCESS
VARIABLE) OPTIMIZATION IN THE AEROSPACE
INDUSTRY**

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Robotic Mirror Finishing Employing KPV Optimization in the Aerospace Industry

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DEDICATION

“To you my stars, who never stopped shining in the west.”

“A ustedes mis estrellas, que nunca dejaron de brillar en el oeste.”

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ABSTRACT

The Aerospace industry has a strong demand for high finish quality in metals, for providing better aerodynamic and mechanical properties, and therefore forcing finishing processes, like polishing, to reach new standards that manual operations are unlikely to deliver. Major concerns rise when performing a polishing process rise, such as repeatability, consistency in force applied and optimization in time. Special developed robotized solutions, utilizing force control, open an unexplored new window, providing alternatives of operation to improve surface texture characteristics when reducing time.

Creating a system capable of producing surface with mirror finish quality is the strategy to be developed in this project. Thanks to methods developed previously for designing experiments, such as the Taguchi method, working parameters are encountered and tuned. Later, using the ANOVA method allows the class definition of the variables and their pertinence in the overall experimentation.

Measurements may prove to be challenging as the instrumentation requires higher resolution. Profile measurements, as well as microscopic views, perform a path to understand the evolution and implications the working parameters have on the surface texture and specifically, the roughness average quality.

Materials such as Stainless Steel, employed for aerospace, have common applications in the fabrication of exhaust collectors, stacks and manifolds, structural and machined parts, springs, castings, tie rods, and control cables; among important factors and depending on the operating environment, light alloys and metals with mirror finish quality can be used for almost any part in aircrafts.

In this research, the author has placed great emphasis involving force control technology in industrial robots, design of experiments, Taguchi method, ANOVA analysis and mirror polishing processes.

NOMENCLATURE

Table 1 indicates the nomenclature employed in this document for ease and understanding of the operations involved.

TABLE 1 NOMENCLATURE AND SYMBOLS

Symbol	Description
G	Grain Size (μm)
$n_{\#}$	Polishing Cycle Number
n_{fc}	Polishing Full Cycles
P_c	Polishing Contact Pressure (KPa)
R_a	Roughness Average (μm)
$R_{a,initial}$	Initial Roughness Average(μm)
$R_{a,Final}$	Final Roughness Average(μm)
T	Polishing Time
v_f	Tool Travel Speed (mm/s)
η	Signal-to-noise ratio
ω	Tool Rotation Speed (rpm)

CHAPTER 1 : INTRODUCTION

Non-uniform distribution of surface defects alter aerodynamic properties in general aviation, therefore suggesting that to vary these characteristics in short time, mirror polishing standards, offered by robotic capabilities are required. The never-ending demand for superior and robust technology, embraces high criterions in the surface finishing of the multiple materials employed in the industrial sectors. Lead time and surface qualities, such as roughness, are critical variables that require optimization and control. It will be impossible to increase productivity and maintain quality in time if current manual tasks continue to be utilized.

FIGURE 1-1 A POLISHING EXAMPLE BY A FANUC ROBOT [1]

From a general perspective, manufacturing processes are classified into two simple types. The initial stage is described as a *processing operation* in which the starting work material is modified attempting to reach the ending desired point. This process adds value and enhances the qualities of the work materials. Polishing (Figure 1-1) is described to be part of a *processing operation* [2] . Secondly, the *assembly*

operation connects multiple work materials to develop a new component that may not be possible to achieve solely with the processing operation.

Polishing and super polishing form part of the group of abrasive processes generally used as finishing operations alongside with honing, buffing and lapping [2]. Unlike grinding, where the objective is to achieve a high removal of material to eliminate imperfections such as scratches or undesired marks, polishing and mirror polishing focus the attention on obtaining a shiner and glossy surfaces for a more appealing end product result, let alone, mechanical properties are enhanced and stress concentrations are relieved. Non-similar

The applications of polishing extend widely in all the manufacturing industrial sectors, especially, but not uniquely, in the secondary industries, see Table 2. The manufacturing industries are established by various groups that satisfy needs providing goods or services. The entities can be classified in three different categories, depending on the company's scope. Primary industries are in charge of extracting and recollecting the raw materials from nature itself. Secondary industries modify the extracted material in order to produce goods and benefits. Tertiary industries are in charge of distributing and provide these services widely.

TABLE 2 CLASSIFIED ENTITIES - THE MANUFACTURING INDUSTRIAL CATEGORIES [2]

Primary	Secondary	Tertiary
Agriculture	Aerospace	
Forestry	Apparel	
Fishing	Automotive	Communications
Livestock	Basic Metals	Entertainment
Quarries	Chemicals	Government
Mining	Computers - Electronics	Information
Petroleum	Constructions	Banking
	Appliances	
	Glass – Ceramics	
	Wood and Furniture	

Polishing in the manufacturing industries is addressed by the need in the quality of the goods. It is possible to encounter, from a set of different ranges that are described by the roughness average measurement, the polishing stages in which every company operates.

The demands on enhancement of results in materials, especially metals, grow when customers' characteristics are required to fulfil diverse tasks involving long endurance and high resistance against corrosion and wear.

Polishing offers stages for all the industrial needs. However, mechanisms of polishing processes are not well comprehended [3]. It is mandatory to evaluate and generate a series of patterns in the experimentations that can allow a repeatability in the future to obtain desired normal values in roughness.

The robotized polishing is a process which tries to replicate the manual polishing and adopts the benefit of the robot accuracy, which manual workers may not possess during long periods of time, and implements it in the process of polishing. A review is performed [4] illustrating the different capabilities robots are able to achieve regarding finishing.

To describe quality, there are parameters that quantify the polishing process. A technical definition, states:

*“**Ra** or **Roughness Average** is the most widely used description of a **surface texture**. This reading relates to a theoretical line where the deviation is measured both up and down from this line, peaks and valleys. In the UK **CLA** or **Center Line Average** is used for calling out surface finish. **CLA** is equivalent to **Ra**.”¹*

In the upper stages of polishing, the process of super mirror polishing is dedicated highly to the optical industries, achieving a roughness average value of $0.002\mu\text{m}$ as

¹Commercial Fluid Power; Surface Finish; [online] Accessed on: 29 Jun 2014
<http://www.commercialfluidpower.com/PDFFiles/SurfaceFinish2010.pdf>;

can be seen in Figure 1-2. Mold and dies, offers a high quality, but the limitations in the mechanical properties increase [4] if there are issues related to inconsistent filling.

FIGURE 1-2 POLISHING STAGES EMPLOYED IN THE MANUFACTURING INDUSTRIES [5]

In a broad description, aerospace employs the polishing requirements mainly residing in the stage #4. The most remarkable example in aerospace exposes the overall drag generated by the different components of the aircraft.

Drag increments associated with roughness can be obtained from construction procedures applied to the skin friction drag in the different parts of the aircraft. These values are found by performing various experiments at different subsonic conditions, comparing the parasite drags with the expected values of drags. Composite aircrafts get smaller drag values [5] associated with roughness, approx. 2%

Even though surface finishing extends highly its quality when employed manually [6], there are parameters, as explained by [7] in 1990, which must be taken into consideration such as productivity, job satisfaction and safety. **Robotic solutions** demonstrate to be beneficial in these tasks and related ones [8]. One efficient way to tackle problematic scenarios is adopting new methods of labor. This implies a re-evaluation of the work area, the type of work performed, whether it is manual or automated, and the tools which are carried to fulfill specific tasks.

Nonetheless, procedures and implementations should be kept in time. On April 7, 2014, [9] reported to Bloomberg news, “*Toyota plans to build a better car company*

by replacing robots with humans”². The situation of Toyota is quite unique, where the world’s largest carmaker will shift to manufacturing platforms that could cut costs by 30 percent. Toyota’s vision is to return to its roots and start off from scratch, solely believing in the skills and exceptional abilities of its employees in the design of cars, to later teach the robots or machines accordingly. This example proves the importance of the optimization in the parameters of the variables which execute processes, rather than the mere fact of producing endless X-amount of elements as Akio Toyoda remarked “He felt Toyota got big-company disease and was too busy getting product out”.

It is then visible, as exposed in the Toyota’s example, that elementary parameters will exceedingly influence the desired outputs and the regulation on them is a decisive factor, and robotic solutions implemented must understand them a priori.

The current difficulty in the aerospace and automobile industry is presented on how to maintain quality and repeatability in a longer term to ensure appropriate standards, without having dependencies on employees that may be prone to commit involuntary errors.

The existent challenges are, the control of critical parameters at levels in which they can operate to produce a satisfactory surface texture. As demonstrated by [10] employing a different robotic solution, the small force ranges could prove crucial in achieving excellent results in surface textures. It is necessary to introduce smaller ranges of operating force control, in combination with other key process variables, which can enhance the overall surface texture.

² Craig Trudell; How Toyota plans to build a better car company by replacing robots with humans; <http://business.financialpost.com/2014/04/07/toyota-robots-humans/>; 07/04/2014

1.1.OBJECTIVES

The main objective of this master thesis project is to determine which variables are influencing in a large scale the response of the robotic polishing process employing metrological techniques. It is believed that the key process variables (KPVs) may offer a description on how to obtain a higher surface texture. “*Surface texture is the combination of short wavelengths deviations, roughness, waviness and lay.*”³

The method in which this objective can be achieved is by constructing a set of data obtained from a number of experimentations, organized in the Taguchi method to later identify the influential input variables to obtain values within a region near the desired nominal value or small variability in the polishing results.

Approaches like ANOVA can be used to help recognize the influential input variables, signal-to-noise ratio, etc. so that the effects of the external factors are minimized.

1.2.METHODOLOGY AND LAYOUT

This project and study offer a broad understanding of the influence of the robotic mirror finishing. It is discussed with mathematical fundamentals and practical reasons the optimal path to achieve the desired output. In a wide view, the experimentation follows a logical path, starting with the identification of variables from a literature review – experience, DOE, data collection, and analysis of variance. The approach taken in this project is not the ultimate and unique solution, rather the creation of motivation to instigate a path of different methods leaping to even higher qualities in shorter times.

The master thesis is organized in chapters to describe in a detailed manner the content.

³ Talati, J. (2008) Surface Roughness – Significance and symbol interpretation in drawing pp. 2

In chapter 1 [***Introduction***], several general key concepts are brought to light, by describing and exemplifying the capabilities of such topics in a real scenario. It also provides information of what is intended to achieve as well as a description of the whole dissertation.

Chapter 2 [***Literature Review***] offers a reconstruction of the evolution in time of the different components that operate in this project, demonstrating that the presented solution has not been performed yet to the letter.

In chapter 3 [***Experimental Design***], a detailed description of the robotic polishing process is carried out, emphasizing the materials in employment (such as the abrasives or consumables and work pieces), the machines in use (such as the robot and the polishing hand tool), and the method (counting with the description of the Area of contact, tool path and experimentation).

Following in chapter 4 [***Results and Discussions***], the offline measurements are presented in a sequential manner, demonstrating the development of the surface as soon as it encounters the different types of elements of polishing. A surface example is illustrated describing the contour change, roughness and waviness alongside the zoomed view. A design of experiment is presented where is argued that mirror finishing can be attained by varying a distinct set of four dimensions

And last but not least, chapter 5 [***Conclusion***], presents the final deductions achieved by the results, fulfilling with the pertinent objectives and offers the future work and direction it may lead.

CHAPTER 2 : THEORETICAL BACKGROUND

This chapter proposes a general description of the principles in the components that have operated in this time, evidencing the changes and the different types of solutions. This chapter introduces the concepts which may close the gaps presented in the previous chapter. Initially displays the polishing principles and different clarifications to then pass to how to identify characteristics on surfaces.

2.1.POLISHING

Generally and historically speaking, polishing has been classified as a manufacturing process, defined in the group of machining, specifically optimized for related abrasive processes (Grinding is an example of abrasive processes) [2]. Although very similar in appearance with the buffing process, polishing is dedicated for the removal of scratches and burrs also smoothing rough surfaces by utilizing abrasive grains attached to a polishing wheel [2]. Buffing's main criteria is to provide shine to make surfaces attractive. This process is regularly performed manually and employs lower speeds. Other processes, such as lapping, differ from polishing in the magnitudes in which abrasives operate.

Polishing is performed using fine abrasive particles to remove surface progressively only in the plastic deformation region without generating brittle fractures on the work surfaces, to create a mirror surface [11]. As can be seen, polishing is a process that involves a surface, abrasives, compounds and high rotational devices that permit the interaction of the previously mentioned agents.

Fine abrasives are particles swaying in the sizes usually between $1\mu\text{m}$ and $30\mu\text{m}$ in length, and in combination with felt end-tools, are used for obtaining mirror finishing. The particles are attached to the felt pad, usually in a liquid form, while a rotational speed is printed on the surface, creating microscopic scratches [11].

Machines developed for polishing have a concentric rotational pad which can be represented as if there is a relative motion mechanism, scratching a workpiece and a polishing pad together. In the past polishing used the relative motion from the operator's hands, and required a higher quantity of time to achieve the desired result.

FIGURE 2-1 PRINCIPLE OF POLISHING - AGENTS INVOLVED

However, the immense variance of the relative human hand's motion was essential for not obtaining accurateness in a straightness surface and a circular surface, and the inadequate work by human operators led to the expansion of lapping and polishing machines [3].

Inaccurateness is not the only problem that requires attention. For maintaining high polishing standards, specific parameters must be maintained in time. Unfortunately, due to the friction produced and the energy dissipated in heat, different phenomena occur. One of them is related to tool wear [12]. As a result, tool wear becomes one of the major inconvenient for large surfaces to be polished.

2.2.CHARACTERIZATION OF SURFACE

Surface has been defined [11] to be as a “*boundary of an object separating an object from another*” and interesting distinctions between the measured surface and the real surface have been represented. The quest of characterizing the real surface extends to a utopic journey due to the fact of the imprecise reconstruction presented in the micrometrical world. It derives an interesting statement, “Dimensions control shape and size of the feature, surface roughness goes one level below and controls the texture of the surface”. The science of metrology encompasses all the possibilities of developing measurement techniques to even minuscule levels. To determine the best settings for measuring the surface texture, three important parameters are identified [13]:

- *Sampling Length;*
- *Evaluation Length;*
- *Traverse Length.*

The **sampling length** relates to the wavelength of the lowest frequency filter. The **evaluation length** can be defined as the total length in the x-axis used for the assessment of the profile under evaluation. The **traverse length** can be defined as the total length of the surface traversed by the stylus in making a measurement [13].

FIGURE 2-2 BASIC COMPONENTS & ELEMENTS OF SURFACE TOPOGRAPHY [14]

SURFACE TEXTURE

From a general perspective, surface texture is defined as a representation of a pulsation travelling along a straight line. It can be performed with contact and non-contact methods. The surface texture is composed by three important elements:

- Form
- Surface Roughness
- Waviness

These elements are registered in the same measurement and are only differentiated for their particular frequencies. Form is characterized for having low frequencies and can be understood as the “longest” wave. Inversely, the surface roughness represents the miniature variations and is described by the high frequencies and in between, the medium frequencies describe the waviness.

FILTERS

Filters are used to delineate and isolate the roughness wavelength band. Unlike the conventional idea, filters are not uniquely related to a mathematical signal treatment. They exist in a mechanical and electronic (or digital) approach.

Mechanical filters are designed in convenience for the reduction of physical system's limitations. One vivid example can be seen throughout the years with the evolution of the Diamond Radius (valley suppression by diamond radius) in contact measurement systems [15]. Typically, the system consists of a stylus, small shaft and a driver motor. For the mechanical filter, the stylus tip has been reducing its size in time allowing the measurement of smaller wavelengths.

Similarly, another property developed, called “skid bridging” on surface valleys, allows the filtering of waviness by manipulating and varying the skid ability in the stylus when performing a linear measurement on a straightness form.

Generally, despite the mechanical filters are designed to have high accuracy in readings, noise is an inherited property of signals [16]. Therefore, digital filter methods are necessary to be robust when dealing signal smoothing.

Essentially, there are two types of filters dealing with noise in signals: signal pre-processing and artificial compensation for inherent noise. For speed (fewer computation hours) and convenience, pre-processing is the most employed method in surface measurements [17].

Developing digital filters may vary in complexity. A single representation of a DC circuit, simulating the analog model of a “resistor and capacitor”, can offer a first order filter. Nevertheless, the requirements for accurate measurements with low capabilities in measurements opened up the opportunity for diverse digital filters to operate. One example is the Gaussian filter.

Mathematically speaking, a Gaussian filter or smoother, is parameterized by its means, μ_f and by the variance, σ_f^2 , equation 1.

$$G_F(\mu_f, \sigma_f^2, t) = \frac{1}{\sqrt{2\pi\sigma_f^2}} e^{-\left(\frac{t-\mu_f}{\sigma_f^2}\right)^2} \quad (1)$$

The Gaussian filter in metrology provides filtered data that is commonly placed around the mean line. However, to arrive at this point, user mainly has to select and choose another crucial parameter named “Cutoff”.

The parameter of cut or “Cutoff” (λ_c) is the longest nominal value of wavelength to be included in roughness [15].

The function of (λ_c) is to define the “line” in which longer wavelengths are discarded and shorter or inferior wavelengths are involved in the measurement.

The length in which the cutoff operates can be seen in Table 3.

TABLE 3 ROUGHNESS “CUTOFF” LENGTH

Millimeters	Inches
0.08	0.003
0.25	0.010
0.8	0.03
2.5	0.10
8	0.3
25	1

Historically, the “specific” boundaries or regimes in which the wavelengths are classified and operate, are usually considered to be higher than 2.5mm for forms or sometimes called errors of form and they are linked to large wavelengths. Wavelengths associated to values less than 0.25mm are related to roughness values. Therefore, waviness is said to be described in the frame of 0.25mm and 2.5mm wavelengths [18].

TABLE 4 SURFACE METROLOGY STANDARDS AND THEIR FIELDS OF APPLICATION

Standard	Roughness	Waviness	Errors of Form
ISO/DIS 12085	X	X	
ISO 1101			X
BS 1134	X	X	
BS 3730			X
ANSI B46.1	X	X	
ANSY Y14.5			X
DIN 4760			X
DIN 4761	X		
DIN 4774		X	

Nonetheless, in the evolution of surface metrology, a notion to identify correctly the separated characteristics of form, waviness and roughness, arouse a need to develop standardized criterions. Table 4 indicates the effort presented to identify the parameters. The identifications presented by different entities around the world

embraced different perspectives as to roughness, waviness and errors of form indicate. Work has been enormous to mitigate and reduce the different perspectives.

Table 4 indicates standardization procedures for surface measurements for straightness in surfaces. A different scheme is presented for roundness in form.

“This International Standard is a geometrical product specification (GPS) standard and is to be regarded as a general GPS standard (see ISO/TR 14638). It influences chain links ... of standards on form, orientation, location and run out, and chain link...”⁴.

ISO STANDARD

- *“ISO 1302 – 2001 Indication of Surface Texture*
- *ISO 3274 – 1996 Nominal Characteristics of Contact (Stylus) Instruments*
- *ISO 4287 – 1997 Terms, Definition and Surface Texture Parameters*
- *ISO 4288 – 1996 Rules and Procedures for Assessment of Surface Texture*
- *ISO 5436-1 – 2000 Calibration, Measurement Standards*
- *ISO 5436-2 – 2000 Calibration, Soft Gages*
- *ISO 8785 – 1999 Surface Imperfections – Terms, Definitions and Parameters*
- *ISO 11562 – 1996 Metrological Characteristics of Phase Correct Filters*
- *ISO 12179 – 2000 Calibration of Contact (Stylus) Instruments*
- *ISO 12085 – 1996 Surface Roughness and Waviness – Motif Method*
 - *ISO 13565-2 – 1996; Geometrical Product Specifications (GPS) – Surface texture: profile method; Surfaces having stratified functional properties – Part 2: Height Characterization using the linear material ratio curve”.*⁵

⁴ ISO 1101:2012 - Geometrical product specifications (GPS) — Geometrical tolerancing — Tolerances of form, orientation, location and run-out, ICS: 01.100.20, 17.040.10, (April 2012)

⁵ Petropoulos P. Georgios, Pandazaras N. Constantinos, and Davim Paulo J. Surface Texture Characterization and Evaluation Related to Machining. Document. (2010) pp. 48-49

FORM

Form is usually described as the profile created from initial processes. Form, waviness and roughness can be modified by different processes including machining, rough grinding and honing among many others. Figure 2-3 displays the obtained average values for roughness after performing a manufacturing process.

FIGURE 2-3 CHART OF TYPICAL SURFACE FINISHES CREATED BY VARIOUS MANUFACTURING PROCESSES [19]

Errors of form are dealt by surface metrology [20]. The concept of form is described as the representation of low frequencies and as described in surface characterization previously, to be visualized, it requires a method for filtering the various wavelength components [21]. Additionally, form possesses different geometric characteristics and they can be listed as: Straightness, planarity, circularity and cylindricity.

LAY

As seen in Figure 2-2, lay may be referred as the defined direction of the process employed on the surface texture. A surface texture may be characterized into two properties, either isotropic or anisotropic.

TYPE	LAY	SYMBOL
Parallel
Perpendicular
Crossed
Multidirectional
Particulate
Circular
Radial

FIGURE 2-4 DIFFERENT KINDS OF LAY AND ASSOCIATED SYMBOLS [22]

When surfaces are machined, heavy patterns are generated and the surface tends to be described as “topographically anisotropic”. Whether a surface is anisotropic then it is said to possess a lay.

Measurement of the surface should possess a stipulated direction, perpendicular to the direction of cut. *“The directional properties affect the tribological function of the surface; also the state of anisotropy can change during function.”*⁶

Diverse numbers of the possible lays exist and are represented as seen in Figure 2-4.

Included to the types of lay presented, another one forms part in the group, lay particulate (Non-directional or protuberant). [23]

SURFACE ROUGHNESS

Roughness average is the key output process variable that requires development and optimization employing the robotic rules. Offering an academic description as said in chapter one, roughness average is defined as *“the area between the roughness profile and its mean line, or the integral of the absolute value of the roughness profile height over the evaluation length”*⁷

A remarkable approach to solve the conundrum including the multi-variable situation to increase the roughness average quality, is applying mathematical procedures in order to delineate the relevance of the different parameters. However, a logical comprehension of the system’s behavior has to be implemented first and it is referred as the design of the experiment.

⁶ Petropoulos P. Georgios, Pandazaras N. Constantinos, and Davim Paulo J. Surface Texture Characterization and Evaluation Related to Machining. Document (2010) pp. 51

⁷ Talati, Jigar. "Significance and symbol representation in drawing," Hexagon Design Centre, May 2012 volume I, pp. 1-9

SURFACE ROUGHNESS PARAMETERS

TABLE 5 AMPLITUDE PARAMETERS

Parameter	Description
Ra	Roughness Average (Ra)
Rq	Root Mean Square (RMS) Roughness
Rt	Maximum height of the profile
Rv, Rm	Maximum profile Valley Depth
Rp	Maximum Profile Peak Height
Rpm	Average Maximum Profile Peak Height
Rz	Average maximum Height of the Profile
Rmax	Maximum Roughness Depth
Rc	Mean Height of the Profile Irregularities
Rz(iso)	Roughness Height
Ry	Maximum Height of the Profile

MATHEMATICAL DESCRIPTION

To comprehend the limitations and extension the influence polishing process may possess, it must be first seen and represented from a mathematical perspective. The representation executed from pioneers in this area, revealed an accurate model implying the constraints and variables. The following equation was developed to represent the arithmetic roughness average in a quantifiable manner.

$$R_a = \frac{1}{l} \int_0^l y \, dl = \frac{\sum_{i=1}^{i=n} y_i}{n} \quad (2)$$

In the arithmetic roughness average equation, y represents the height and depth values from the respective mean line alongside the length, l .

The numeric representation offers an accurate convergence when defining an output. Rather than before, when a technical skillful employee determined by experience which surface surpassed the threshold and which not, now it is determined by roughness average as a first measure.

WAVINESS

Waviness represents the intermediate wavelength band. When a metal surface is polished or treated in general, parameters are affected as a “side effect” of the main purpose. Waviness is a clear example.

According to [24], to describe the waviness profile, the initial profile is filtered utilizing the Gaussian profile filter with a large cut-off wavelength value L_c . The sampling length L_w at the beginning and at the end of the profile will be lost.

The profile is divided into continuous segments. The segments are equally distributed and should be similar in length to the sampling length. To maintain harmony, if the last segment is not equal in length to the sampling length then it is detached. The resulting profile is called the waviness profile. Figure 2-5 displays a visual illustration of waviness height.

FIGURE 2-5 ILLUSTRATION OF WAVINESS HEIGHT⁸

⁸ Cost Effective Machined parts [online] Created on:[March 2010] Accessed on:[July 12th 2014]
[http://images.connect2communities.com/articles/37448/pic1_37448.jpg]

2.3.MEASUREMENT SYSTEMS

Systems defined for measurement can exist in a variety of contact and non-contact devices. Recurring only to visual means to dictate the quality of the mirror finishing on a surface might not be enough to identify patterns produced and left behind by the different manufacturing processes.

Different concepts must be understood primarily, before deepening into the notion of contact and non-contact measurement systems.

“Precision: degree of “fineness” or resolution that can be checked by Repeatability.

Repeatability: the ability to duplicate the result.

Accuracy: conformity to a standard checked against a standard

Resolution (or Discrimination):

- *The amount of change from a reference value that an instrument can detect and faithfully indicate. The measure of this ability is typically the value of the smallest graduation on the scale of the instrument.*

Tool Error: inherent instrument error

Observational Error: error from the eye

Manipulative Error: error from the hand

Bias: unconscious influence causing error”⁹

Higher standards of selections based the criteria upon the previously exposed concepts. In some optical cases, the definition of resolution may seem abstract as image or spatial resolution is cited. Nevertheless, the ideologies remain the same for the metrology systems.

⁹ Measurement System Analysis (MSA) [online] Accessed on: July 2014 Created on: Jan 2012 [https://www.moresteam.com/toolbox/measurement-system-analysis.cfm] Definitions

STATE-OF-ART

NON-CONTACT MEASUREMENT – OPTICAL SYSTEMS

The best example, but not uniquely, of optical systems for surface metrology are microscopes. A microscope in general operates under the principle of magnification of images through the employment of correct glass magnifiers.

The best microscopes are described to have the adequate levels of:

- Resolution
- Magnification and Imaging
- Illumination

The magnifications of the surface at higher scales are necessary to properly visualize in a 2-D plane the patterns created by the polishing tools. Most notably, tool work scratches are left as half-moon patterns (if the end tool is circular shape). As defined earlier, resolution is the capability of the device to identify tiny objects clearly, allowing seeing the space in-between. The concept operates with the modification of the wavelength of light and with the correct lenses.

A model developed describes the smallest distance separating small objects:

$$d_{\min} = \frac{1.22 * \text{Wavelength}}{\text{N. A objective}} + \text{N. A Condenser} \quad (3)$$

The previous equation determines the smallest possible distance in function of the wavelength value. N.A indicates a numerical aperture representing the light absorption of the lens.

The principle of magnification results in the combination of multiple pieces (usually six) of glass that look forward to creating a clear image of a small surface or object [25]. These are needed to correct the so-called spatial aberrations, suffered from refractions in the light beams. Spatial aberrations are corrected by using different curvatures in the lenses with different chromatic properties, enabling less distortion when obtaining an image.

Illumination is another key aspect when trying to obtain an image. The best way to illuminate the specimen involves another lens system, known as a condenser [25]. The front element of the condenser is usually a large, compacted lens that rests beneath the element of measurement.

More properties of non-contact measurement systems are the operation of vertical and horizontal scanning. In the vertical scanning, interferometers are in charge of obtaining relevant information from the electromagnetic waves. While in the horizontal scanning, structured-light scanning takes its part by allowing systematically the creation of patterns of beams of light from different angles. These principles allow the reduction of spatial resolution.

CONTACT MEASUREMENT SYSTEMS

When it comes to contact measurement systems, it is possible to devise the image of a system “touching” the respective surface in a defined distance. The sensor is called a tactile probe.

The tactile probe is based on variations of a magnetic field induced created by a primary coil and later sensed in a secondary coil [26]. In the far extreme, a diamond tip, often referred as diamond stylus, is attached to the beam and connects to a carcass where the coils are set.

The principle of the sensor is based upon the small variations created from the movement of the diamond stylus. The variation of these two coils can be seen in the schematic on Figure 2-6.

Figure 2-6 presents an AC bridge in which there is an unknown inductance produced by the variation of the stylus L_x . Two resistors and a standard inductance known L_s , determine the ranges of tolerances in AC voltage the bridge can offer.

FIGURE 2-6 AC BRIDGE - INDUCTANCE TYPE [27]

Phase is given by direction of measurement. Generally, the standard inductance is variable, to enable calibrations in the future.

JUDGMENT OF THE SYSTEMS

Several projects have been performed comparing surface metrology systems [26]. Identifying correct set-ups for comparing measurement systems is the main objective to find an unbiased result.

The project presented in [26] is developed upon a VLSI Step-Height Standards (SHS 880-QC) - 88 nm height step. Comparison is also carried out using an AFM (Atomic Force Microscope). The conclusions presented are:

“The results show that the tactile measurements are more accurate than the optical measurements. A second comparison is performed on the VLSI Step-Height Standards (SHS 880-QC). Both optical and tactile scans are compared to the AFM measurement and reveal that the tactile scanning and the AFM measurement deviate by only 0.1 nm. The evaluation of the uncertainty budget reveals that it depends on the scanning range of the probe and is equal to 30 nm when the tactile probe is working in the range of 0–100µm”¹⁰

It is possible now to draw the different advantages and disadvantages from both the measurement systems.

TABLE 6 ADVANTAGES AND DISADVANTAGES OF MEASUREMENT SYSTEMS

Non-Contact Measurement	Contact Measurement
No contact with the surface, no possibilities of damaging surface.	Reflective properties attained to light never affect measurement.
Measurement speed is higher.	Ease for use.
For extremely soft or extremely hard materials.	Requires periodic calibration.
Zoom in to respective defined locations.	Affected by vibrations.
3D surface scanning.	Perform better measurements in optics and mirror polishing metals.

¹⁰ H. Nouria et al., "Setup of a high-precision profilometer and comparison of tactile and optical measurements of standards," Laboratoire Commun de Métrologie (LNE-CNAM), Laboratoire National de Métrologie et d'Essais, Paris, France, Research Publication Sci. 2014 – pp. 13

2.4. ROBOTICS

Currently, different efforts have been implemented to create a robotized environment for polishing processes [28].

To comprehend the magnitude, a perspective in the past must exist along with the awareness of the different solutions executed. It is possible to evidence the tendency within the last 50 years of constant improvement in reduction of costs and improvement of efficiency.

For instance, [29] described that, by the end of the 60s, Japan was concerned with the enhancement of the manufacturing process and the JIRA (Japanese Industrial Robot Association) was established to further increase the use of robots in the industry. Japan was then set, as one of the few pioneers with numerous of its companies thriving to remain at the vanguard of the world's technology. Kawasaki in 1972 and Hitachi in 1974 are vivid examples of the path this limitless technology would turn to in specific circumstances.

Robots in manufacturing did not stop there. Following with the example of GM in 1977 with its vision and initiative to compete, believed in the potential Victor Scheinman possessed. The "standard arm" as it is known, proved to be the starting point of a larger desire, the PUMA. Unimation was responsible of this prominent investigation.

Among the major influences affecting the development of robotics, [30] also referred to these as the repeatability, rise in payload capability, work envelope and logically as time proved, "Intelligence".

Aerospace has been no stranger to robotics and it is one of the most prominent industries to push for further developments. In recent times, FANUC ROBOTICS developed an adequate robotic system for arc welding procedures.

The FANUC ARC Mate Series model robots are versatile and are keen on adding value to the automated welding processes by increasing weld quality and improving the quality and security of the workplace.

One emotive and delightful example of the extent of robotic is held within the field of Aerospace and Space Exploration. [29] Described it as:

“All can be remotely operated and have had a common theme of removing mankind from difficult or impossible settings.”¹¹

Industrial robotics’ main capability is the specialization for manufacturing processes. They are necessary because of their high endurance, velocity and precision. Figure 2-7 describes the contribution of robots in different industrial sectors in the market.

FIGURE 2-7 INDUSTRIAL ROBOT PARTICIPATION IN DIFFERENT INDUSTRIES [31]

¹¹ Wesley L. Stone, Robotics and Automation Handbook, 1st ed., Cullowhee, North Carolina, United States of America: CRC Press, 2005. **The History of Robotics** 1.1.9 Space Exploration pp. 16

Accomplishing these tasks, require versatility and diverse characteristics that sometimes cannot be implemented in a single robotic solution, reason why they are subdivided and categorized:

- *Articulated Robot*
- *SCARA* (Selective Compliant Articulated Robot Arm)
- *DELTA*
- *Cartesian Coordinate*

Articulated Robots [Figure 2-8] possess joints to link arms and are able to rotate in their own axes.

FIGURE 2-8 ARTICULATE ROBOT – REVOLUTE [32]

SCARA robots are conformed by a variety of combinations in the type of motions at every joint. The working principle can be seen in Figure 2-9, as it introduces a two initial revolute joints, a translational one for the third axis and a final revolute joint as an end effector.

Different combinations are possible, and it comes in the end to select the best possible for the required task. Many industries opt for having selective robotic solutions that can be fast, repetitive and accurate. These types of robots are found in in the healthcare and food industries mainly.¹²

FIGURE 2-9 SCARA ROBOT [33]

Cartesian coordinate Robots tend to be confused with SCARA robots, because of their similarities. However, a main distinction between them is the ability Cartesian coordinate robots have when moving in multiple linear directions.

¹² Long-reach SCARA robot; January 3rd 2011;
<http://www.healthcarepackaging.com/machine-attributes/robotic/long-reach-scara-robot>;

FIGURE 2-10 CARTESIAN COORDINATE ROBOT [34]

The principle of the Cartesian coordinate robot is to be able to move in a 3D-space, using all the linear directions, being able to have a higher repeatability than the SCARA robot. It is used for soldering circuits, sorting elements, etc.

FIGURE 2-11 DELTA ROBOT PRINCIPLE [35]

Lastly, DELTA robots [Figure 2-11] are functional robots, designed for tasks that require high velocities. Furthermore, the specifications it has involve accuracy, it works in small workspaces and additionally it can operate with high accelerations.

Once the four types of robots have been defined for the respective tasks, the industrial robots are distributed by the most important and influential companies. Among them, it is possible to find ABB Robotics Limited, FANUC, KAWASAKI Robotics Limited, KUKA Robotics LTD, STAUBLI LTD and YASKAWA LTD.¹³

POLISHING SYSTEMS

Polishing machines are devices utilized for performing polishing tasks. They involve manually operated machines and attachable end-tools for robotic purposes.

Polishing machines that operate for one-shaped component include copy polishing machines, semi-automatic polishing machines and centre less polishing machines.¹⁴

A key parameter in the categorization of polishing tools is the noise production thanks to the vibration produced by the inner mechanisms such as high speed gear rotation, etc. When performing a mirror polishing quality component, vibration must be set at very low values or diminished if possible.

Professional manual tools, such as the one provided by the company Minimo, from Japan, offer low noise at high rotational speeds. The hand tool can reach up to 30000rpm offering moderate noise. However, polishing requires tools capable of having low rpms and medium rpms (around 5000 to 12000), provided by Minimo as well.

¹³ British Automation and Robot Association - Robot & Automation Technology Providers [online] [<http://www.bara.org.uk/memberslist.asp>] Accessed on: July 2014 – Created on: July 14th 2012.

¹⁴ Lea Manufacturing – Polishing Machines [online] Accessed on: July 2014 – Created on: 2014 [<http://www.lea.co.uk/products/automation/polishing-machines.php>]

CHAPTER TWO SUMMARY

This chapter, theoretical background, commenced offering a general description of the polishing process in general, describing the polishing levels to the point of achieving mirror finishing qualities.

However, to visualize from a scientific perspective the polishing levels, the chapter continued offering digital methods to identify the characteristic signals. Here, filters and ISO Standards for identifying properties in the signals are given. A short and easy mathematical description is offered additionally.

Also, it is mentioned the types of instruments employed in surface metrology, starting from contact measurement systems and finishing with optical systems. A brief description highlighting advantages and disadvantages is presented.

By the end of the chapter, a historical review is offered for the robotic evolution and the present need as to a possible reason why companies in the future might migrate to adapt this technology. A list of the best companies is shown. For culminating the process, a general description of polishing devices is discussed, giving qualitative and quantitative details to employ certain tools for achieving mirror polishing standards.

Hopefully, the description in this chapter allows a superior understanding on the concepts developed worldwide and in time. Chapter three will perform a more specific illustration of the technologies highlighted here.

CHAPTER 3 : DESIGN AND MODEL

In this chapter, the robotic polishing process is described, providing specific information with respect to the machines utilized, including the robotic solution and the tools to perform a precision polish. Furthermore, the form in which materials are used is described, and the method is thoroughly explained.

The method proposed by [36] is followed because of its optimum solution, establishing an interesting approach to determine the correct variables by using the orthogonal arrays.

3.1.CONVENTIONAL DESCRIPTION

In the configuration of the experiment, different high technological devices (counting from abrasive materials to robotic solutions) combined performed a number of trials focused to find the best configuration for obtaining a mirror finishing result.

The system designated for obtaining the mirror finish operated with a robotic arm. The robot was programmed and controlled by a pendant having different logical sequences of command or algorithms fulfilling the desired path of work and force deployment onto the surface of the material dedicated for the test. The tool path, in which the device of precision polishing had to travel, was a modified S-Scanning path. The main purpose of this modification was to generate extra contact between the surface and the abrasive tool, in a back-and-forth pattern, maintaining the selected feed-rate and force. This is also due to the Minimo precision tool's limitations, as it does not permit an elongated contact time since it may generate heat from the friction and propel damage inside the tool.

3.2.MACHINES

ROBOTIC SOLUTIONS

ABB IRB2400 – 16

As described in chapter two, there are several distinctions in robotic solutions. The ABB IRB 2400 industrial robot (Figure 3-1) is an articulated robot possessing joint links being capable of rotating on its own multiple axes. Also able of following continuous paths established into Cartesian coordinates from point to point. It is also reliable, robust, accurate and fast. [37].

FIGURE 3-1 ABB IRB 2400 – 16 AT ARTC - SINGAPORE

Finishing processes and more specifically polishing processes require a higher force control range. ABB Robotics particularly, has developed different solutions for low force operations.

The IRB 2400 is a dedicated model for low force ranges and possesses grippers and other devices for grasping, modifying or transporting materials, among other utilities. Furthermore, the robot offers the possibility of a 3D scenario representation, which will be shown later, allowing users a clear and concise view of the operation to be performed.

Benefits from the ABB also include a large work envelope that allows higher dimensions to be polished, arc welded, cut, glued, machined or simply transported towards to tools of operation. This is important as the ideal scenario is to develop a tool to piece environment in which the application may be improved in shorter lapses of time. Moreover, ABB offers a system to manipulate accurately the different joins and define end-points, etc. with a FlexPendant attached to the controller.

Also, software for simulation has been researched in order to encounter the best representation of real life scenarios. RobotStudio™ provides a decent exemplification [Figure 3-2]. Given the characteristics of the ABB IRB 2400, it was intended to perform a teaching, embodying the multiple parameters.

This was possible using the software of ABB RobotStudio™, which enabled the creation of object-oriented programming giving attributes in the code to the workpiece and work tool. A trajectory of work was created covering the surfaces in which the polishing process was supposed to take place.

Alternatively, for online operation, safety is always a main priority and the FlexPendant offers an emergency stop button plus a safe operation control located in the backside of the FlexPendant and needs to be pressed repeatedly when manual operation mode is on. It can be considered as a normally-open gate.

FIGURE 3-2 SIMULATION IN ROBOTSTUDIO - IRB2400

When employing a robotic solution for surface finishing, as highlighted in chapter two, there are multiple variables that have an impact on the result. Robotic solutions, guarantee continuity and repeatability in a long term operation.

IRC5 CONTROLLER - PENDANT

The controller is the centralized unit dedicated to performing the mathematical calculations of the robot's kinematics, interface between programmer and robot, network communication, etc. It contains a device that permits to have communication with ease with end-users and the robot. Figure 3-3 displays a controller.

FIGURE 3-3 IRC5 CONTROLLER

In the controller, it was planned to store the logical algorithm with the respective parameters, to enable an easy repetition of the procedures.

As mentioned previously, the FlexPendant allowed safe operations when teaching coordinates, orientations or jogging. A neat and clear interface which allows performing modifications to established programs. Furthermore, the FlexPendant allows calibrations and determines I/O ports.

Several coordinates were taught, from the border to border, allowing a visual comprehension of where the tool had to travel. This procedure had to be done distinctively of the wet and dry process, in order to enhance the results per stage.

FIGURE 3-4 IRC5 FLEXPENDANTMENU FOR AUTOMOBILE OPERATION

POLISHING TOOL

MINIMO – MINITOR M212H

Minimo-Minitor hand tool (Figure 3-5) is a precision instrument that enables fast rotational speeds without the generation of high vibrations that can halt, limit and disrupt the final polishing qualities in the test coupon.

Figure 3-5 Dimensions of Minimo - Handtool with Rotating Tool – units in mm

External control function [38] enabled the option to adapt the hand tool or precision electrical driven hand grinder or polisher, inside the robot domain.

Its weight and characteristics were measured prior to commence any polishing process. The force applied might vary if calibration is not carried out properly and the polishing results may decay to some extent.

CHARACTERIZATION MACHINES

STYLUS PROFILOMETER

Profilometers are divided into two categories, contact and non-contact instruments. Both have properties that adapt to perform readings in circumstances where one type would not deliver a credible and accurate reading.

High accurate readings are obtained when measurements are performed by a contact profilometer.

Contact profilometers are characterized by having a high vertical resolution. According to the Taylor Hobson Company, the gauge range is 12.5mm and the vertical resolution is around 0.2nm.¹⁵ Figure 3-6 displays a measurement example of a curved surface in which the stylus is travelling in a traverse length.

To understand the value proposed by Taylor Hobson of a vertical resolution, that indicates the smallest possible change in an upright manner, it is necessary to visualize different dimensions firstly. From a visual scale a human hair has the value of approximately 100µm in width. A bacterium (bacteriophage) has dimensions in height of around 200nm which is also the same the last visible object from an electronic microscope.¹⁶

Yet, the theoretical vertical resolution presented by the profilometer indicates at least a motion 10 times inferior, compared to the last visual capability of an electronic microscope, 2Å (1Å=0.1nm=10⁻¹⁰m). However, measurements in industry, locate the vertical resolution around 8Å.

¹⁵ Taylor Hobson Co. Form Talysurf PGI 1240 – Accessed on: July 2014 – Created on: 2012 [online] [<http://www.taylor-hobson.com/products/10/110.html#Form-Talysurf-PGI-1240>]

¹⁶ Cary and Michael Huang - The Scale of the Universe [Online] [<http://htwins.net/scale2/>] Accessed on: 1st July 2014 – Created on: 2012

FIGURE 3-6 PROFILOMETER PGI 1240 DISPLAYING VERTICAL CAPABILITY ON A CURVED SURFACE

The Taylor Hobson PGI 1240 is specifically designed for form measurements for small to medium sized optics. This indicates a valid advantage for measuring “mirror finishing” properties.

ZEISS SMARTZOOM5

ZEISS is one of the world leading manufacturers of microscopes [39]. Carl Zeiss Microscopy is a German provider of microscope solutions in the life sciences and materials and also produces optical sensors. It is necessary to understand the mission to properly be able to visualize to potential and capabilities, the Zeiss microscopes possess.

FIGURE 3-7 ZEISS SMARTZOOM 5

Magnification results in the magnifying power the lenses possess. Objective magnification varies in different ranges. In the case of the Zeiss Smartzoom 5, the ranges come from 34X to 500X. This information sometimes differs as it is claimed to have a maximum magnification power of 1011X.¹⁷

The high advantage of the Zeiss Smartzoom 5 is the high image resolution of spatial resolution. As explained in chapter two, what makes an advantage of visual systems is not the ability to have a high number of pixels in a matrix, rather the maximum resolution. In this case, the microscope has around $\sim 1\mu\text{m}$ of spatial resolution.

¹⁷ Zeiss - Smartzoom 5 Technical Data [online] Accessed on: July 2014 – Created on: 2013
[[http://applications.zeiss.com/C125792900358A3F/0/E09242CB71E42F2CC1257CAF00468641/\\$FILE/EN_42_011_126_Smartzoom-5.pdf](http://applications.zeiss.com/C125792900358A3F/0/E09242CB71E42F2CC1257CAF00468641/$FILE/EN_42_011_126_Smartzoom-5.pdf)]

3.3.MATERIALS

ABRASIVE MATERIALS AND POLISHING TOOLS

The range of existing Abrasives is extensive and varies according to the application.

Generally, polishing processes demand two methods for having high finishing requirements; the dry method and wet method. In this experimentation setting, both methods were followed.

Primarily, a dry method offered high removal of material permitting the leveling with cuts that may be present from the initial conditions or from fabrications.

Completing the initial dry method required the variation of grit. The abrasive components were key process variables in accomplishing the optimum and desired normal roughness average value. This method did not require external media to enhance the process. Figure 3-8 displays the dimensions of the abrasive adhesive discs. G#600 describes a rougher, and therefore, more aggressive material remover.

FIGURE 3-8 COATED ABRASIVE DISCS - FROM LEFT TO RIGHT - G#600 || G#1000

Subsequently, the wet polishing method is used for higher qualities in the mirror polishing results. This method was employed when the roughness of the surface was already reduced and realistically, this is the step that offers super polishing and mirror polishing.

FIGURE 3-9 BACKING TOOLS & POLISHING TOOLS- FROM LEFT TO RIGHT - BIG CUSHION DISC - CUSHION DISC - HARD BOB FELT

The polishing tools utilized for the wet polishing method are the hard Bob Felts as can be seen in Figure 3-10. Sizes and areas of contact did play a role factor in the quality of the product but a standard was maintained to avoid large variations, ensuring the pressure contact and using the 2.5cm diameter model.

FIGURE 3-10 BOB FELTS - MINIMO

The difficulty in the design of the experiment lays on the fact that it is not only by one method that it is possible to achieve the smallest roughness average, rather than by a sequence of sweeps using the respective abrasives, however, with the design of the experiment it is possible to evaluate the pertinence and influence of every variable and determine which one is best to be employed at determined stages of the mirror polishing process.

Grit sizes varied in the wet polishing stages, 20 μ m and 3 μ m Alumina slurry compound (Figure 3-11), being the highest the indicator for rougher stages or super polishing and the latter for finer and mirror polishing.

FIGURE 3-11 3 μ AND 20 μ ALUMINA SLURRY COMPOUND

3.4.METHOD

AREA OF CONTACT

Robot's coordinate locations were defined as a main priority, for the polishing tool and work objects or test coupons with respect to the world frame of coordinates. It is necessary to highlight that these coordinates were displacing in X and Y when performing the polishing procedure. However at the moment of performing the teaching of initial points, the ideal settings in the Design of Experiment, required to have different levels of contact pressures by varying the force and area.

Achieving different levels of forces and contact pressures required two different axial rotations from joints three and five. There are two ways of varying the contact area as seen in Figure 3-12.

FIGURE 3-12 CONTACT AREA VARIATION.

The first sketch in Figure 3-12 is done by translation with rotation of fifth joint in the pitch axis so only the last part is having contact. This method is used for grinding at the early stages.

The second sketch is using rotation in the fifth joint in three of its axis, as varying the pitch, yaw and roll in an airplane frame. Not used in many of the trials as many tool traces could be left behind in the test coupon originating waviness.

Correct orientation requires several parameters to be taken into account:

- The orientation must not affect external elements that can halt the movement of the tool's direction.
- A clearance before touching the surface for the first time must exist in order to prevent unexpected scratches.

Physical visualization of this procedure cannot be seen applied unless there is a marker-proof on top of the coupon's surface to demonstrate the area of force.

In Figure 3-13, it is possible to evidence the setting in which the experimentations were carried, allowing the design of experiments to be performed.

FIGURE 3-13 CUSHION DISC SETTING THE ANGLE

TOOL PATH

Right after the angles and the polishing tool's coordinates in the robot's world frame were taught, an evaluation of the most appropriate pattern was performed.

At this stage, it is possible to advance in a positive manner towards achieving mirror polishing. The basic principle of polishing is the smoothing of the material without causing too much material removal that may generate deformations or short customers' requirements. The articulated robot is set and established defining the TCP's tools and test coupons coordinates within its controller.

The polishing and mirror polishing processes must have had this into account because it dictated the force, contact pressure and feed rate to be employed in the surface of the metal piece. Figure 3-14 describes graphically the process.

Figure 3-14 Polishing principle

This process is repeated starting from initial conditions, going from polishing, super-polishing until reaching mirror polishing using changed abrasives.

Several studies indicated that the tool path had a major influence in achieving the right conditions for polishing [40], and despite it was vastly suggested that weaving paths generate better surface's finishes [36], it was opted to have a go for the S-scanning path. S-scanning paths were easy to implement in software and this tool path followed the contour of the test coupon or flat workpiece.

The follow of the contour is a valuable element that did not take part in this particular project, because it was not a shape-changing object. It is suggested that for further research in free-form elements, extensive methods should be explored to ensure that total coverage of areas that require polishing.

The general path can be visualized in Figure 3-15. The abrasive disc in the project, travelled from point A to point B in a repetitive manner until reaching and completing the cycles stipulated to cover the third part of the area.

Figure 3-15 S-Scanning Path [40]

The particularity of the modified s-scan path in this project was based upon different characteristics that are inherited from the manual polishing treatments. Follow the best example of manual polishing for a vehicle, employing a rotational tool (Refinish Network, 2012).

The key in the manual polishing process is the repetition of the polishing mechanism on top of the surface, not only going one time, rather a back-and-forth movement, taking advantage of the polishing efficiency. [36]

The process was established to have an offset of 0.7071cm having a pad diameter of 21mm, avoiding high waviness on the surface. This was set to ensure less tool marks after concluding the process. Moderate differences in waviness were evidenced if a larger value was set.

The offset displacement operated in the Y-positive coordinate as can be seen in the schematic of Figure 3-15.

This modification also varied the time in which the whole process and cycles were terminated. From 10 to 18 minutes was the range with the best configurations of time in which the ABB robot had to operate.

The feed rate was set through software and even though there is a high participation of this key process variable in the final roughness average and material removal results, a more relevant constraint was found as the Minimo hand tool cannot operate for large periods of time maintaining similar magnitudes in force values.

Distance from point A to point B was altered in several occasions to visualize initial contact problems and force overshoot in the system's response. These inherent behaviors are currently being reviewed in an adaptive robotized material removal study. [28].

TEST COUPON - SAMPLES

In the screening experiment, one material was studied in particular, Stainless Steel. However, two different mechanical properties were embraced. Hardness does play a role in the polishing effect as an initial input. However, as a reduction of process variables in determining the optimal conditions for polishing, the most hardened material was preferred for achieving easier mirror polishing.

Test coupon's sizes, dimensions, areas and material properties determined the initial parameters in which the experiments were carried out. Not to forget, that initial conditions ruled the performance and requirements such as deep cuts priorities or chipped edges. Figure 3-16 shows the SUS 304 – Stainless Steel.

The test coupon is a flat surface of 14cm x 7cm, in which there are no high variations in the contour in the Z-direction.

FIGURE 3-16 SUS304 - STAINLESS STEEL - 4 SAMPLES – RA INITIAL CONDITIONS
[MICROMETERS]

The annealed stainless steel was the material employed to perform the tests. Figure 3-17 displays the initial conditions in which the samples were given by the preferred vendor.

FIGURE 3-17 STAVAX STAINLESS STEEL - TEST COUPON 5 – SIDE A

These coupons had the peculiarity of having deep cuts and other scratches. The initial roughness of the coupons could be averaged to the order of $0.2865 \mu\text{m}$. See Table 7.

The coupons' initial condition elaborated an image of what type of abrasive would perform best. However, the deep cuts forced to initiate with an aggressive abrasive, #G-600.

These results can be observed in Chapter 4. Additionally, to these initial coupons, five different samples were received later having higher Roughness Average values. However, the settings learned in this design proved to be correct and applicable for the different cases using Stavax.

TABLE 7 INITIAL ROUGHNESS VALUES - FROM VENDOR

<i>Initial Roughness Value in Coupons. [Stavax Stainless Steel]</i>		
<u>Test Coupon</u>	<u>Roughness Value [μm]</u>	
	<u>Side A</u>	<u>Side B</u>
Coupon 5	0.2834	0.3419
Coupon 6	0.311	0.2370
Coupon 7	0.2523	0.240
Coupon 8	0.410	0.244
Coupon 9	0.279	0.2669
Average	0.3071	0.2660
Tot. Average	0.2865	
Variance	0.0027	

The values registered as the initial roughness quantities are assertive quantities due to the measurement system employed. Resolution of the measurement system is theoretically 0.2nm or 2Å (1Å=0.1nm= 10^{-10}m). The problem begins at the moment when values in readings indicate an inferior magnitude.

Initially, the stainless steel samples received, were measured and analysed using the profilometer.

Table 8 and Table 9 display the readings performed by the profilometer in the “raw” surfaces. More work pieces were measured and the relevant information is displayed. Do note that samples have only one side, counting with four parts to demonstrate the evolution of the polishing method.

TABLE 8 ROUGHNESS AVERAGE - INITIAL CONDITIONS - 6 COUPONS

Roughness Average - Initial Condition – 304 Stainless Steel			
Test Coupon 1	Initial Condition	Test Coupon 5	Initial Condition
Side A	(μm)	Side A	(μm)
<i>Part 1</i>	0.366	<i>Part 1</i>	0.283
<i>Part 2</i>	0.395	<i>Part 2</i>	0.283
<i>Part 3</i>	0.105	<i>Part 3</i>	0.283
Side B		Side B	
<i>Part 1</i>	0.644	<i>Part 1</i>	0.342
<i>Part 2</i>	0.644	<i>Part 2</i>	0.342
<i>Part 3</i>	0.644	<i>Part 3</i>	0.342
Roughness Average - Initial Condition – 304 Stainless Steel			
Test Coupon 2	Initial Condition	Test Coupon 6	Initial Condition
Side A	(μm)	Side A	(μm)
<i>Part 1</i>	0.273	<i>Part 1</i>	0.310
<i>Part 2</i>	0.244	<i>Part 2</i>	0.310
<i>Part 3</i>	0.498	<i>Part 3</i>	0.310
Side B		Side B	
<i>Part 1</i>	0.241	<i>Part 1</i>	0.237
<i>Part 2</i>	0.380	<i>Part 2</i>	0.237
<i>Part 3</i>	0.380	<i>Part 3</i>	0.237

It can be noted that in average, the initial four test coupons (made of 304 Stainless Steel) registered an average value of 0.401 μm and the test coupons five, six, seven, eight and nine (Stavax Stainless Steel), showed an average input value of 0.287 μm , while the samples (Also made from Stainless Steel) indicated a 0.656 μm as an input condition.

Samples and test coupons made of Stavax Stainless Steel had deep cuts which increase the roughness arithmetic value. The input conditions also varied in waviness and form.

TABLE 9 ROUGHNESS AVERAGE - INITIAL CONDITIONS - 7-12 COUPONS

Roughness Average – Initial Conditions – 304 Stainless Steel					
Test Coupon 7	Initial Condition	Test Coupon 9	Initial Condition		Initial Condition
Side A	(μm)	Side A	(μm)	Sample 4 Side A	(μm)
Part 1	0.252	Part 1	0.279	Part 1	0.628
Part 2	0.252	Part 2	0.279	Part 2	0.628
Part 3	0.252	Part 3	0.279	Part 3	0.675
Side B		Side B		Part 4	0.705
Part 1	0.240	Part 1	0.267		
Part 2	0.240	Part 2	0.267		
Part 3	0.240	Part 3	0.267		
Roughness Average – Initial Conditions – 304 Stainless Steel					
Test Coupon 8	Initial Condition		Initial Condition		Initial Condition
Side A	(μm)	Sample 5 Side A	(μm)	Sample 1 Side A	(μm)
Part 1	0.410	Part 1	0.599	Part 1	0.563
Part 2	0.410	Part 2	0.633	Part 2	0.636
Part 3	0.410	Part 3	0.698	Part 3	0.704
Side B		Part 4	0.689	Part 4	0.706
Part 1	0.244				
Part 2	0.244				
Part 3	0.244				

EXPERIMENTAL DESIGN

Correct analysis of data and information, regardless the type of experimentation carried, should reveal the pertinent information and the crucial facts with respect to other variables. Effects and interventions (maybe dependencies) are the main focus and expected relevant information that can be discovered and visualized.

According to [41] the best way to allocate a new experimental test is at the highest calculation of variance. Moreover, the best allocation of experimental resources can depend on the relative cost of trials at one arrangement compared to the cost of trials at a different arrangement.

The DOE (Design of Experiment) plays a crucial factor setting the variables that will be targeted within the approach and their influence in the future outcome.

Having structured the DOE's organization, the mathematical procedure is ready to be employed. The technique is called the Taguchi orthogonal array. The method is versatile and has a high accuracy (linear experiments) when dealing with optimization. It will be evident later the importance of this method when performing a limited n-number of experiments with different patterns (either because of budget limitation or materials lifespan or steps in polishing efficiency).

Taguchi method adapts finest to describe the best platform operating the diverse experimentations.

Defining the amount of minimum experiments to be carried out in the Taguchi method, knowing the degrees of freedom in the system related to the amount of possible combinations deducting one (Equation 3). Deciding then the orthogonal matrix becomes a task of understanding which variables are truly more pertinent.

$$N_{Taguchi} = 1 + \sum_{i=1}^{NV} (L_i - 1) \quad (4)$$

In equation 3, it is possible to identify NV, which indicates the “Number of Variables” as well as L_i which indicates the levels in the variables. For instance, there are three levels in the variable of rotational speed as it includes 6000, 9000 and 12000rpms.

In this experimentation, $N_{Taguchi}$ indicates $L_9(3^4)$.

There have been different advances in the Taguchi method; nonetheless, in this case, results will be upon the-smaller-the-better standard due to the nature of the experiment itself, the reduction of roughness.

3.5. ALGORITHM AND FLOW DIAGRAM

Initially, the indication developed in the software was to identify the process that was being executed. In the initial stages of polishing, as described previously, Dry processes are better received as they helped achieve a higher removal of material (Figure 3-23). This process, however, required a different kind of tool, abrasive discs that were attached to backing polymers in the Minimo's hand tool.

FIGURE 3-18 DRY PROCESS COORDINATES

Alternatively, the same logic applies for the following stages in the polishing and mirror polishing processes. Different coordinates with changed orientations, were implemented because of the cushion disc's altered dimensions. (Figure 3-19)

FIGURE 3-19 WET PROCESS COORDINATES

Other important inputs in the system, or process variables, were entered and established as soon as the coordinates were taught and set. Figure 3-20 displays graphically the logic and sequences in which this step was done. Sequentially, the selection of the path opened up different possibilities in the polishing quality. After evaluating the different possibilities, the most appropriate for the project was the S-Scan modified path, which offered the best results in terms of waviness and visual appearance.

FIGURE 3-20 KEY IN INPUTS

The following process in the algorithm was to determine the path or way the robot must displace. S-Scan modified path was the chosen pattern, in which the best outcome was perceived and measured.

The initial judgment was to develop an imaginary line, in which the tool could travel. pStart (Starting Point), pEnd (Ending Point), pA (Point A) and pB (Point B) are created and established for this purpose. The coordinates are set to operate in the test coupon frame of work.

FIGURE 3-21 S-SCAN PATH PROCESS

The final step is to retrieve data from measurement units. Repeat as required. Figure 3-22

FIGURE 3-22 RETRIEVE DATA FROM STYLUS AND ZEISS

Finally, to understand the overall picture, it is possible to refer to Figure 3-23 where it was described the whole algorithm and logic behind. This process could be replicated in the future for ease of different requirements; however the most important factor is the adjustment of all the key process variables which are described in the results chapter.

FIGURE 3-23 FLOWCHART OF POLISHING PROCESS USING ABB IRB2400

CHAPTER THREE SUMMARY

This chapter started proposing more detailed information regarding the machines and specialized devices to be utilized. After a general perspective was offered in chapter two, it was possible to view in detail the ABB 2400 articulated robot being described with its functionalities including a snapshot of the simulation capabilities offered by RobotStudio™.

Subsequently, a brief description of a polishing tool, specifically the Minimo One is given. Particular reasons on why the selection of the tool is offered.

Chapter three offered an in-depth explanation highlighting important considerations such as machines' resolutions for both contact measurement systems (Stylus Profilometer PGI 1240) and optical systems (Zeiss Smartzoom 5).

Consequently, presented in images and with a description of the abrasive degree, coated abrasives were presented alongside with cushioned discs and others pertinent to the polishing process.

Continuing with the essence of the polishing process, a methodology is explained, showing the best configuration patterns for having best values in area of contacts and pressures in the system. In addition, other technical methods for implementation in the polishing process such as tool paths and experimental designs are highlighted. Quantitative values are shown for defining initial roughness average values.

In the final part of the chapter three, the algorithm of the implementation for polishing system is displayed. To a certain degree, explaining deeply the reasons of why some tools should be used, it is intended for ease in future replications.

In chapter four is expected to continue with the presentation of the experimentation that is intended to be carried on. Results are specified equally.

CHAPTER 4 : RESULTS AND DISCUSSIONS

This chapter presents a design of experiment where physical settings and data are displayed and the acquisition of the mirror finishing varying a set of various parameters is discussed. Additionally, offline measurements displaying the progression of the surface as it encounters the elements of polishing is illustrated and explained.

DESIGN OF EXPERIMENT

PHYSICAL DESCRIPTION

A physical description of the polishing set up is displayed in Figure 4-1.

FIGURE 4-1 PHYSICAL SCHEMATIC OF ROBOT OPERATION IN POLISHING SETTING

In Figure 4-1, the respective elements presented in chapter three, can be seen representing the performance of the polishing process.

The test coupon or additional samples were clamped to a fixture with different screws to maintain the same positions and orientations during the polishing process avoiding any kind of undesired variations in the polishing path. Figure 4-2 displays a dry process in which a clamped sample is polished.

FIGURE 4-2 SAMPLE BEING POLISHED WITH GRIT 1000 - FROM RIGHT TO LEFT

This process was repeated in three stages (four to further remove material in case of deep cuts) in a total area of 75.9cm^2 . Nevertheless, to simplify and optimize the polishing time in experimentation, three smaller areas were chosen covering 24.15cm^2 each, with dimensions of $6.9\text{cm} \times 3.5\text{cm}$. The wet process followed the same ideology in order to enhance the quality of the surface.

The time result was dependent on the configuration set. In the surface quality, the objective was to match a Ra of $0.01\mu\text{m}$.

The test coupon could not be analyzed online at the moment of the polishing process due to the complexity it carried to adapt a device with non-contact measurement functionality.

Nonetheless, the profilometer from the company Taylor Hobson was dedicated for the measurement of the test coupons.

FIGURE 4-3 TEST COUPON 6 EXAMINED BY PROFILOMETER

Figure 4-3 demonstrates the way in which the profiles, waviness and roughness average were calculated. The measurement was performed normal to the direction of cut.

Furthermore, to have a more detailed analysis, it was possible to utilize the Smartzoom 5 from Zeiss, obtaining the microscopic damages and pattern results from the processed parts in the test coupons.

TAGUCHI METHOD

The experimentation (most of the cases) involves the manipulation and interaction of distinct variables towards different outputs. It is not necessarily the sought output and may or may not vary linearly.

The first step adopted in the Design of the Experiment, was to establish what kind of system and process, theoretically, existed, evaluating key references and previous experimentations, let alone industrial progress and real vicissitudes at the moment of achieving actual and tangible results. The selected approach to dealing with multiple variables is to carry a factorial experiment analysis. The strategy of experimentation allowed a general approach to planning and leading the tests, converging to clear responses.

Table 10**Error! Reference source not found.** describes the configuration adopted from the Taguchi Method to best represent the experimentation selecting only four variables and varying their three levels.

For reasons of time optimization, procedure and economic motives, only four variables were selected. Secondly, in accordance to what other prominent authors have been researching, similar methods were followed.

Openly, it might represent a step forward, as the employment of robotic solutions with higher devices capable of actuating and sensing at lower forces increment the possibilities of higher quality on the metal surfaces.

TABLE 10 THE ORTHOGONAL ARRAY (OA) W/ KPVS & LEVELS; TWO CYCLES ("SCRATCHES"); S-SCAN PATH - L_9 (3^4) ARRAY

	Control Factor							
Experiment	A	B	C	D	Grit Size Number	Force Control (Newton)	Tool Rotational Speed	Feed Rate
1	1	1	1	1	# 1000	1.00	6000	10
2	1	2	2	2	# 1000	3.00	9000	15
3	1	3	3	3	# 1000	5.00	12000	20
4	2	1	2	3	20 μm	1.00	9000	20
5	2	2	3	1	20 μm	3.00	12,000	10
6	2	3	1	2	20 μm	5.00	6000	15
7	3	1	3	2	3 μm	1.00	12,000	15
8	3	2	1	3	3 μm	3.00	6000	20
9	3	3	2	1	3 μm	5.00	9,000	10

The established settings to perform the experiments are given in Table 10. It is possible to visualize that nine configurations were set, having the priority of Grit sizes and force control values.

TAGUCHI METHOD - ANOVA

Once the initial data had been collected, as could be seen previously in Table 8 and Table 9, the initial testing is reading to be conducted.

From Table 10, it is possible to see the nine conditions to conduct the experiments. Generally, it is indicated to conduct, 3^2 settings and 2^{3-1} experimentations for these combinations.

Results are observed in Table 11 and Table 12 respectively. The first three experimentations, counted with a much rougher surface that was treated previously to reduce to an extent the high roughness values that were not able to be treated with a 600 Grit size for the abrasive.

TABLE 11 EXPERIMENTATION RESULTS OF R_a

Experiment	Count	Sum	Average	Variance
Experiment 1	3	0.045	0.0151	1.1E-05
Experiment 2	3	0.029	0.0096	3.5E-06
Experiment 3	3	0.053	0.0178	2.0E-06
Experiment 4	3	0.034	0.0115	9.2E-06
Experiment 5	3	0.051	0.0170	5.8E-05
Experiment 6	3	0.036	0.0120	2.0E-06
Experiment 7	3	0.026	0.0085	5.3E-07
Experiment 8	3	0.02	0.0067	2.0E-06
Experiment 9	3	0.022	0.0073	2.0E-07

High force values did not indicate a higher reduction in roughness, rather a proper combination of settings indicated better R_a values and higher quality in the surface

texture. Meritorious to highlight the small results obtained for variance as they would indicate small fluctuations for future repetitions in the experimentation.

TABLE 12 ANOVA RESULTS

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.000	2.000	0.000	0.022	0.979	3.403
Within Groups	0.001	24.000	0.000			
Total	0.001	26.000				

ANOVA single factor method was employed. A linear model behavior was postulated, independent from observation. Table 12 presents the SS (Sum of Squares) and DoF (Degrees of Freedom) presented in the group. F and P-Value indicates whether the standard deviations are different from the data obtained. Evidently, Table 12 indicates the null hypothesis is fulfilled, for what it means, maintaining the variance is obtained.

FIGURE 4-4 INDIVIDUAL RESULTS PER EXPERIMENT SETTING

Scattered data is shown in Figure 4-4 dividing from the results in every experiment setting. Figure 4-5 constructs the overall logarithmic evolution of all the data. The equation represents the stages of the experimentation with respect to the R_a .

FIGURE 4-5 ROUGHNESS AV TREND - EXPERIMENT SETTING - LOG REPRESENTATION

The R^2 represents how well a trend line or regression line represents a set of information or data. In Figure 4-5 the representation does not adjust due to the variation of independent results and a trend line does not match the evolution of polishing. A pattern of repetition cannot be extended initially. Figure 4-6 defines the means of experiments to obtain mirror polishing qualities progressively correctly.

TABLE 13 THE HIERARCHY IN EXPERIMENTATIONS TO OBTAIN MIRROR FINISHING

Parameters in Experiment	Mean Roughness Average
Exp. 3	0.017791
Exp. 5	0.017043
Exp. 1	0.015107
Exp. 6	0.011973
Exp. 4	0.011452
Exp. 2	0.0096
Exp. 7	0.008525
Exp. 9	0.007268
Exp. 8	0.006676

FIGURE 4-6 SELECTION OF EXPERIMENTS TO OBTAIN MIRROR FINISHING

Nevertheless, if the experiments are replicated in future occasions, it must be clear that the expected response, in accordance to the experimental setting, should be in a near range of Ra visualized in Figure 4-6.

TABLE 14 OUTPUT AVERAGE WITH VARIANCE

Computing the output of [Mean and Variance] variation			
Output #	Output	Mean	Variance
Y(A1)	$Y(Y1+Y2+Y3)/3$	0.0142	5.5E-06
Y(A2)	$Y(Y4+Y5+Y6)/3$	0.0135	2.3E-05
Y(A3)	$Y(Y7+Y8+Y9)/3$	0.0075	9.2E-07
Y(B1)	$Y(Y1+Y4+Y7)/3$	0.0088	7.0E-06
Y(B2)	$Y(Y2+Y5+Y8)/3$	0.0111	2.1E-05
Y(B3)	$Y(Y3+Y6+Y9)/3$	0.0123	1.4E-06
Y(C1)	$Y(Y1+Y6+Y8)/3$	0.0113	5.1E-06
Y(C2)	$Y(Y2+Y4+Y9)/3$	0.0094	4.3E-06
Y(C3)	$Y(Y3+Y5+Y7)/3$	0.0145	2.0E-05
Y(D1)	$Y(Y1+Y5+Y9)/3$	0.0131	2.3E-05
Y(D2)	$Y(Y2+Y6+Y7)/3$	0.0100	2.0E-06
Y(D3)	$Y(Y3+Y4+Y8)/3$	0.0120	4.4E-06
		0.0115	9.9E-06

Table 14 shows the means, with respect to the factors. The data describes the average in which every factor interacts and represents a 1X12 vector.

FIGURE 4-7 MEAN RESPONSE FACTOR VALUES

Figure 4-7 and Figure 4-8, show the mean and variance of the average output relationship with the factors.

FIGURE 4-8 VARIANCE RESPONSE FACTOR VALUES

MICROSCOPIC TRAJECTORY

In addition to understand the improvement generated on the surface, a trajectory has been developed to visualize microscopic changes.

FIGURE 4-9 SAMPLE 5 - SIDE A - INITIAL CONDITION

FIGURE 4-10 SAMPLE 5; PART 1; INITIAL CONDITION- 1 μ M

Figure 4-10 demonstrates the initial conditions in which the stainless steel is presented. Samples and test coupons are usually received with prior grinding processes and present high waviness as well as high R_a . Initially, grit size of 600 is employed to remove these high variations on the surface.

Figure 4-11 displays the intrinsic quality of using grit coarse 1000. It is possible to see the different scratches and not so-fine end-result of the surface. However, the high variations on the surface have mainly disappeared and present a more flat texture. In Figure 4-11 is possible to see several burn marks in the centre.

FIGURE 4-11 SURFACE RESPONSE TO GRIT 1000; 12000RPM; 5 NEWTON; 20 MM/S

In Figure 4-12 it is possible to visualize a higher reduction in scratches; however the material's own nature (Cushion Felt) still produces tool path scratches. Wet process is required to achieve better results.

FIGURE 4-12 SURFACE RESPONSE TO 20 μ M; 12000RPM; 3 NEWTON; 10 MM/S

Figure 4-12 offers a magnification of a surface polished with water-based 20 μ m silicon carbide compound. In the figure, it is possible to visualize in the left a reflective quality (not completely mirror) already on the surface.

However, when approximation is performed on the surface, it is possible to see (right frame) that tool scratches are present. It was possible to measure the scratch angle visually. At this stage, it is necessary to further continue polishing to achieve super mirror finishing levels.

To envision the quality at higher levels, it is recommended to increase the zooming to a point where the scratches are seen from a general perspective (Truly depends on quality but approx. 60X-100X).

After following the respective parameters in polishing [3 μ m; 12000rpm; 1 Newton; 15 mm/s], Figure 4-13 and Figure 4-14 show mirror finishing results. With the qualities presented, there still present scratches no larger in general than 1mm.

FIGURE 4-13 SAMPLE 5 PART 1 MIRROR FINISHING QUALITY

Finally, Figure 4-13 offers a mirror quality reflecting the Zeiss microscope. Water traces can be seen as drops dried on the surface after ultrasonic cleaning.

FIGURE 4-14 SURFACE RESPONSE TO 3UM; 12000RPM; 1 NEWTON; 15 MM/S

Interestingly, when a visual filter is applied to Figure 4-14, it can be seen that in Figure 4-15 and Figure 4-16, that it provides detailed information on the characteristics of the last stage of polishing.

That is to say that the scratches produced by the tool are within a same frequency and represent a particularity of the polishing stage. Additionally, it provides information about the initial deep scratches, offering information regarding the material removal as well. 1mm in general is the visual maximum value for the tool scratches. Figure 4-15 is also interesting as some hidden detail to the eye, such as the random dots. This information is pertinent requiring improvement and might increase (if treated) in the future the quality of the polishing process.

FIGURE 4-15 MIXED FILTER APPLIED TO SURFACE RESPONSE TO 3 μ M ABRASIVE SOLUTION

FIGURE 4-16 SECOND EXAMPLE - MIXED FILTER -SURFACE RESPONSE TO 3µM
ABRASIVE SOLUTION

CHAPTER FOUR SUMMARY

In the chapter of results and experiments, specific descriptions relating the robotic and machine settings with the respective experimentation is revealed.

Initially, a sketch is offered, showing the position in which the respective elements are placed to commence the mirror polishing process. The initial image is intended to be displayed in that manner, for ease in the comprehension of the process.

Consequently, a short description is given on how the polishing process needed to be set, performed and analysed. In this part, small details are skipped as more relevance is given to the pertinent results.

Subsequently, an explanation of the Taguchi method takes place. The reason why it was necessary to take a L_9 type of configuration is offered. Dimensions, results obtained and ANOVA were later positioned in tables.

Graphs were also included in the results, proposing polishing behaviours when using different experimentations. Also, statistical charts were displayed demonstrating the best parameters in this experimentation for obtaining mirror polishing criteria. A3, B1, C2, D2.

By the end of the chapter of results and discussion, images of the evolution of a surface are offered at microscopic levels. This is in fact a microscopic trajectory emphasizing on the results not seen by simple eye. In some cases, zoomed out pictures are offered comparing the zoomed in picture.

CHAPTER 5 : CONCLUSIONS AND FUTURE WORK

From the use of the Taguchi method and the Design of Experiment, it was found that, the manipulation of four KPV variables (Grit Size #, Force, Rotational Speed and Feed Rate) facilitate the obtainment of the mirror polishing quality in a metal, in this case, stainless steel.

The experimentation results prove clearly, the effects on surface texture and more specifically on roughness average in Stavax [Stainless Steel] are reduced by 95% in the first initial step using a #1000 grit size course (a previous step of grinding has been performed). Continuously, the wet process contributes initially, with an increase of 0.3% in the roughness average quality using the 20 μ m abrasive slurry. To conclude, a further enhancement in the result is applied by an increase of 44% using the 3 μ m abrasive compared to the previous R_a value obtained with the 20 μ m abrasive, for a general improvement of 97.4%. Besides, it must be affirmed, that for the improvement in the final stages, controlled low force levels have implications in the quality results in a positive manner.

Nonetheless, waviness and tool scratches still remain visible in the polishing and super polishing stages and have a quality effect in the final stage.

It is feasible to conclude, mirror finishing qualities, are achievable as long as parameters of control such as force control and correct grit size number are correctly selected according to the initial condition, while rotational speed and feed rate are settle to reduce the variance and tune the response. (In this case, the variables of force control and grit size are Class I; rotational speed and feed rate are classified as Class III).

The results exposed in this project should include more output variables such as waviness variance, tool life and material removal. Future scenarios may imply working on non-flat surface, for what is necessary to develop new techniques to control force and other KPVs.

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CHAPTER 7 : APPENDICES

APPENDIX A – MATERIAL PROPERTIES

Table 15 describes the properties of Figure 3-16 before the annealing process in the stainless steel coupons.

TABLE 15 SUS304 - MECHANICAL PROPERTIES

Property	Value
<i>Brinell Hardness (HB)</i>	201
<i>Rockwell Hardness</i>	92
<i>Density (kg/m³)</i>	8000
<i>Young's Modulus (GPa)</i>	190
<i>Tensile Strength (Mpa)</i>	515
<i>Yield Strength (Mpa)</i>	205
<i>Poisson's ratio</i>	0.27-0.30

The characterization of the polishing process of one batch of test coupons had enormous variations with respect to the former one. It was possible to find the reason of this change was given by the gradient in hardness of the two different materials.

TABLE 16 STAVAX STAINLESS STEEL - MECHANICAL PROPERTIES

Property	Value
<i>Brinell Hardness (HB)</i>	88
<i>Rockwell Hardness</i>	50
<i>Density (kg/m³)</i>	8000
<i>Young's Modulus (GPa)</i>	190
<i>Tensile Strength (Mpa)</i>	520
<i>Yield Strength (Mpa)</i>	240
<i>Poisson's ratio</i>	0.27-0.30

APPENDIX B – ROBOTSTUDIO CODE FOR POLISHING AND GRINDING

!!!!!! This code has been reduced and some functions have been set aside!!! Only one method using a felt point has been introduced here.

MODULE MirrorPolishing

VAR num offs_Dis := 0;

VAR num count := 0;

VAR num count2 := 0;

VAR num scratch := 0;

VAR num scratch2 := 0;

VAR num fr := 0;

VAR num total_DisX := 0;

VAR num loop_DisX := 0;

VAR num loop_DisX_middle := 0;

VAR num loop_DisY := 0;

VAR num loop_DisY_2 := 0;

!!!Numbers for big loop

VAR num outer_offs_Dis := 0;

VAR num outer_count := 0;

!!!

VAR robtarget loop_p1:=[[67.03,31.64,0.84],[0.0121263,0.999923,0.00190221,-0.00179282],[-1,-1,0,0],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];

!!! Variables Defining the four points to operate the robot with.

VAR robtarget pA:=[[67.03,31.64,0.84],[0.0121263,0.999923,0.00190221,-0.00179282],[-1,-1,0,0],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];

VAR robtarget pB:=[[9.87,31.63,0.82],[0.0121263,0.999923,0.00190221,-0.00179282],[-1,-1,0,0],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];

VAR robtarget pStart:=[[67.02,31.64,2.84],[0.0121263,0.999923,0.00190221,-0.00179282],[-1,-1,0,0],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];

VAR robtarget pEnd:=[[9.87,31.63,4.42],[0.0121263,0.999923,0.00190221,-0.00179282],[-1,-1,0,0],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];

VAR robtarget pSafe:=[[-136.50,190.50,305.75],[0.000952102,-0.930989,0.0111815,-0.364876],[-1,-1,0,0],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];

!!!Used for Online Teaching !!!Coordinates for Final Safe Postion

CONST robtarget PERM_pSafeFinal:=[[-136.50,190.50,305.75],[0.000952102,-0.930989,0.0111815,-0.364876],[-1,-1,0,0],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];

!Test Coupon Coordinates for Stick Disc - Abrasives G#600 & G#1000

CONST robtarget Xxxxx_Dis:=[[74.01,27.15,-6.67],[x,x,x,x],[-1,-1,0,0],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];

CONST robtarget PERM_pB_Dis:=[[6.12,27.15,-6.67],[0.0109794,0.999697,0.00167092,-0.021962],[-1,-1,0,0],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];


```
CONST robtarget PERM_pStart_Disc:=[[74.01,27.15,-
2.07],[0.010979,0.999697,0.00167238,-0.0219606],[-1,-
1,0,0],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
CONST robtarget PERM_pEnd_Disc:=[[6.12,27.15,-
1.66],[0.0109798,0.999697,0.00167156,-0.0219611],[-1,-
1,0,0],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
```

```
CONST robtarget Xxxxx_BorderDisc:=[[75.58,26.03,-6.15],[0.0230525,-0.999608,-
0.00494866,-0.0150824],[-1,-1,0,0],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
CONST robtarget PERM_pB_BorderDisc:=[[9.05,26.06,-6.15],[0.0230459,-0.999608,-
0.00495043,-0.0150844],[-1,-1,0,0],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
CONST robtarget PERM_pStart_BorderDisc:=[[75.58,26.03,-2.15],[0.0230554,-0.999608,-
0.00494673,-0.0150814],[-1,-1,0,0],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
CONST robtarget PERM_pEnd_BorderDisc:=[[9.05,26.05,1.30],[0.0230542,-0.999608,-
0.00494859,-0.0150828],[-1,-1,0,0],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
```

!New Sample Coordinates for stick discs - Abrasives #600 & #1000

```
CONST robtarget NS_pA_Disc:=[[71.81,20.47,-2.30],[6.41607E-
05,0.998955,0.00137541,-0.0456846],[-1,-
1,0,0],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
CONST robtarget NS_pB_Disc:=[[1.69,19.99,-2.30],[5.78519E-05,0.998955,0.00137103,-
0.0456859],[-1,-1,0,0],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
CONST robtarget NS_pStart_Disc:=[[71.81,20.47,1.90],[6.44339E-
05,0.998955,0.00137603,-0.0456866],[-1,-
1,0,0],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
CONST robtarget NS_pEnd_Disc:=[[1.69,19.99,2.10],[5.80498E-
05,0.998955,0.00137129,-0.0456866],[-1,-
1,0,0],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
```

!!!New Sample Coordinates for Cushion discs - Abrasives 20u & 3u

```
CONST robtarget NS_pA_Cushion_Disc:=[[77.82,21.88,3.49],[1.52545E-
05,0.999983,0.00137422,-0.00570061],[-1,-
1,0,0],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
CONST robtarget NS_pB_Cushion_Disc:=[[11.89,21.88,3.49],[1.57357E-
05,0.999983,0.00137423,-0.00570082],[-1,-
1,0,0],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
CONST robtarget NS_pStart_Cushion_Disc:=[[80.02,21.88,10.69],[6.34762E-06,-
0.999923,-0.00137448,-0.0122978],[-1,-
1,0,0],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
CONST robtarget NS_pEnd_Cushion_Disc:=[[11.89,21.88,8.62],[1.84045E-
05,0.999983,0.00137419,-0.00570053],[-1,-
1,0,0],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
```

!!!Test Coupon Coordinates for Hard Bob Felt - Abrasives 20u & 3u

```
CONST robtarget Xxxxx_BobFeltHard:=[[71.14,29.36,-
0.70],[0.00672209,0.999976,0.00192147,6.57301E-05],[-1,-
1,0,0],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
CONST robtarget PERM_pB_BobFeltHard:=[[13.94,29.36,-
0.70],[0.00672164,0.999976,0.00192043,6.58143E-05],[-1,-
1,0,0],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
```

```

CONST robtarget
PERM_pStart_BobFeltHard:=[[71.14,29.36,5.10],[0.00672413,0.999976,0.00192263,6.573
01E-05],[-1,-1,0,0],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
CONST robtarget
PERM_pEnd_BobFeltHard:=[[13.94,29.36,4.70],[0.00672324,0.999975,0.00192069,6.636
17E-05],[-1,-1,0,0],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];

!Test Coupon Coordinates for Cushion Discs - Abrasives 20u & 3u
CONST robtarget Xxxxx_CushionDisc:=[[75.21,27.64,-
1.36],[0.0109271,0.999864,0.00178157,-0.012238],[-1,-
1,0,0],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
CONST robtarget PERM_pB_CushionDisc:=[[4.96,27.64,-
1.36],[0.0109269,0.999864,0.00178208,-0.0122397],[-1,-
1,0,0],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
CONST robtarget
PERM_pStart_CushionDisc:=[[75.21,27.63,3.07],[0.0109262,0.999864,0.00177933,-
0.0122375],[-1,-1,0,0],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
CONST robtarget
PERM_pEnd_CushionDisc:=[[4.96,27.64,4.03],[0.0109254,0.999864,0.00178131,-
0.0122392],[-1,-1,0,0],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];

!Test Coupon Coordinates for Big Cushion Disc - Abrasives 20u & 3u
CONST robtarget Xxxxx_BigCushionFelt:=[[63.61,39.39,-
0.59],[0.00984282,0.999729,0.00162666,-0.0210186],[-1,-
1,0,0],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
CONST robtarget PERM_pB_BigCushionFelt:=[[9.29,39.39,-
0.59],[0.00984147,0.999729,0.00162579,-0.0210202],[-1,-
1,0,0],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
CONST robtarget
PERM_pStart_BigCushionFelt:=[[63.61,39.39,6.10],[0.00984116,0.999729,0.00162561,-
0.0210195],[-1,-1,0,0],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
CONST robtarget
PERM_pEnd_BigCushionFelt:=[[9.29,39.39,4.32],[0.00984699,0.999729,0.00162665,-
0.0210185],[-1,-1,0,0],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];

!PERS tooldata
SharpTip_Minimo:=[TRUE,[[220.21,2.30017,124.257],[0,0.704015,0,0.710185]],1.66058,
[21.8931,-0.819387,50.1408],[1,0,0,0],0,0,0]; (0)
PERS tooldata
SharpTip_Minimo:=[TRUE,[[220.025,1.79744,124.655],[0,0.707106781,0,0.707106781]],1.
66062,[21.318,0.00840508,50.0732],[1,0,0,0],0,0,0];

! Close to surface (0.5)
!PERS tooldata FeltPoint:=[TRUE,
[[196.025,3.67291,136.488],[0,0.716301943,0,0.69779046]],1.66058,[21.8931,-
0.819387,50.1408],[1,0,0,0],0,0,0];
PERS tooldata FeltPoint:=[TRUE,
[[196.025,3.67291,136.488],[0,0.716301943,0,0.69779046]],1.66062,
[21.318,0.00840508,50.0732],[1,0,0,0],0,0,0];
! Far to surface (3.5)
PERS tooldata DiscPoint:=[TRUE,
[[196.025,3.67291,136.488],[0,0.69779046,0,0.716301943]],1.66062,
[21.318,0.00840508,50.0732],[1,0,0,0],0,0,0];

```

```
!PERS wobjdata testcoupon:=[FALSE,TRUE,"",[[0,0,0],[1,0,0,0]],[[1285.29,-
228.543,391.371],[0.999994,-0.0019767,0.00209957,-0.0019386]]];
```

```
PERS wobjdata testcoupon:=[FALSE,TRUE,"",[[0,0,0],[1,0,0,0]],[[1285.2,-
228.877,391.531],[1,0,0,0]]];
```

```
PERS loaddata Load_2400_Minino:=[1.65984, [21.2538,0.116448,50.1857],[1,0,0,0],
0,0,0];
```

```
PERS speeddata v1 := [1,500,5000,1000];
PERS speeddata v2 := [2,500,5000,1000];
PERS speeddata v3 := [3,500,5000,1000];
PERS speeddata v8 := [8,500,5000,1000];
PERS speeddata v15 := [15,500,5000,1000];
PERS speeddata v25 := [25,500,5000,1000];
```

```
PROC MirrorPolish_Straight_Felt()
```

```
count := 0;
scratch := 0;
@@@@
```

```
FCCalib Load_2400_Minino;
```

```
!pA := Xxxxx_BobFeltHard;
!pB := PERM_pB_BobFeltHard;
!pStart := PERM_pStart_BobFeltHard;
!pEnd := PERM_pEnd_BobFeltHard;
```

```
pA := PERM2_pA_BobFeltHard;
pB := PERM2_pB_BobFeltHard;
pStart := PERM2_pStart_BobFeltHard;
pEnd := PERM2_pEnd_BobFeltHard;
```

```
!pA := PERM3_pA_BobFeltHard;
!pB := PERM3_pB_BobFeltHard;
!pStart := PERM3_pStart_BobFeltHard;
!pEnd := PERM3_pEnd_BobFeltHard;
```

```
WHILE count <= cccc DO
    MoveJ Offs(pStart,0,offs_Dis,0),v50,z1,FeltPoint\Wobj:=testcoupon;
    FCPress1LStart
    Offs(pA,0,offs_Dis,0),v5\Fz:=infinite,75\ForceFrameRef:=FC_REFFRAME_TOOL\Fz
    Change:=100\DampingTune:=60\TimeOut:=60,z1,FeltPoint\Wobj:=testcoupon;
    FCPress1L Offs(pB,0,offs_Dis,0),v5,fr,z1;
```

```
WHILE scratch <= yyyy DO
    FCPress1L Offs(pA,0,offs_Dis,0),v20,fr,z1;
    FCPress1L Offs(pB,0,offs_Dis,0),v20,fr,z1;
    scratch := scratch + 1;
ENDWHILE
```

```

    FCPressLEnd Offs(pEnd,0,offs_Dis,0),v5 \ForceChange:=100
\ZeroContactValue:=10;
        offs_Dis := offs_Dis + 0.7071;
        count := count + 1;
    scratch := 0;
        TPwrite "The counter is " \Num:=count;
        ENDWHILE

    DeactiveFC;
    MoveJ Offs(pSafe,0,0,0),v50,z1,DiscPoint\Wobj:=testcoupon;

ENDPROC

PROC MirrorPolish_BigCushionFelt()
    count := 0;
    scratch := 0;
    @@@#@#

    FCCalib Load_2400_Minino;

    pA := Xxxxx_BigCushionFelt;
    pB := PERM_pB_BigCushionFelt;
    pStart := PERM_pStart_BigCushionFelt;
    pEnd := PERM_pEnd_BigCushionFelt;

    !pA := PERM2_pA_BigCushionFelt;
    !pB := PERM2_pB_BigCushionFelt;
    !pStart := PERM2_pStart_BigCushionFelt;
    !pEnd := PERM2_pEnd_BigCushionFelt;

    WHILE count <= rrr DO
        MoveJ Offs(pStart,0,offs_Dis,0),v50,z1,FeltPoint\Wobj:=testcoupon;
        FCPress1LStart
        Offs(pA,0,offs_Dis,0),v5\Fz:=fr,75\ForceFrameRef:=FC_REFFRAME_TOOL\ForceChan
ge:=100\DampingTune:=60\TimeOut:=60,z1,FeltPoint\Wobj:=testcoupon;
        FCPress1L Offs(pB,0,offs_Dis,0),v5,fr,z1;

        WHILE scratch <= yyyyyyyyyyyyyy DO
            FCPress1L Offs(pA,0,offs_Dis,0),v15,fr,z1;
            FCPress1L Offs(pB,0,offs_Dis,0),v15,fr,z1;
            scratch := scratch + 1;
        ENDWHILE

        FCPressLEnd Offs(pEnd,0,offs_Dis,0),v5 \ForceChange:=100/ZeroContactValue:=10;
            offs_Dis := offs_Dis + 0.7071;
            count := count + 1;
        scratch := 0;
            TPwrite "The counter is " \Num:=count;
            ENDWHILE
        DeactiveFC;

ENDPROC
ENDMODULE

```

APPENDIX C – IRB 2400 CHARACTERISTICS

Electrical Connections		
Supply voltage	200–600 V, 50/60 Hz	
Power consumption	ISO-Cube at max speed 0.67 kW	
Environment		
Ambient temperature for mechanical unit:		
During operation	+5°C (41°F) to + 45°C (113°F)	
Relative humidity	Max. 95%	
Degree of protection		
	IRB 2400-10	IRB 2400-16
Standard	IP54	IP54
Foundry Plus 2 version	IP67	IP67
Noise level		
	Max. 70 dB (A)	
Emission		
	EMC/EMI-shielded	
Data and dimensions may be changed without notice		

Working range

IRB 2400-10, IRB 2400-16

Main applications

Arc welding, cutting/deburring, glueing/sealing, grinding/polishing,
machine tending, material handling

Specification

Variants	Reach	Payload	Protection
IRB 2400-10	1.55 m	12 kg	FoundryPlus
IRB 2400-16	1.55 m	20 kg	FoundryPlus

Number of axes 6

Mounting Floor and inverted all versions.

Wall IRB 2400-10

Supplementary load IRB 2400-10 IRB 2400-16

Upper arm

-wrist end 2 kg 2 kg

-rear end 10 kg 10 kg

Base unit 35 kg 35 kg

Physical

Dimensions	IRB 2400-10	IRB 2400-16
Total height	1564 mm	1564 mm
Robot base	723x600 mm	723x600 mm
Robot weight	380 kg	380 kg

Performance (according to ISO 9283)

Position repeatability (RP) 0.03 mm

Path repeatability 0.11-0.15 mm depending on variant

Movements

Axis	IRB 2400-10	IRB 2400-16
Working range		
Axis 1	360°*	360°
Axis 2	210°	210°
Axis 3	125°	125°
Axis 4	400°	400°
Axis 4, Option	Unlimited	Unlimited
Axis 5	240°	240°
Axis 6	800°	800°
Axis 6, Option	Unlimited	Unlimited

Max. speed

Axis 1	150°/s 90° **	150°/s
Axis 2	150°/s 90° **	150°/s
Axis 3	150°/s 90° **	150°/s
Axis 4	360°/s	360°/s
Axis 5	360°/s	360°/s
Axis 6	450°/s	450°/s

**) For wall mounted version

*) ± 30° for wall mounted robot

APPENDIX D – PROFILOMETER TRAJECTORY

FIGURE 7-1 INITIAL PROFILE - TEST COUPON 9

TABLE 17 ISO 4287 SURFACE TEXTURE TABLE – INITIAL CONDITION

ISO 4287			
Amplitude parameters - Roughness profile			
Rp	1.155534	μm	Gaussian filter, 0.8 mm
Rv	1.169144	μm	Gaussian filter, 0.8 mm
Rz	2.324678	μm	Gaussian filter, 0.8 mm
Ra	0.279470	μm	Gaussian filter, 0.8 mm
Amplitude parameters - Primary profile			
Pa	20.700245	μm	
Amplitude parameters - Waviness profile			
Wp	0.533808	μm	Gaussian filter, 0.8 mm
Wv	1.792247	μm	Gaussian filter, 0.8 mm
Wz	2.328058	μm	Gaussian filter, 0.8 mm
Wa	19.894890	μm	Gaussian filter, 0.8 mm

FIGURE 7-2 GRIT 600 - TEST COUPON 9

TABLE 18 ISO 4287 SURFACE TEXTURE TABLE – GRIT 600

ISO 4287			
Amplitude parameters - Roughness profile			
Rp	0.124727	µm	Gaussian filter, 0.25 mm
Rv	0.074979	µm	Gaussian filter, 0.25 mm
Rz	0.199705	µm	Gaussian filter, 0.25 mm
Ra	0.029346	µm	Gaussian filter, 0.25 mm
Amplitude parameters - Primary profile			
Pa	0.538314	µm	
Amplitude parameters - Waviness profile			
Wp	0.060006	µm	Gaussian filter, 0.25 mm
Wv	0.050919	µm	Gaussian filter, 0.25 mm
Wz	0.110924	µm	Gaussian filter, 0.25 mm
Wa	0.524026	µm	Gaussian filter, 0.25 mm

FIGURE 7-3 GRIT 1000 - TEST COUPON 9

TABLE 19 ISO 4287 SURFACE TEXTURE TABLE – GRIT 1000

ISO 4287			
Amplitude parameters - Roughness profile			
Rp	0.126238	µm	Gaussian filter, 0.25 mm
Rv	0.058837	µm	Gaussian filter, 0.25 mm
Rz	0.185075	µm	Gaussian filter, 0.25 mm
Ra	0.021345	µm	Gaussian filter, 0.25 mm
Amplitude parameters - Primary profile			
Pa	0.654951	µm	
Amplitude parameters - Waviness profile			
Wp	0.227316	µm	Gaussian filter, 0.8 mm
Wv	0.093404	µm	Gaussian filter, 0.8 mm
Wz	0.320719	µm	Gaussian filter, 0.8 mm
Wa	0.602294	µm	Gaussian filter, 0.8 mm

FIGURE 7-4 20 μm ABRASIVE - TEST COUPON 9

TABLE 20 ISO 4287 SURFACE TEXTURE TABLE – 20 μm ABRASIVE

ISO 4287			
Amplitude parameters - Roughness profile			
Rp	0.033624	μm	Gaussian filter, 0.08 mm
Rv	0.033771	μm	Gaussian filter, 0.08 mm
Rz	0.067385	μm	Gaussian filter, 0.08 mm
Ra	0.010872	μm	Gaussian filter, 0.08 mm
Amplitude parameters - Primary profile			
Pa	0.738600	μm	
Amplitude parameters - Waviness profile			
Wp	0.027365	μm	Gaussian filter, 0.08 mm
Wv	0.018659	μm	Gaussian filter, 0.08 mm
Wz	0.046024	μm	Gaussian filter, 0.08 mm
Wa	0.731983	μm	Gaussian filter, 0.08 mm

FIGURE 7-5 3 µM ABRASIVE - TEST COUPON 9

TABLE 21 ISO 4287 SURFACE TEXTURE TABLE – 3 µM ABRASIVE

ISO 4287			
Amplitude parameters - Roughness profile			
Rp	0.024031	µm	Gaussian filter, 0.08 mm
Rv	0.024294	µm	Gaussian filter, 0.08 mm
Rz	0.048325	µm	Gaussian filter, 0.08 mm
Ra	0.007726	µm	Gaussian filter, 0.08 mm
Amplitude parameters - Primary profile			
Pa	0.508196	µm	
Amplitude parameters - Waviness profile			
Wp	0.021148	µm	Gaussian filter, 0.08 mm
Wv	0.023802	µm	Gaussian filter, 0.08 mm
Wz	0.044750	µm	Gaussian filter, 0.08 mm
Wa	0.504348	µm	Gaussian filter, 0.08 mm