INDUSTRY IMPLICATIONS OF ASME Y14.5-2018 RULE (S) AND THE NESTED PRINCIPLE

by

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ABSTRACT

ATTILIO MENNUTI. Industry Implications of ASME Y14.5-2018 Rule (s) and the "Nested" Principle. (Under the direction of DR. EDWARD MORSE)

ASME Y14.5-2018 Section 4.2 Rule S states "Unless otherwise specified (UOS), elements of a surface include surface texture and flaws (e.g., burrs and scratches). All elements of a surface shall be within the applicable specified tolerance zone boundaries." [1]. The newly released rule in the standard effectively puts in writing what the standards committee has been "implying" for years, that every imperfection of the surface should be included in GD&T callouts. This is essentially an impossible task because there is no practical instrument in existence that can measure the actual depth of all imperfections in a part surface - especially in the case of large surfaces. Furthermore, this rule bases the "true value" of the measurand on an unknown feature, like the bottom of a crack or pore. Without a well-defined GD&T measurand, there is no way to claim an uncertainty from measurements. As a result of the inability to quantify surface roughness and surface defects, they have historically been viewed as negligible in GD&T measurement practice. Adhering to the new Y14.5 would call for the inclusion of *all* surface roughness and defects. Including these truly unknown quantities will lead to significant changes in the reported values of almost all surface measurement machines. As a result of rule s in the Y14.5-2018 standard, an argument can be made that GD&T measurands are not reportable since the true extent of surface roughness and surface defects cannot be completely detected in actual measurement systems.

For the purpose of this work, the terms "Size" and "form" will be used to describe aspects of a surface rather than the common definitions outside of GD&T. The Y14.5 standard utilizes the "nested" principle imbedded in GD&T. This plays out in the concept

that size includes all elements of the surface (including form, texture, and defects). Similarly, form includes all sub-elements of the surface (including texture and defects). Essentially this means that a form tolerance such as straightness, roundness, flatness, and cylindricity includes the surface's underlying shape, its waviness, its roughness, and its defects in its reported value. In common practice metrology professionals and measurement suppliers smooth out roughness and defects when they report form results based on a print. Over the years this practice became commonplace and is widely accepted throughout industry. There was never specific literature in any standard claiming it was *necessary* to include the roughness and defects… until the release of rule s.

Under the newly specified method of form GD&T, the vast majority of currently used measurement machines will have to be replaced as they don't have the capability to include surface roughness and defects in GD&T measurements. In fact, for relatively large surfaces (perhaps in the order of 0.25m by 0.25m), measurement technologies do not commercially exist for measurement according to this requirement.

ASME clearly states that Y14.5 is "not intended as a gaging standard" so it should not be used by metrologist as a measurement standard. However, it is important to understand that measurement plans are heavily influenced by Y14.5 because print tolerances are often generated based on conclusions drawn from measurement data. Since the difference between GD&T and the actual measurement plan can be quite ambiguous, the literature in the GD&T standard has a huge impact on common measurement procedures. Furthermore, the combination of the part specification and the meaning of the specification per Y14.5 serves as a contractual agreement between the customer and the measurement supplier. If we are unable to measure, we are unable to do commerce.

A measurement plan is often referred to as a supplement to the drawing that was provided by the designer. For the purpose of this work a designer will represent any person working in the drafting discipline and is responsible for assigning part tolerances on a print. An argument can be made that this rule s problem can be addressed with a proper measurement plan. However, section 4.2.2 of the ASME B89.7.2 Measurement Planning standard states “workpiece drawings… define the measurand (for which the measurement plan is to be created.)” [15]. In the case of rule s, the drawing defines a measurand with an unattainable uncertainty. Thus, a measurement plan cannot be created according to standards.

Rule s may seem like a miniscule clarification in the grand scheme of the GD&T and manufacturing landscape, however it introduces a significant change in industry. Accepting this change comes at a massive cost. A cost in terms of a shift to a whole new definition of characteristics as well as a commercial cost.

This work seeks to explore the implications of the inclusion of surface texture and defects in GD&T. The technical challenges as well as the economic challenges will be discussed as they relate to a "nested" model versus a "partitioned" model for the control of surface geometries.

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Also, I would like to thank Greg Caskey for his assistance in performing the measurements for the experiment section of this work. His expertise was essential in conducting the most effective experiment.

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CHAPTER 1: INTRODUCTION

> *"(s) UOS*, elements of a surface include surface texture and flaws (e.g., burrs and scratches). All elements of a surface shall be within the applicable specified tolerance zone boundaries."
>
> *ASME Y14.5:2018 rule 4.1(s)*

1.1 Motivation

This work seeks to explore the repercussions that could stem from the addition of rule s to Y14.5. Rule s will be thoroughly examined so that a conclusion can be made regarding its longevity in industry. The following aspects of rule s will be investigated in detail to provide a basis for which an opinion could be formed on recommendations for the future of Y14.5.

In practice, surface features are commonly decomposed into different aspects that are more discretely controllable and measurable. When analyzing form (e.g. straightness), aspects of waviness, roughness, and defects are typically filtered out. The measurement of roughness normally avoids defects as they are often specified and controlled separately. This common measurement practice does not utilize the "proper" interpretation of GD&T form callouts, as defined in Y14.5-2018, when reporting such values from a print.

Additive manufacturing, specifically metal 3D printing, is currently receiving the most publicity among all manufacturing research topics. However, what all the advertising is neglecting to talk about is the fact that additive surfaces provide significant complications in surface evaluation. These surfaces are covered in small holes, bumps, and lumps. Additively manufactured surfaces are a perfect example of where the nested principle of GD&T breaks down. According to the new rule, the surface texture of additive manufacturing makes it nearly impossible to report any size measurements with a CMM.

The measurement process according to the “proper” Y14.5 interpretation would be costly, time consuming, result in much higher measurement uncertainties, and most importantly… is basically impossible. The highest accuracy measurement systems typically operate in isolated wavelength "domains". For example, we have accurate "large scale" systems that cannot see short wavelengths. We also have accurate small-scale systems that cannot handle large features. As shown in the Stedman Diagram (Figure 10), there is currently no machine available that has the ability to cross this threshold and measure large-scale systems at short wavelengths.

Those that create GD&T-based drawings may see great value in the new rule if they desire control over every molecule of a part to ensure proper fit and tolerance stacking. They need to assume all surface imperfections are included in their form tolerances to make a theoretically perfect design. But what is the difference between a theoretically perfect design and a measurable design? Is it really up to the metrologist to do the impossible and measure to perfection?

Y14.5 leaves a dangerous opening for large costs in the manufacturing community. In the commercial world the drawing is an essential component of the contract between the buyer and the supplier. It is important to understand that the drawing, print, and CAD Model are visual representations of the part GD&T. There are billions of dollars spent every year on these GD&T based measurement contracts. The inclusion of this new rule can potentially shut down the use of all CMM's, and many other measurement machines, to report any form tolerances. CMM's are a crucial part of most measurement labs, however they don’t have the capability to measure surface roughness and surface defects to the level required in the new rule. Deeming the most widely used piece of measurement equipment as incapable could bankrupt an alarming number of companies both large and small.

This is not an overreaction to a series of "what if" scenarios targeting the new rule. For example, let's say a customer decides to include the sub-micron surface porosity of a cylinder bore in a roundness measurement result to accommodate Y14.5. An example profile from a porous cylinder bore is shown below in figure 1.

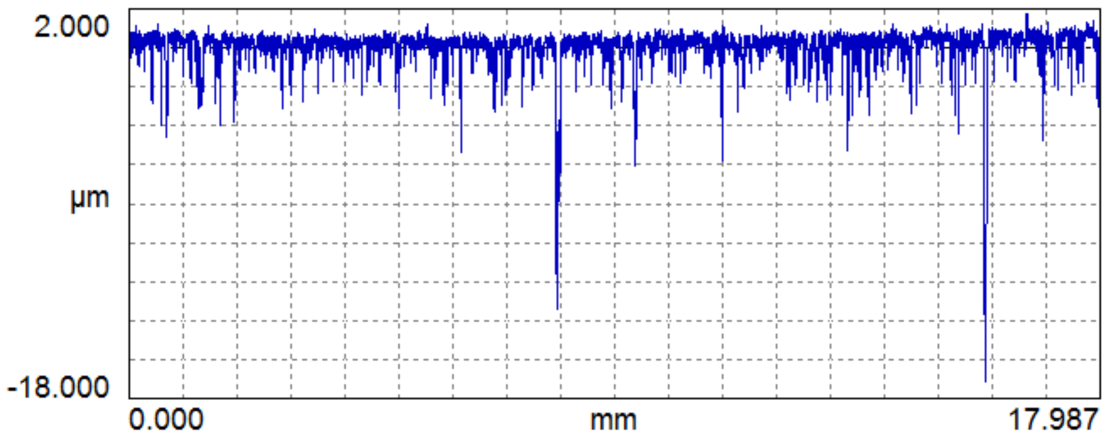

Figure 1: Roundness data from a porous cylinder bore [6].

As you can see, if the huge valleys were to be included in the roundness analysis, the result would show an out of tolerance part. However, the measurement supplier knows the surface defects must be filtered out to determine the functional roundness trend of the cylinder bore. Therefore, the supplier filters out the porosity based on common practice with available instruments. The customer, on the other hand, has every right to reject the measurement because it does not adhere to the new standard rule. How much money are we willing to spend as an industry to ensure that all contracts follow the "all elements including defects" methodology? If all companies are asked to include surface roughness and defects in their form tolerance reports they will need to drastically increase their measurement costs and will likely have to increase their production costs.

The implications of this revision draw alarming similarities to the 1980's GIDEP alert whereby CMMs were deemed "unusable" for GD&T features. This "crisis" was simply based on a difference in a measurement *method*. Massive costs arose from this small difference in measuring methodology alone. Rule s has the potential to be an even larger issue being that it represents a difference in a *definition*.

Y14.5-2018 is the first standard to specify the use of the nested principle in clearly stated terms. For the purpose of this work, the nested principle is defined as the idea that a size tolerance includes all other aspects of the surface including form, waviness, roughness, and defects. This principle is the concept behind rule s that leads to all the alarming implications outlined in further chapters. Figure 2 below illustrates how the nested principle plays out in surface measurements. It is important to note that some large defects can affect all domains, not just roughness.

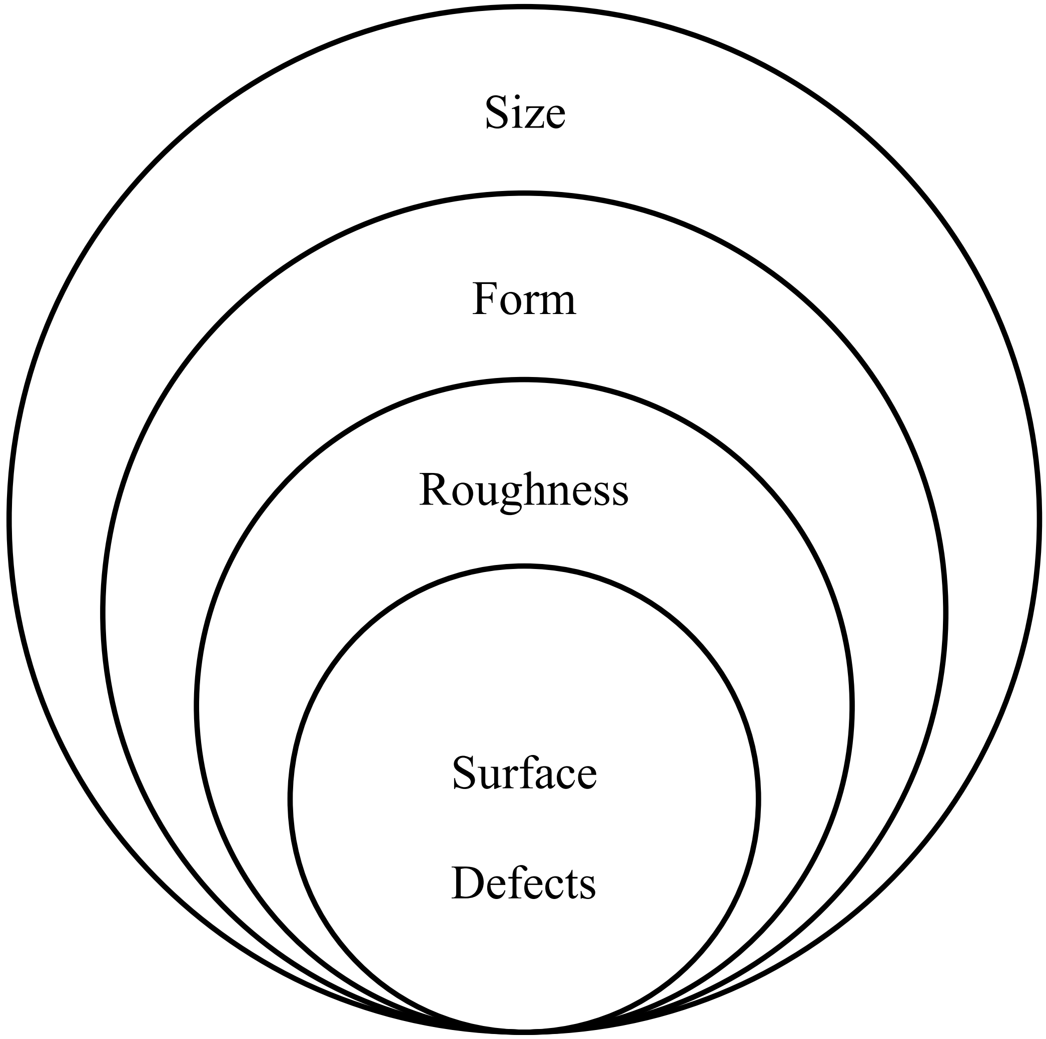

Figure 2: Nested Principle overview graphic.

The release of this standard has dangerous implications in industry and provides ample confusion among standards. To assume that size includes form, form incudes waviness, and so on places designers in a difficult position because they are now unable to separate critical surfaces/components and control them individually. Figure 3 below depicts how the nested principle can impact industry and provided motivation for this work.

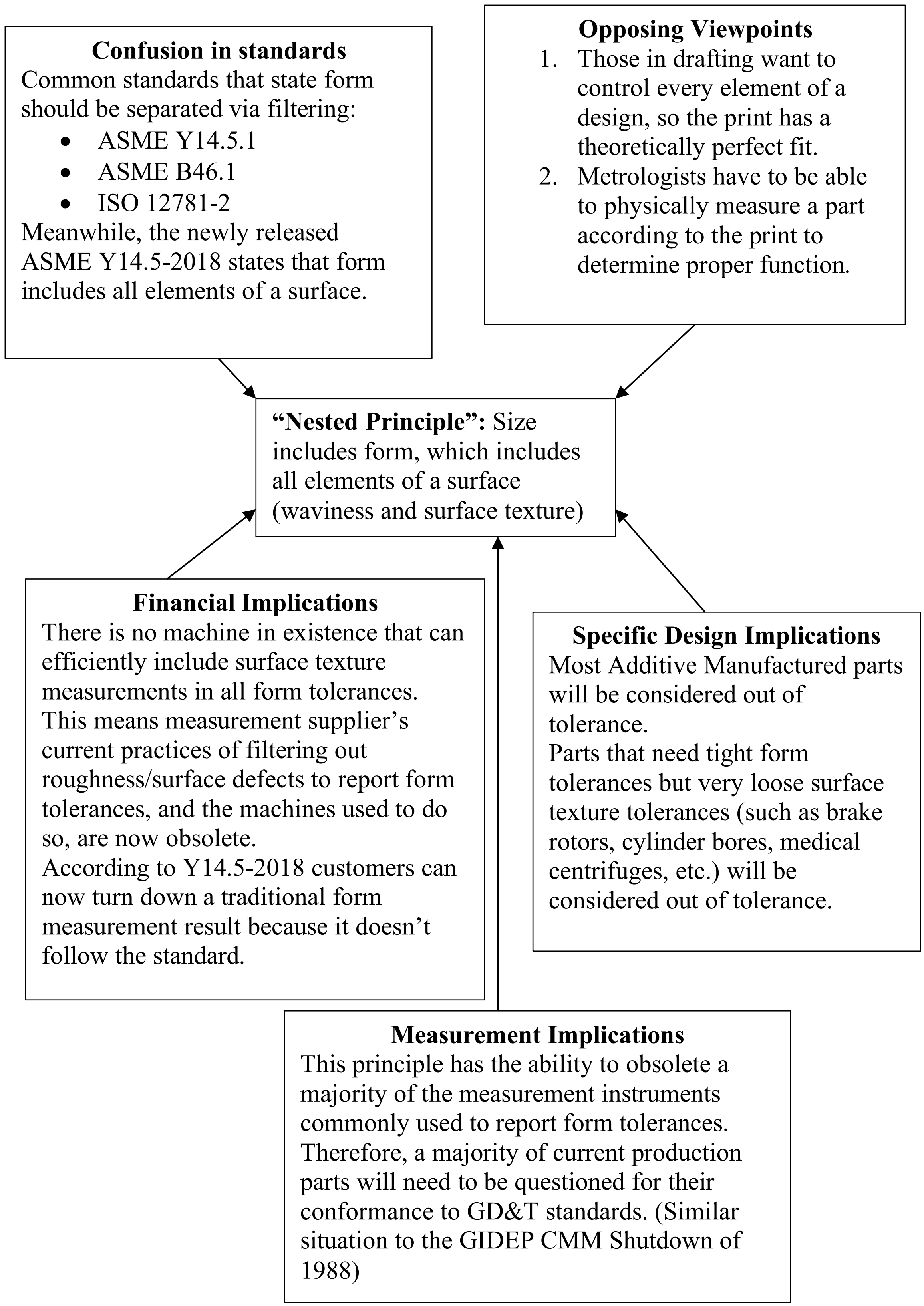

Figure 3: Nested Principle motivation outline.

1.2 Brief History of Surface Texture

Since the beginning of industrialization, designers have dimensioned parts on the basis that "every element" fits inside of their defined form tolerances. At that time, this practice was determined to be the most efficient method for design engineering. The industrial revolution led to a new generation of part production, where a "good" surface texture was the ultimate prize, and it became necessary to measure and quantify surface finish [2]. Now that manufacturing was advancing and process control was making its mark, it was no longer enough to blindly follow the designer's assumptions for surface finish. When it came time to check the quality of these parts it was obvious that "every element" is un-measurable. As a matter of fact, most of the early surface finish measuring techniques, such as scratching the part surface with a fingernail, visually comparing it to a reference, or viewing the surface through a microscope, were highly subjective [2]. Surface finish qualification remained an educated guess until much later in the century.

While the evolution of surface roughness measurement was transpiring in America, it was being paralleled, and even said to have begun, in the United Kingdom. David Whitehouse reviews the detailed history of surface measurement machines in chapter 6.2.3 of his book *Surfaces and their Measurement*. Whitehouse states that the first stylus instrument was developed in the UK in 1929 by Dr. Schmaltz [16]. Schmaltz's motivation for creating such an instrument came from watching American automotive manufacturers use the "fingernail" test to control the quality of surfaces on the production line. He created a stylus instrument in hopes to give manufacturers the ability to unambiguously quantify the surface finish of their parts. This type of stylus instrument was rudimentary but caught the attention of Dr. Abbott in America who was able to improve the design to support numerical quantification, leading to a giant leap for the technology [16].

In 1933 a new stylus contact instrument was invented by E.J. Abbot that allowed surface texture to be quantified numerically [2]. Now that a surface could finally be deemed good or bad, proper process control could be put into place. The next major leap in surface measurement technology came with the realization that the stylus itself was a limiting factor. By the 1960's part surfaces were viewed as key components to any good design and the use of 2RC filters, various new measurement instruments, and early roughness parameters (e.g Ra, Rq, and Rz) were becoming popular across all facets of manufacturing [2]. 2RC filters are essentially an electronic way to separate high frequencies from low frequencies. The 2RC filtering method served as an analog (hardware-based) method of separating roughness and waviness from a measured signal in real time. This involved placing a resistor and capacitor network between the measurement sensor signal and the plot recorder. This filtering method was standardized in ASME B46.1 - 1995 and the long wavelength (waviness) transmission characteristic was given as:

$$\frac{Filtering\ Output}{Filtering\ Input} = \left(\frac{1 - ik\lambda_s}{\lambda}\right)^{-2}$$

Where the constant $k = \frac{1}{\sqrt{3}}$, i is the imaginary number $\sqrt{-1}$, λ is the measured wavelength, and λ_s is the filter's cutoff wavelength [25].

Similarly, the short wavelength (roughness) producing filter is given by ASME B46.1 – 1995 as:

$$\frac{Filtering\ Output}{Filtering\ Input} = \left(\frac{1 - ik\lambda}{\lambda_c}\right)^{-2}$$

Where the constant $k = \frac{1}{\sqrt{3}}$, i is the imaginary number $\sqrt{-1}$, λ is the measured wavelength, and λ_c is the filter's cutoff wavelength [25].

The 2RC filter design involved converting wavelengths to frequency and tuning the filter accordingly based on the tracing speed. With the advent of digital surface texture analysis, 2RC filters were quickly abandoned in favor of Gaussian filters which did not have phase lagging and provide sharper transmission characteristics. Moreover, 2RC filters are virtually non-existent in today's surface texture instruments and analyses. In the late 1900's Abbot's analog surface signal from the stylus was able to be digitalized and the resulting surface profile trace was born, along with filters far more advanced than the 2RC filter. From that point on technology has been advancing and continues to develop new ways to break surface texture down to its smallest elements. However, measurement equipment is still a long way off from being able to quantify every element of a surface.

The most common type of surface roughness measuring instrument currently used comes in the form of a stylus contact system. Modern systems stem from the designs introduced by Schmaltz and Abbot almost a century ago. Essentially, this machine drags a stylus along the surface of a part to measure the surface height as a function of displacement. The data can then be analyzed to report a quantifiable value. Figure 4 below shows a high-level overview of how a stylus contact system operates to measure a surface. R_{max} is defined as the largest depth within the evaluation length and R_t is defined as the distance between the highest and lowest points within the evaluation length [17].

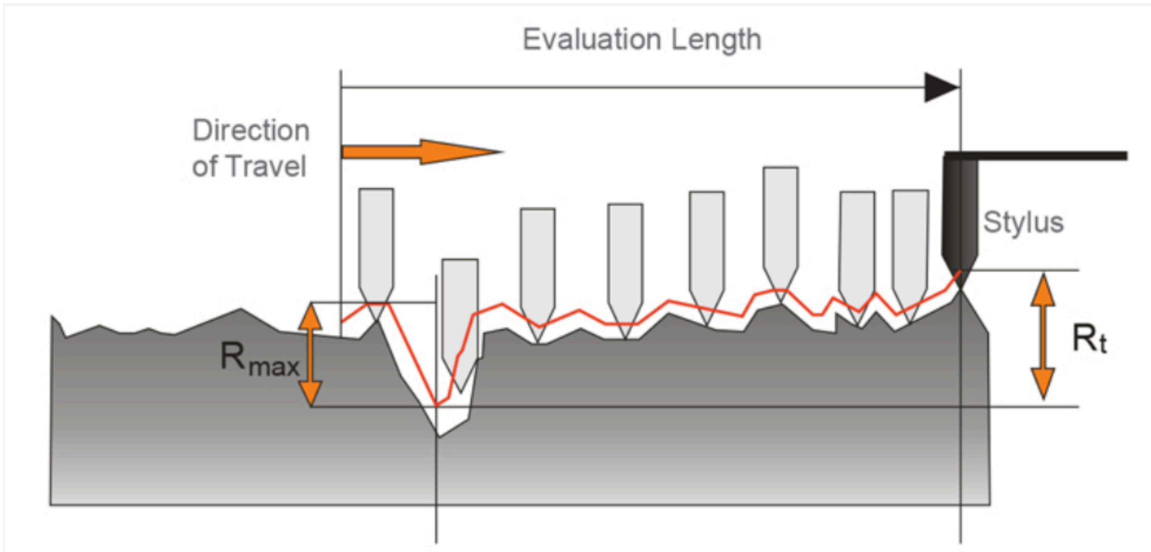

Figure 4: Representation of how a stylus contact system works [17].

For over a century it has been *assumed* by part designers that form tolerances on a print include all elements of the surface so that the GD&T callouts lead to a theoretically "perfect" design. This assumption was put in place to clear ambiguity present in part design. In other words, this design method eliminates the gray area involving the limits of what the GD&T callout controls on a part… it simply controls every molecule.

Historically, the magnitude of surface roughness hasn't been great enough to influence form. Therefore, there was no reason to question the inclusion of all elements in a part tolerance. In present times, the case where roughness level wavelengths can impact form controls is common in many mass-produced parts (such as cylinder bores, brake rotors, surface plates, etc.). While the assumption that tolerances include all elements of the surface seems like a novel idea to keep part design simple, the implications are much more complicated. Specific parts have specific fits, forms, and functions that likely require special attention to critical surfaces. Separating surface elements arguably remains the only way to effectively implement measurable part quality with the technology currently at our disposal.

1.3 Possible Effects of Y14.5-2018 rule s in Industry

As outlined in Figure 3, the addition of rule s to such a widely used standard has the potential to cause some serious trouble throughout the manufacturing community. If this standard is to be followed as written, there is cause for a high amount of concern in existing measurements, specific designs, and of course commercially. The following major implications of rule s will be discussed in detail in chapter 3.

First, current measurement systems such as CMM's, tactile surface instruments, various hard gages, optical instruments, etc. are often used to report form measurements from a print. Each of these instruments are incapable of measuring "all elements of a surface" as technology does not yet exist to quantify surfaces to that extent. Even if results from the most accurate surface measurement machines were considered to be in compliance with the standard, they often take a single sub millimeter trace at a time. To measure even a small surface area using this type of accuracy would take days if not weeks, deeming it useless in a production environment.

Second, there is then the case of specific functional designs. Predominantly in the automotive industry, certain parts are intentionally designed to have very strict form tolerances while maintaining loose surface texture tolerances. For example, cylinder bores and brake rotors require incredibly tight straightness and flatness tolerances respectively but need deep groves, pits, and pores to function properly. Also, additive manufactured parts are becoming more and more popular however their surface textures are notoriously rough. If rule s was to be followed in these cases a large majority of the parts produced would have to be considered scrap (i.e. would not conform to the current specifications).

Finally, the possible financial implications of employing rule s throughout industry are alarming. As explained above, currently available measurement machines are incapable of adhering to the new rule. That opens a door for customers to reject the form results delivered by measurement suppliers as they do not comply with the standard. The current common practice of filtering out roughness is no longer applicable which essentially sends all measurement suppliers back to the drawing board. Not to mention this could cause the shutdown of government and certified corporate labs until a solution is found, being that the current machines used are incapable of reliably determining the conformance of 'every element' of the surface.

1.4 Objective

This thesis serves to explore many of the possible outcomes that stem from the introduction of rule s into industry. A comprehensive review of the literature produced very few references, or even acknowledgement, of this new rule s. With that being said, the goal of this thesis is to raise awareness of the issue. This thesis seeks to provide sufficient relevant information and guidance so that the reader may draw their own informed decision about how to proceed. Hopefully this will spark discussion among industry leaders and give this issue the attention it deserves. Most importantly, a complete examination of all applicable areas will be conducted so that an answer can be presented for the question that has been brushed off for far too long… Should form (e.g. roundness, straightness, flatness, cylindricity etc.) include all elements of a surface?

CHAPTER 2: DETAILED BREAKDOWN OF RULE S

ASME Y14.5 is a standard provided and managed by professionals in industry and academia under the auspices of the American Society of Mechanical Engineers (ASME). Y14.5 focuses on defining the proper methodology, exact definitions, and best communication practices for geometric dimensioning and tolerancing (GD&T). ASME has amended and updated Y14.5 eight times over the last 50 years to keep up with the ever-changing landscape of the engineering and technology sector. These changes result from several years of committee meeting discussions in order to release the most beneficial standard to the customer. Standards committees are comprised of measurement equipment manufacturers, consumers, and academics so that standards are not biased towards one division of the field.

However, since Y14.5 is a GD&T standard its committee consists of a higher concentration of members who are responsible for implementing specifications and tolerances on drawings. Their work typically does not include developing, measuring, and testing prototypes. Therefore, the Y14.5 committee is primarily motivated by the function of "fit" rather than other surface related functions like sliding, sealing/adhesion, vibration, noise, etc.

When ASME Y14.5-2018 was released, there were not many significant modifications as compared to its predecessor ASME Y14.5-2009. However, tucked away in the *Fundamental Rules* section of the 2018 revision, a rule was added that gives cause for discussion. Rule s states "Unless otherwise specified (UOS), elements of a surface include surface texture and flaws (e.g., burrs and scratches). All elements of a surface shall be within the applicable specified tolerance zone boundaries." [1]. There is no further explanation offered on the rule, but it is so clear that further elaboration is unnecessary. These two sentences clear all the ambiguity involved in determining the acceptable data density and smoothing that has been lingering around for decades. According to experts in the field, this rule was always *implied* but never written because of all the complexities that go along with it.

The addition of this rule stems from the simple definition of what is really included in form tolerance. Form tolerances such as straightness, roundness, flatness, and cylindricity can all look very differently depending on the sampling size and filtering applied. Starting with a definition of a form tolerance, Y14.5-2018 Section 3.37 defines flatness as "the condition of a surface or derived median plane having all elements in one plane." [1]. It is important to understand what is considered as "all elements" of a surface. Interpretation is no longer needed as rule s clearly states that "elements of a surface include surface texture and flaws (e.g., burrs and scratches)." It can now be understood that form tolerances include all wavelengths of surface roughness.

Mark Malburg, CEO of Digital Metrology, shows that when reporting form tolerances, the surface wavelengths significantly influence the result. Figure 5 below shows an example of a surface trace measurement result, with both images in the same scale, from Digital Metrology's OmniSurf3D software.

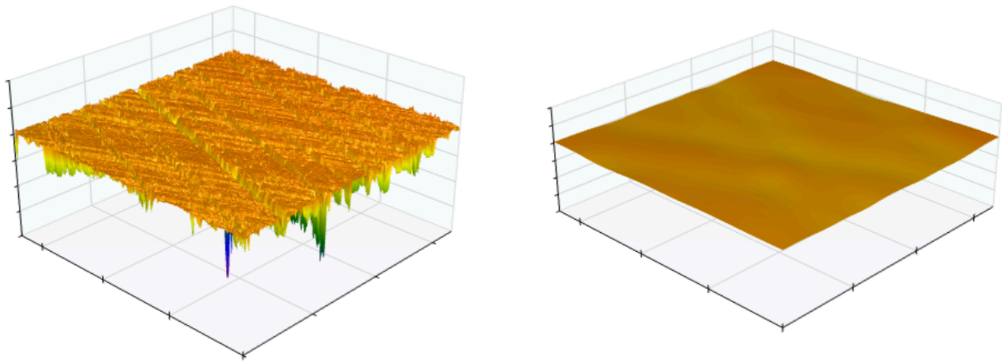

Figure 5: OmniSurf3D flatness result without filtering (Left) and with filtering (Right) [3].

In Figure 5 the software was set to include all wavelengths, resulting in the left image, then filtering was added to only report the larger wavelengths, resulting in the right image [3]. It is clear from this figure how much filtering impacts the measurement results. This seemingly elementary example is vital to understand how filtering delivers the resulting overall trend or “shape” of a surface at different sensitivities.

The second sentence of rule s states that “all elements of a surface shall be within the applicable specified tolerance zone boundaries." This is interpreted as: no matter how small, all surface deviations must remain inside the tolerance specified on the print. For example, a parts surface texture might contain a deep pit/pore or a sharp burr that is way out of tolerance but is so small that it has no effect on the actual function. Furthermore, it is likely that the “highest” molecule will be removed during assembly. The second part of rule s clearly states that every one of these deviations must be included anyway. This has a potentially detrimental effect on assessing part quality.

To put this into perspective let’s say a supplier has been making a part that conforms to a flatness tolerance with appropriate filtering, getting results similar to the image on the right of Figure 5. This part functions without issue as long as this flatness is within the tolerance agreed upon with the supplier, utilizing reasonable filtering. Essentially, the surface finish (i.e. the lower level “noise”) of the part does not affect its function (i.e. sliding, sealing, vibration, noise, etc.). However, the high-level flatness is vital to avoid defective parts. For example, a brake rotor will vibrate heavily if its surface is not flat at larger wavelengths, however the smaller wavelength roughness will have no impact.

The part flatness with no filtering looks like the image on the left of Figure 5. While the supplier’s parts will mostly fall within the tolerance when filtering is applied, defining the critical trend of the surface, they will not conform without the use of filtering. So, if the supplier was to attempt to be in conformance with Y14.5 they would not only have to make parts that have great a high-level flatness but great surface texture as well. For this part’s purpose, that would be unnecessary, incredibly expensive, and would likely put the supplier out of business.

It is important to distinguish between what features actually matter for part function. For example, when focused on sliding or rolling one surface over the other do “all elements” matter? The surface porosity or burrs may have no impact while large “lumps” may cause a massive failure. Figure 6 below shows a simple example of the sliding function of a part along three different surfaces.

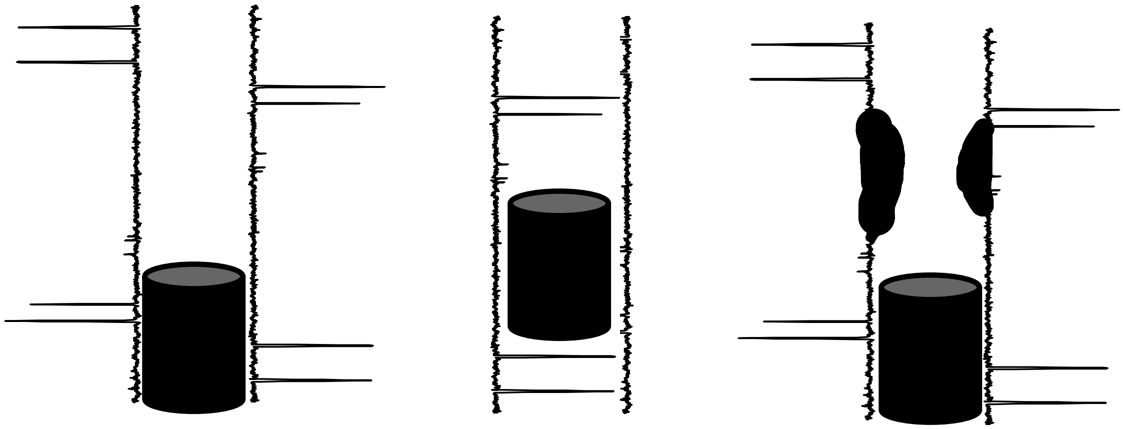

Figure 6: Cylinder sliding along a porous/burred surface (left/middle) vs. Cylinder sliding along a lumped surface (right).

From figure 6 it is clear that the cylinder can easily slide along the porous surface (left) while it will seize if it travels along the lumped surface (right). It is also important to note the case where sharp burrs are present on the internal surface (middle). In this case, the internal burrs will likely be removed immediately when the cylinder completes its first few traverses along the surface, resulting in no impact on successful part function. This exemplifies how the distinction between large and small wavelengths play in important role in designing any part that will slide, roll, traverse etc.

In order to keep part production manageable and realistic it is vital to determine what level of control is actually intended when a form tolerance (e.g. roundness, straightness, flatness, cylindricity etc.) is defined on a surface. The *functional surface* is defined as the specific surface that is controlled by the tolerance and is taken into careful consideration in the design process. Flatness is a very coarse tool for a designer to use, especially when there are a wide variety of functions that might be required from a flat surface. Therefore, a possibly filtered result may produce the shape that can be required to completely fit inside a flatness tolerance zone. It is important to note that the functional surface is not the actual part surface but the result of some processing.

The form controls of functional surfaces contain different levels of “strictness” that allow designers to choose to what level of scrutiny is needed on a part by part basis. For example, is the form tolerance a critical feature of the functional surface where the mating of components requires a near “perfect” surface finish? Or is the form there for the purpose of defining a datum, or simply there to ensure aesthetics, where the general trend needs to be flat, straight, etc. while the roughness has no impact? Many surfaces will fall into the latter. Trying to analyze the surface texture of the entire panel of a car door would be ridiculous, but necessary in order to follow rule s.

The lack of filtering called for in rule s could lead to a productivity halt on the production line of countless products. Malburg concluded that s claims form tolerances must include an infinite sampling size with no smoothing [3]. How will manufacturing facilities function without filtering? With the 2018 revision of Y14.5 comes a daunting number of implications that could affect the manufacturing industry as a whole.

CHAPTER 3: IMPLICATIONS OF RULE S

3.1 Current Measuring Machines

Now that it is clear how the application of rule s actually plays out, the possible implications can be broken down further. As previously stated, rule s has alarming implications on almost all measurement machines currently in use, designs with specific functional tolerances, and on the economy of manufacturing as a whole.

First, the implications of rule s on current measurement machines will be discussed. It is important to realize that the inclusion of *all elements* in the measurement of every surface is currently physically impossible. For example, Tactile measurements are vastly limited by the size of the stylus tip. While small wavelengths can be detected with a 2 μm diamond stylus tips, they are unable to travel down to the true depths of surface imperfections [3]. A stylus measurement might report a sizable pit, pore, or valley but the true value could be substantially greater.

With that being said, optical instruments are often viewed as the solution to the argument about rule s. Manufacturers market these machines as faster, easier, and more accurate then stylus systems, so it is easy to understand the basis of these assumptions. Yet, optical roughness instruments have several serious limitations. Peter DeGroot points to an alarming misinterpretation in published optical machine performance specifications in his presentation at the 5th International Conference on Surface Metrology. It is very important to understand that manufacturers often attempt to quantify their machines performance by claiming its “vertical resolution.” However, there is no internationally accepted definition to vertical resolution so its quoted value is subject to heavy discrepancy, by as much as two orders of magnitude [18]. With no clear way to quantify optical roughness instruments performance, some manufacturers report “resolution” and “accuracy” as interchangeable values as seen in Table 1 below (put together by Peter DeGroot from Zygo Corporation). It is clear from this table that the specification differences for similar machines are substantial.

Table 1: Various manufacturers published specifications of their 3D interference Microscopes. Table used from [18].

Instrument	Specification	Value (nm)
A	Repeatability of surface RMS (Z)	0.003
B	RMS repeatability (RMSσ)	<0.01
C	Vertical resolution	0.01
D	RMS repeatability of surface accuracy	0.01
E	RMS repeatability	<0.02
F	Noise floor	0.05
G	Vertical resolution	<0.1
H	Vertical resolution	0.1
I	RMS repeatability	0.3 RMS
J	Vertical resolution	1

DeGroot points to several other limitations in optical roughness measurement [18]. First, most systems use cameras on the order of 1024x1024 which forms a pixel limit, especially at low magnifications. There is also a subtle, yet important, diffraction limit at high magnifications. Finally, the optics (lenses) themselves introduce a resolution limit. These realizations can lead to the fact that optical machines are actually no more accurate than the stylus systems they are claiming to outperform. Therefore, optical systems cannot be viewed as the “magic solution” to the problems presented by rule s.

In Richard Leach’s article “Open questions in surface topography measurement” in the *Surface Topography: Metrology and Properties* textbook focused solely on finding the limitations of surface texture measurements, it was concluded that current technology is incapable of quantifying the true magnitude of surface imperfections [4]. Leach and colleagues focused on light scattering techniques as they have proven to be the most accurate method to detect the presence of surface defects. They were able to generate a roughness measurement with vertical and lateral resolutions down to 0.05 nm, for a 0.4 µm area [4]. It is important to note that these tests are done on precision optics in strictly controlled cleanroom environments. Atomic Force Microscopy (AFM) is also claimed to have similar, marginally better, sub-nanometer resolutions. But these are limited to a working area of around 50 mm. These forms of optical methods represent the forefront of surface measurement technology where scientists continue to seek higher resolutions. While this level of sensitivity is incredibly impressive, the technology is currently in beginning stages as they are still trying to understand and reduce the uncertainty involved in this method so that it can be applied to a wider range of surfaces. In conclusion, even for the most groundbreaking optical technology it is impossible to truly quantify *all* aspects of a surface.

If all elements of a surface cannot actually be measured, then what does that mean for the measurement instruments currently in use to report form tolerances (e.g. roundness, straightness, flatness, cylindricity etc.)? Since CMMs are currently the most widely utilized measurement machines in manufacturing it is critical to investigate their capability for measuring surface texture. Even if we were to interpret compliance to rule s as being able to report surface texture at resolutions that are currently possible, Coordinate Measuring Machines (CMMs) would automatically be discredited.

At an international conference for Computed Tomography (CT) a study was conducted to compare CMMs ability to measure surface texture to that of a CT system. This comparison was presented because the traceability used to establish a measurement uncertainty of a CT system is among the worst in the metrology community. Meanwhile, the traceability of a CMM is one of the best in the metrology community. A top of the line Zeiss O-Inspect 322 CMM was used in the experiment and the general maximum permissible error (MPE) for surface roughness was listed as 3.2 μm [5]. Taking that MPE as a universal value for all CMMs would already discredit them as a measurement tool. This MPE value is far too great to report surface defects according to rule s. The study incorporated different probe diameters, sampling sizes/speeds, measurement forces, and part surface finish qualities. The results showed high variations between all experiments. It was found that the probes were unable to adequately quantify the parts surface roughness as the stylus didn't travel into surface abnormalities, sliding over them instead, unable to capture the depth. Furthermore, the mathematical filtering at the foundation of a CMMs operation limit the allowable accuracy of dense sampling strategies such as surface texture measurements. The study concluded that the CMM "is not traceable for this measurement task" [5]. Essentially, CMMs shouldn't be used to measure surface roughness at sub-micron levels, let alone to measure *all* elements of a surface.

As stated above even the most accurate method of measuring surface texture is currently unable to truly quantify a surface. It is then reasonable to state that all other measuring machines including interferometers, tactile surface probes, roundness gauges, etc. should not be claimed to unambiguously determine conformance to tolerances specified according to ASME Y14.5 – 2018.

3.2 Designs with specific intent

Most current product development occurs by measuring and testing prototype parts throughout their use cycle to establish tolerance values based on the limits of acceptable function. Therefore, production tolerances are often based on these measured values, not simply theoretical predictions. A large number of measurement labs exist because there is no theoretical way to decide what an appropriate tolerance is for each individual part. Measurement labs measure and test so that they can assign tolerances based on functional necessity. In simple terms, there is no theoretical “book” that tells you what your roundness, straightness, flatness, etc. for a specific part should be to function effectively. Essentially, geometric modeling of parts captures the function of "fit", but not friction, contact deformation, or any other aspect of actual part function. There are rarely warranty issues based on proper fit of a part since it is easy to control. Most postproduction issues are based on failures that can only be discovered via testing and measurement [5].

The engineering field is consistently at the forefront of technological advancements. Armed with cutting edge technology, the manufacturing community is rapidly evolving to deliver the best products for the consumer. As products are becoming more advanced, so are the innovative designs behind them. Rule s has the ability to rob specific freedoms that allow for these advanced designs. In design it is common to have strict form tolerances but purposely loose surface texture tolerances for proper part function. Due to the addition of rule s, this widely used interpretation of "form and finish" is explicitly forbidden by the Y14.5 standard.

This discussion will focus on two of the most common examples used in manufacturing, cylinder bores and brake rotors. Both of these parts require excellent form tolerances (e.g. roundness, straightness, flatness, cylindricity etc.) but rely on “poor” surface finish to function properly.

Cylinder bores require a near perfect fit with the complimentary piston to minimize blow-by, so the wall of the bores must be incredibly straight and round. However, for the piston to move efficiently and freely, oil must be able to travel over deep grooves in the cylinder bore. This ensures the mating surfaces remain lubricated and debris can be collected. If these two aspects of the surface did not work together the engine would likely seize. An ordinary longitudinal surface trace of a cylinder bore wall is shown below in Figure 7 to represent a perfectly functioning part. For a frame of reference, a typical roundness tolerance of a cylinder bore is in the order of 4 μm [6].

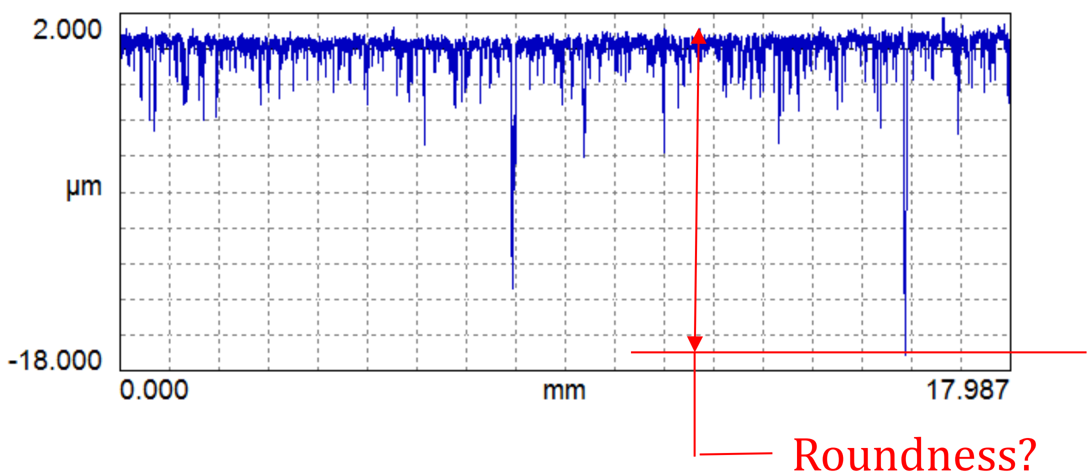

Figure 7: Surface trace of a cylinder bore [6].

However, Figure 7 depicts surface deviations in the order of 15 μm. It is clear that if this part were to conform to rule s the roundness tolerance would have to increase by around 15 μm. This would allow for the bores to be manufactured with lobing, causing major malfunctions.

Another example of this type of design is brake rotors. These parts need to have exceptionally flat form over the entire surface area so that the brake system doesn’t vibrate or pulse as it is employed. On the other hand, the more friction present when the braking system is applied, the better it functions to slow the vehicle down. To create the most amount of friction, rotors are designed to have rough, porous surfaces with high peaks and deep valleys. Not to mention, if these parts were required to be very smooth the cost of manufacturing would skyrocket. Peak to valley roughness in the order of 20 μm is frequently reported when analyzing a rotor, as seen below in figure 8.

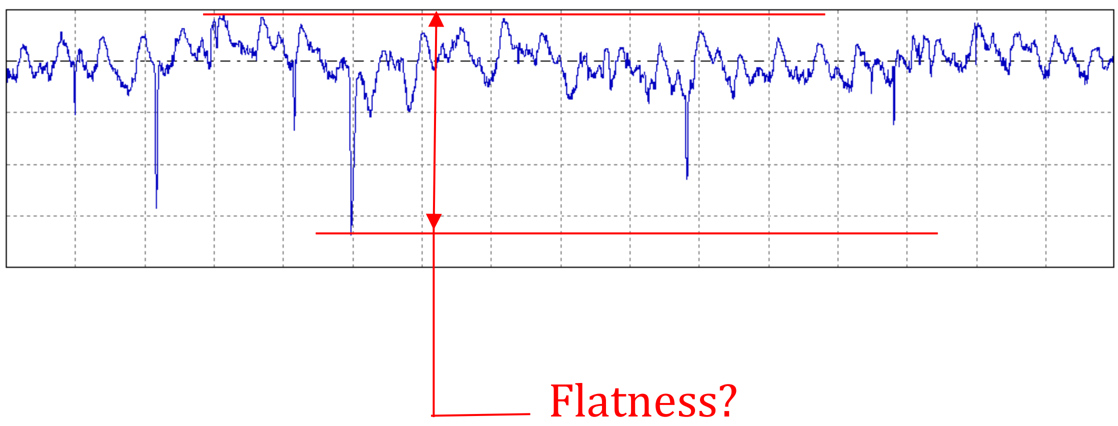

Figure 8: Surface trace of a brake rotor [6].

It is also noted that the typical flatness tolerance of brake rotors is in the order of 6 μm [6]. Again, to conform to rule s we would have to increase the tolerance by around 15 μm which would allow rotors to be manufactured with and arc or a "potato chip" shape. Yet another common consumer part would catastrophically malfunction.

The cylinder bore and brake rotor represent very important functions regarding everyday safety and the environment. However, these surfaces do not follow the nesting principle and the ideas of rule s since they can and, in fact, must have roughness features that are greater than underlying "form".

Another very common surface where small wavelengths are negligible is a granite surface plate. The upper surface must be very flat so that parts and gauges can slide uniformly. Yet the surface porosity can be, and usually will be, deep without affecting the function of the surface plate. Granite is a great material for a robust, overall flat surface, however it would be impossible to manufacture it without its inherent porosity.

These few examples demonstrate the importance of defining the *functional surface* of a part. In both the cylinder bore and the brake rotor, the functional surface can be distinctly defined by selecting the amount of filtering used in measurement. Appropriate filtering allows key surfaces to function properly without over restriction. Filtering permits the overall form to be flat or round while the surface can remain rough. This practice is used commonly throughout manufacturing and has allowed engines, brake systems, and many other complex parts to function for generations. However, rule s would consider the functional surface as the *entire* surface with no regard for the use of specific filtering.

Of course, most experienced companies will simply utilize the "Unless otherwise specified" portion written in the rule to mitigate the issue. However, ensuring to add this clause to every print that utilizes the separable model will be a difficult, tedious task. Form tolerances are commonly applied to a surface under the assumption that filtering will be utilized in the evaluation process. It is likely that these form tolerances will be overlooked amongst the hundreds of other callouts. Or even more probable, the designer assumes that those down the line know the difference between form and roughness and will measure accordingly. Effectively, manufacturers will be held to including all elements of the surface in their measurement results if the "Unless otherwise specified" clause is not added to every print where the partitioned model is utilized.

Filtering is currently common practice in manufacturing and allows these parts to be manufactured without issue. But what if rule s takes over as common practice instead? Many companies will likely encounter many out of tolerance parts, failures, and even recalls before they realize and fix the issue.

3.3 Financial Implications of Rule S

It is clear that rule s can bring current measurement equipment into question, now it is important to look at how it can affect the financial sector of manufacturing. The saying "time is money" applies directly to the effect of conformance to the new rule. Including surface texture in all form measurements welcomes the idea of higher measurement cycle times and costs. It has been shown above that truly following rule s is physically impossible. Essentially, since we cannot strictly follow the rule, the economic analysis will focus on measuring to the level that is currently possible, without the use of filtering.

Let's say we were to consider *all elements* of a surface to be the smallest limit we can physically measure with methods currently available. Now compliance to rule s shifts from impossible to highly impractical. A typical "precision" surface texture measurement consists of a 2 μm radius diamond stylus tip with 0.5 μm data point spacing [3]. This measurement will result in a high-sensitivity representation of the sampled surface. However, the area actually sampled is likely a single trace that is 4 millimeters long and less than a micron wide. A 4 mm evaluation trace, traversing at 0.5 mm/sec, takes around 15 seconds total. Furthermore, at 0.5 μm point spacing, we analyze around 8000 points in this measurement [3]. To put this into perspective, a 4 mm by 4 mm area for this quality of measurement contains around one million data points. The operator would now have to repeat this measurement for the entire length of the surface for which the form tolerance controls.

If we were to integrate techniques that could measure form tolerances well enough to conform to rule s, how much longer would typical measurements take? According to NISTIR

89-4088 there are three main techniques to measure surface roughness *accurately* enough to comply with rule s: using a tactile stylus based instrument (described in the example above and by far the most common), profiling techniques (including interferometers, STM, ATM, etc.), and area techniques (optical scattering, ultrasonics, etc.) [7]. It is important to note that the area techniques only give averaging results (i.e. no height maps or profiles). All of these techniques are discussed and compared in a detailed tutorial of surface finish metrology. These techniques are capable of measuring to nanometer resolution. For surface roughness measurements NIST reports a typical measurement speed for a stylus instrument as 1 mm/second, a typical scan area for profiling techniques to be roughly 0.7mm x 0.7mm, and a typical spot size for area techniques is in the range of 1mm x 1mm [7]. These general numbers will be used to better understand the time requirements for high accuracy surface measurements.

Reporting the flatness of the critical mating surface of an engine block head according to rule s would require one of the three methods listed above be used to sample the entire surface. Even a small engine block with less than a square foot (92903 mm^2) of surface area would take a week or more to measure. From past experience, a single 30 mm trace takes around 3-4 minutes to complete. For the engine block example, thousands of these scans would need to be taken to cover the surface. Most importantly, a large amount of measurement uncertainty would need to be added to accommodate the stitching of small areas to reproduce the entire surface. Utilizing a high accuracy optical system can possibly cut the measurement time in half, but they come with other issues such as limited to measuring perpendicular geometries, cost, part surface reflectivity, etc. The sheer volume of extra time that would need to be taken on common form measurements can cripple any facility's productivity.

Now let's apply this to a simple example. Let's say a metrology lab technician makes $40 an hour. An average roundness measurement would take a trained operator around 30 minutes on a stylus instrument. However, if we were to evaluate roundness according to rule s, and stay with 0.5 micron spacing between traces, we will need thousands of traces to cover a cylinder bore. Therefore, complying with rule s, the same measurement could take hours, days, or even weeks. The company currently paying the operator $20 for a perfectly good measurement would now have to spend around 1,000 times more to get the result. Not to mention that the operator is taken away from other paying customers work, decreasing the throughput of the lab. Even a few of these form measurements a month can destroy the profits of a measurement lab.

A large majority of all form measurements can function without issue by filtering out surface texture. This is, by definition, not in compliance with rule s. However, filtering allows form tolerances to be measured by much more efficient measuring equipment such as CMMs. For this reason, manufacturing facilities are able to employ larger sampling sizes in their control procedures, further improving part quality.

It is clear how this sampling requirement can cause a rippling effect throughout an entire quality control strategy. Process improvement techniques, such as 6-sigma, exist to minimize time spent on activities where little value is added to the company. Measuring the surface texture of a part that can function properly with a reasonably "rough" surface is contradicting all process improvement techniques. Complying to rule s when it does not capture a functional need seems to be going against everything manufacturing has been working towards to become more and more efficient. It is almost inconceivable to go through this process for every measurement plan involving some sort of form tolerance.

3.4 The Stedman Diagram

Over the past few decades surface texture measuring instruments have come a long way. Less than half a century ago the only option to measure roughness was tracing an analog contact stylus across the surface. Today metrologists have a wide array of instruments at their disposal ranging from high accuracy contact stylus systems to confocal scanning microscopes. Even CMM's are now becoming sensitive enough to measure wavelengths *near* the surface roughness threshold. Figure 9 below shows the evolution of measurement technology and the surface parameters they cover. The top image represents the historical spectrum while the bottom image represents the current spectrum, as of the early 2000's.

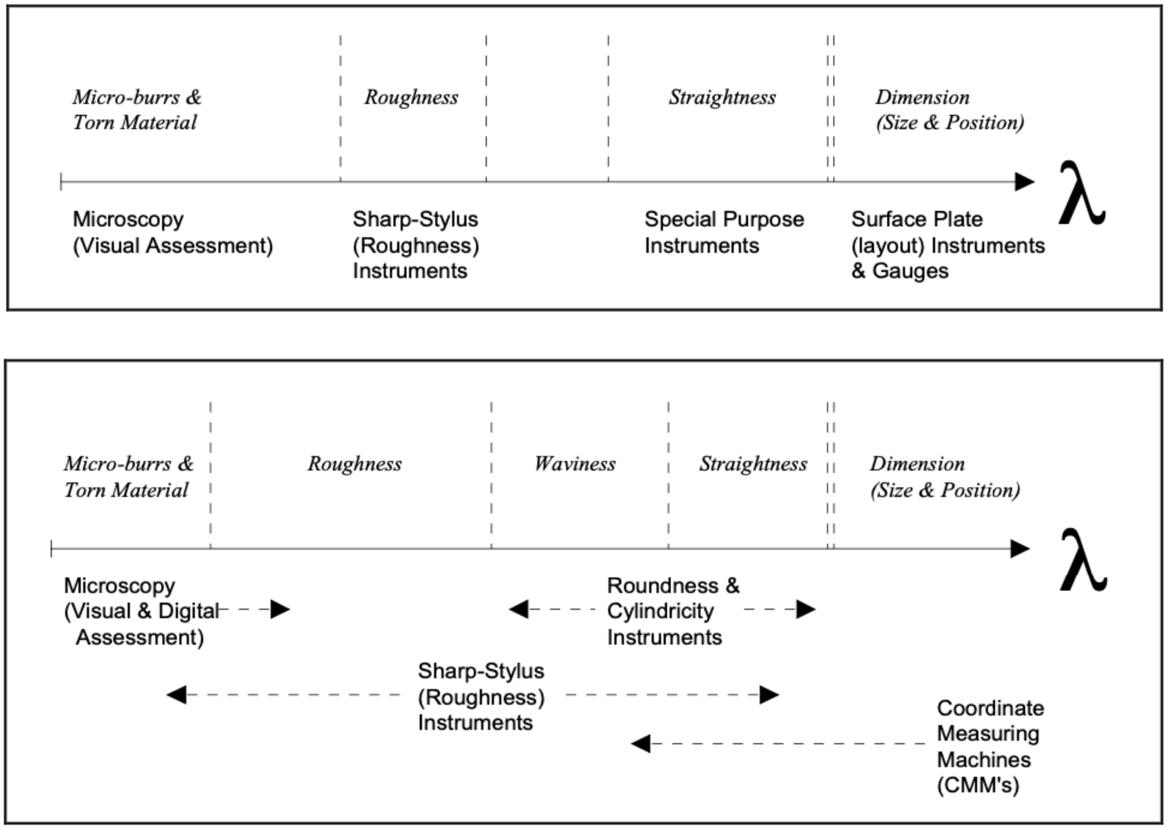

Figure 9: The historic (top) vs. the current (bottom) range of surface parameter measurement methods [19].

Figure 9 provides a better understanding of how measurement technology has evolved to the point where there is no clear line between which instruments are necessary to measure which surface parameter. Choosing an appropriate machine for a task is even more difficult now that the line differentiating between surface parameters is becoming blurred as well. Being that these machines can easily exceed $100,000 in cost, choosing the correct tool for the job at hand can be a daunting task. The Stedman Diagram was created to simplify this assessment process and is widely accepted as a technique to compare the performance of various surface roughness measurement machines [8].

In the simplest terms, the Stedman Diagram creates a two-dimensional area in log space that represents the measuring capability of an instrument. Any space outside of the specified area is considered unmeasurable by the instrument in question. Figure 10 below shows the traditional Stedman Diagram (left) along with a general global adaptation for a better understanding (right).

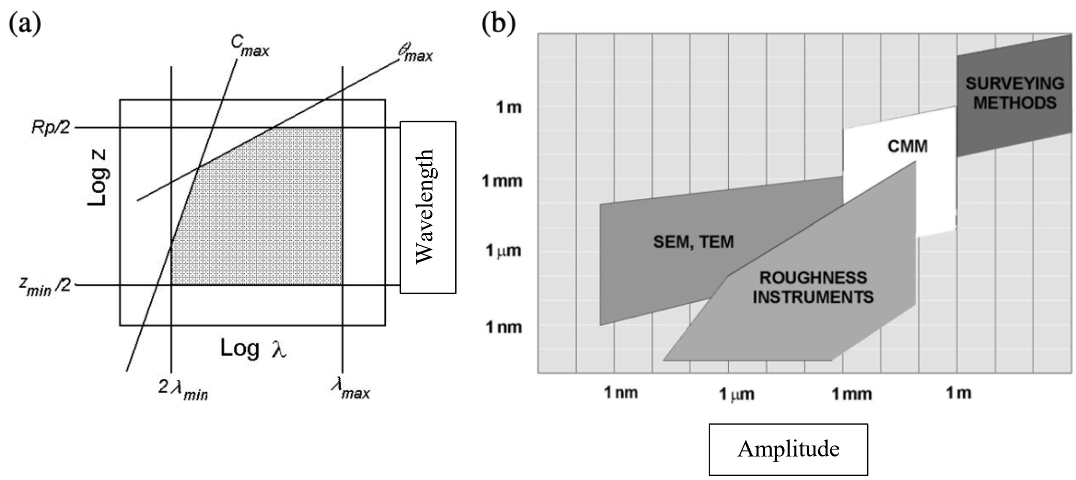

Figure 10: (a) Traditional Stedman Diagram (b) Global Adaptation of the Stedman (wavelength on the X-Axis and amplitude on the Y-Axis). Image reused from [8].

Z_{min} is the minimum possible height that the instrument can measure, λ_{max} and λ_{min} are the longest and shortest wavelengths respectively, θ_{max} is the steepest measurable slope, C_{max} is the sharpest measurable curvature, and *RP* is the amplitude [8]. With these parameters a Stedman Diagram can be constructed for any surface measuring instrument to get a good idea of its measuring capabilities.

Rosen and colleagues have revisited the Stedman diagram in order to analyze if it can be amended to coincide with the evolution of surface measurement technology. They explored adding a measuring velocity component to the diagram, making it a 3-Dimensional system (Amplitude, Wavelength, and Velocity). They evaluated instruments from several different manufactures and represented all common surface measurement instruments (e.g. white light interferometer, fringe projection, confocal, stylus, AFM, etc.). Utilizing the revised diagram, they discovered more detailed relationships between instruments that enabled a more precise selection of the correct tool for the job. However, the most interesting finding was that every single instrument was limited in their ability to quantify deep features such as valleys, pits, pores, etc. It was ultimately determined that none of the instruments can truly quantify a surface.

This study provides further understanding on the industry wide implications of compliance to rule s. As can be seen in Figure 10, the Stedman Diagram provides evidence that there is currently not an instrument in existence that allows for measurement of every element of a surface. Rosen concludes that “there is a de facto diagonal cutoff that makes the top left-hand area of the Stedman diagram inaccessible, i.e. large amplitudes at short wavelengths are, in practice, unmeasurable” [8]. This is alarming because large amplitudes at short wavelengths encompass most of the surface flaws seen in manufacturing. Essentially, it was determined that most surface flaws are unmeasurable. Therefore, it is apparent from Rosen’s work that compliance with AMSE Y14.5 is unachievable when it states *surface texture and flaws (e.g. burrs and scratches)* must be included in all form measurements.

CHAPTER 4: BREAKDOWN OF THE “NESTED” MODEL

4.1 Definition of the “Nested” Model

According to ASME Y14.5, Geometric Dimensioning and Tolerancing (GD&T), geometric specifications (callouts) control surface geometries based on what has recently been referred to in this thesis as the *nested principle*. The nested principle has previously been explained and laid out visually in figure 2. Y14.5 does not use the word “nested” but this principle is actually what is defined when the standard states "Unless otherwise specified (UOS), elements of a surface include surface texture and flaws (e.g., burrs and scratches). All elements of a surface shall be within the applicable specified tolerance zone boundaries." [1] At a high level, this principle can be defined as a tolerancing application where form controls include all wavelengths. Essentially this means that if there is no roughness callout on the print (such as Ra, Rz, Rc, etc.) then the form tolerance will include all wavelengths and amplitudes of that surface.

The nested model remained an unwritten code in industry until it was adopted by ASME Y14.5–2018 as the American GD&T specification for form tolerances. If a company wants to follow the standard without specifying otherwise, they must adopt the nested principle in their measurement plans and are no longer permitted to use any filtering in their form measurements (such as roundness, straightness, flatness, cylindricity etc.). Unless the print specifies that it does not follow rule s. The absence of filtering means any deep surface flaw (pits, pores, valleys, ect.) must be included in the final result. Even if pores are necessary and/or do not impact the function of the surface, they must be within the defined form tolerance.

The nested principle is based on the idea of fit – any molecule on the surface can keep from a non-interference fit. However, fit is only one function. Sealing, vibration, load-carrying, sliding/friction, bonding/adhesion, appearance, ergonomics, etc. are design functions that are not related to fit. Therefore, the idea of nesting does not apply to these necessary functions.

Also, a very important distinction to note is the actual meaning of the word "form" across different disciplines. The word form includes *all* deviations from the nominal in the GD&T world. The word form in the surface texture sector means only the long wavelengths. The difference in definition leads the ample confusion when designing and manufacturing a part. This notion supports the need for a final decision on whether industry is going to follow a nested model or a partitioned model.

4.2 The Nested Model vs. The Partitioned Model

It is difficult to adhere to the nested principle in most practical measurement applications. Measurement plans have developed over the years to follow their own principle focused around functionality of the surface in question. This principle is referred to in this work as the *Partitioned Model* because it distinctly separates size from form, form from waviness, and waviness from roughness. Where the nested model assesses all surface parameters together, the partitioned model assesses them one by one. Figure 11 below shows an example of how a surface trace is broken down into its three components by filtering out specific wavelengths. Surface defects (such as pits, pores, scratches, etc.) essentially represent the "fourth" separable component. Defects provide an additional level of detail and control to surface texture characterization. It is also important to note that there is a domain present in surface topographies with shorter wavelengths than roughness. This wavelength domain is not able to be considered part of the defect domain, as the amplitudes are too small.

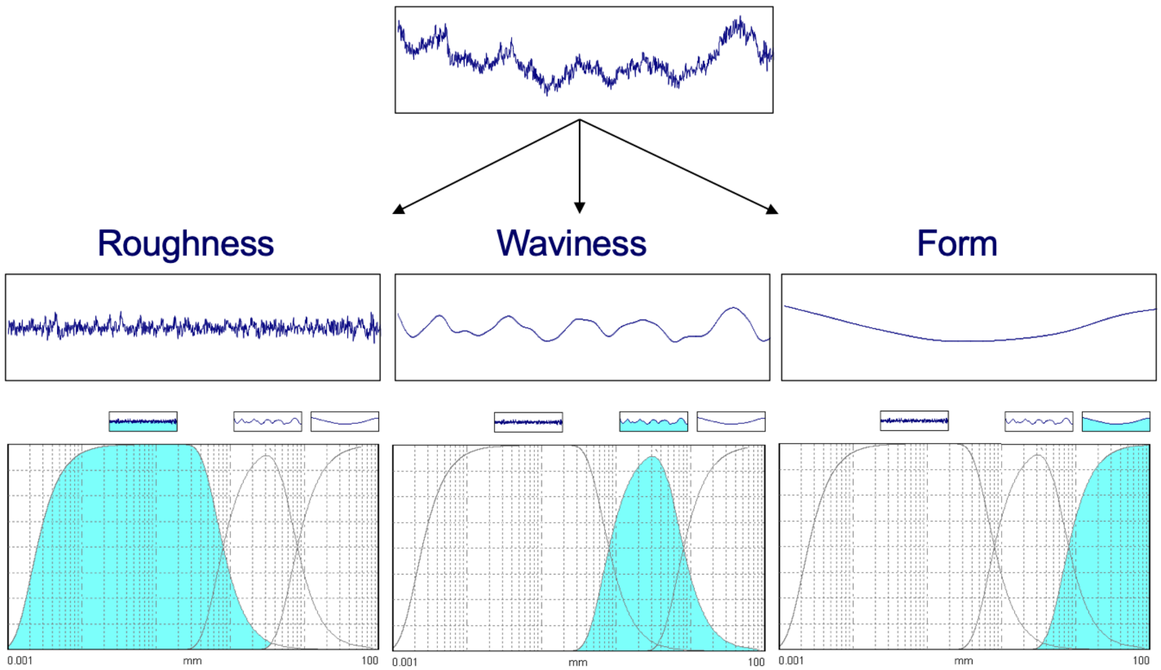

Figure 11: Illustration of how the partitioned model plays out on a surface measurement [6].

It is clear that the distinction between characteristics is defined by rather sharp wavelength cutoffs. This separation method gives designers the freedom to control surfaces based on their overall function. If a critical surface must be very smooth, a roughness parameter can be applied. Similarly, if a surface is acting as a reference datum or just for a clean appearance, a form tolerance can be applied. The partitioned model saves wasted time and money on unnecessarily strict controls when they have no impact on the part function. Meanwhile the nested model requires such measurements and additional costs.

For the partitioned model to work properly an appropriate filter must be applied to separate the wavelengths. To truly understand how the partitioned model differs from the nested model, the filtering that represents the foundation of the partitioned model must be understood. The most common filter for surface wavelength separation is the Gaussian filter.

ISO 16610-21 gives a detailed breakdown of the concepts behind the Gaussian filter, specifically how to separate long and short wavelengths of a surface. Essentially, the Gaussian filter is based on a weighted, moving average (convolution). ISO 16610-21 presents the Gaussian filter equation as a continuous weighting function $s(x)$ defined by:

$$s(x) = \frac{1}{\alpha\lambda_c} \exp\left[-\pi\left(\frac{x}{\alpha\lambda_c}\right)^2\right]$$

Where x is the distance from the center (maximum) of the weighting function, λ_c is the cut-off wavelength, and α is a constant to provide 50% transmission characteristic at the cut-off λ_c given by [20]:

$$\alpha = \sqrt{\frac{ln2}{\pi}} \approx 0.4697$$

The Fourier Transform of the weighting function $s(x)$ gives the transformation characteristic of the long wave component as:

$$\frac{a_1}{a_o} = \exp\left[-\pi\left(\frac{\alpha\lambda_c}{\lambda}\right)^2\right]$$

Where a_o is the amplitude of a sine wave profile before filtering, $a_1$is the amplitude of this sine profile in the mean line, and λ is the wavelength of this sine profile [20]. This transformation function is shown below in Figure 12.

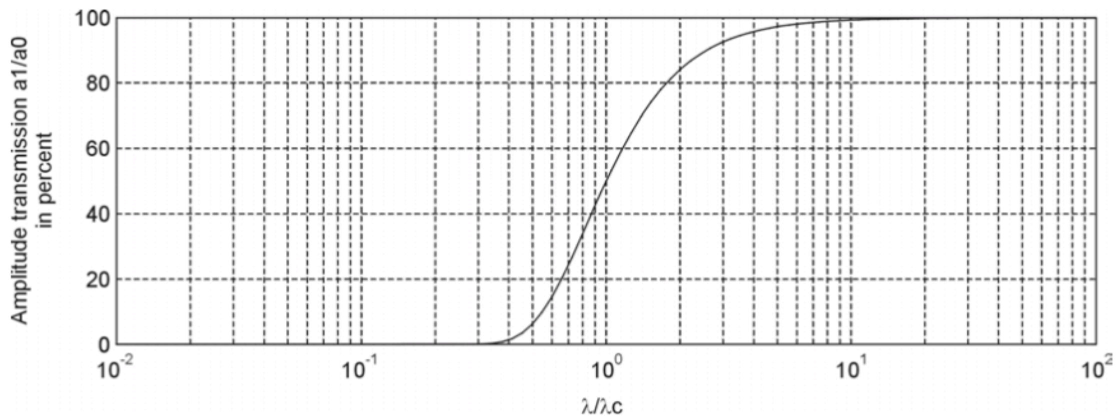

Figure 12: Gaussian Filter Transformation Characteristic of the long wave component for open profiles. Image reused from [20].

The Gaussian filter allows designers to isolate specific wavelengths so that form, waviness, and roughness can be analyzed independently. Filtering of surfaces gives true design freedom to control all aspects of a parts surface.

The long, medium, and short wavelength domains mean very different things in the eyes of the designer, or product developer, and in terms of process control. Figure 13 below presents examples of how these 3 domains have distinctive implications in different areas of industry. The graphic signifies how specific issues often present themselves in different domains, which allows for a much faster diagnosis. However, this would not be possible if the nested principle was to be followed as it does not support domain separation. This notion adds evidence to support the importance of separation of wavelengths to protect part quality. Domain separation is vital to both design and manufacturing to ensure parts are made efficiently/effectively and will function as expected in the field.

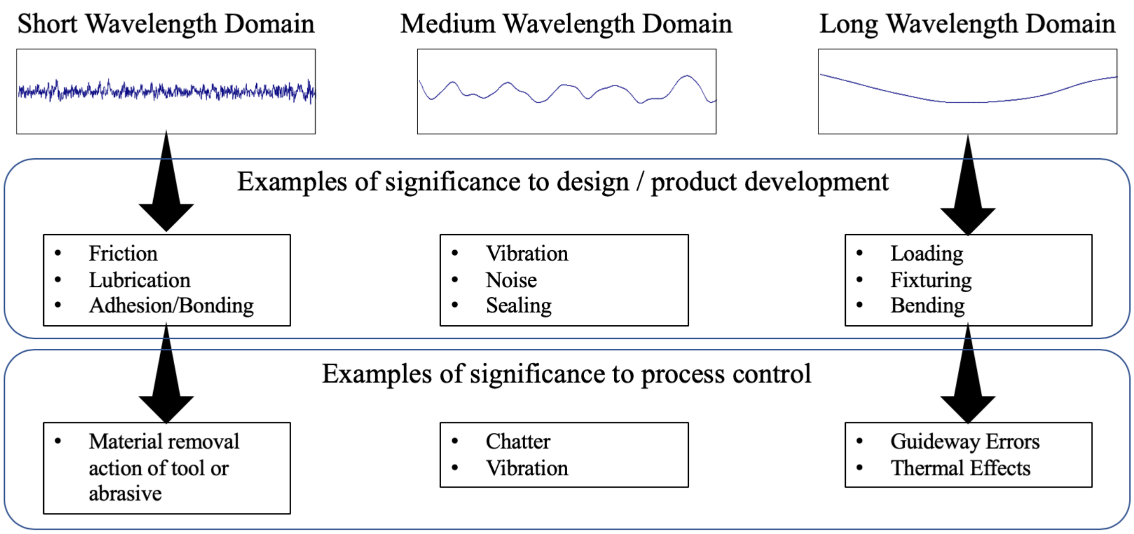

Figure 13: Significance of the 3 wavelength domains to design and process control.

Numerous standards support the use of filtering and even give clear definitions and best practices for their application. ISO 4288-1996 guides the reader through a process of choosing a wavelength cutoff. It states that the roughness/waviness cutoff should be 0.8 mm for most machining processes and the form cutoff should be 8mm [9]. Moreover, ISO and ASME standards recommend the form cutoff to be approximately 10 times the roughness cutoff. However, this should be viewed as a baseline and appropriate cutoffs should be determined on a case to case basis. ISO 4288 does provide a good starting point for surface measurements. For example, a variety of filters can be applied to focus only on wavelengths longer than 0.8 mm. Any data below that range can be considered roughness. Also, any data between the 8mm cutoff and the roughness cutoff is considered waviness. This notion allows for the isolation of wavelengths in all domains.

Figure 14 below shows an example of how a Gaussian filter acts on a surface trace. This trace is a “two-domain” example to convey the impact of filtering. At the next level, the waviness would be filtered to get the surfaces overall form (such as straightness, roundness, flatness, etc.).

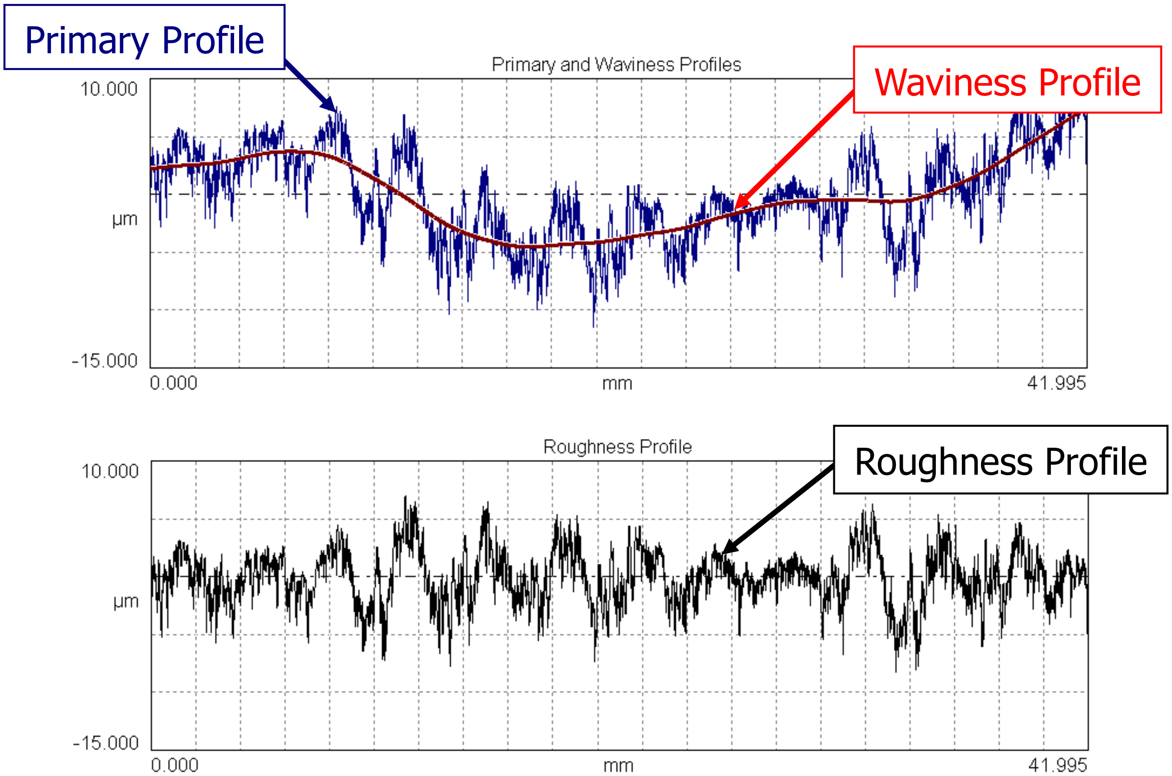

Figure 14: Example of the effect of Gaussian filtering on shorter wavelengths [6].

Figure 14 also provides a visual understanding of how the partitioned model actually applies to a surface measurement while applying a filter to distinguish waviness from roughness. In simple terms, waviness is the long-wavelength trend of the surface while roughness is comprised of the short-wavelength details that are superimposed on the waviness. If the engineer was only looking for the overall waviness, all of the details picked up from the roughness wavelengths would be filtered out because it is unnecessary information.

Figure 15 below provides a similar visual to recognize how the nested model plays out in a surface measurement. Including unfiltered roughness in the final result is often not what the customer actually wants to see and can lead to confusion. For example, let’s say the customer was looking for the general straightness trend of a surface. A report utilizing the nested principle would be of no use as it gives high sensitivity detail and does not isolate the trend. Figure 15 demonstrates how the nested report would show the straightness is way out of tolerance because it includes miniscule, possibly irrelevant, surface flaws. This image is effectively the definition of straightness according to rule s.

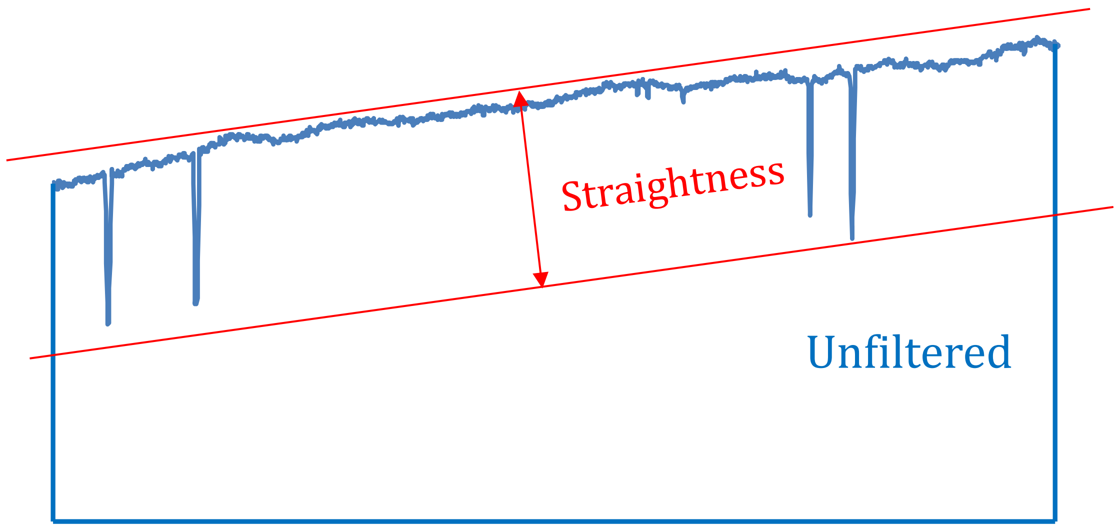

Figure 15: Illustration of how the nested principle plays out on a surface measurement [6].

Conversely, figure 16 below shows the straightness as it is defined in the partitioned model and according to common surface texture practices. These images illustrate how the same surface trace can lead to very different results depending on which principle is used.

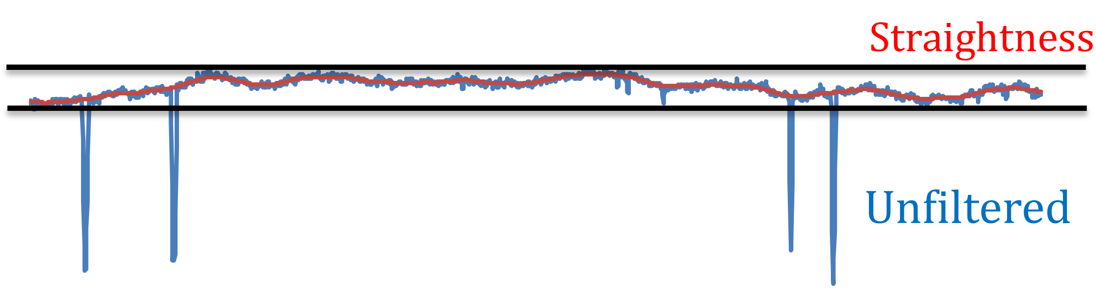

Figure 16: Illustration of how the partitioned model plays out on a surface measurement [6].

The straightness in the partitioned model is given as a result of the filtered trend of the surface instead of the "all elements of the surface" as called for in the nested model.

For the past century roughness was assumed to be very small in comparison to form tolerances (such as roundness, straightness, flatness, cylindricity etc.). This is largely due to the fact that the sensitivity of the common measuring instruments at the time were not capable of displaying small wavelengths of a surface with confidence. Present manufacturing processes and measurement instruments are becoming so advanced that there is no longer a clear separation from surface texture to form tolerances. As technology advances the line between roughness and form is starting to blend. The nested principle only works when each one of the nested features is remarkably small when compared to its parent. Effectively, the nested principle is useful when roughness is so small compared to the overall form that it is unable to be measured. This is no longer the case as even general CMM's now have the capability to pick up finer details and surface defects.

In NIST's "Surface Finish Metrology Tutorial" [7] numerous advantages of using a partitioned model are cited. The report also implies that separating form from wavelength and roughness is vital to successful design of critical surfaces. As a matter of fact, they state that "It has been shown, but not conclusively proven that the functional effects of form error, waviness, and roughness are different. Therefore, it has become an excepted practice to exclude waviness before roughness is numerically assessed" [7]. It can be concluded from the document that the national laboratory sees measuring form error separately from the other two surface parameters as recommended practice. NIST distinctly follows the wavelength separation parameters defined in the ISO standard along with the ASME B46.1 test procedure to calibrate their surface finish machines. This points to the fact that the most prominent metrology institution in America chooses to utilize the partitioned model over the nested model when analyzing a surface.

Dr. Bhushan from the Ohio State University released a journal article “Analysis of Surface Roughness” [10] that gives a detailed update on the current practices of surface roughness analysis from the manufacturing level to the cutting-edge experimentation level. The journal cites the importance of using the filtering components defined in the ISO standard and ASME B46.1 when measuring *any* geometrical feature to get a clear understanding of the integrity of the manufactured part [10]. The work goes on to examine all the possible causes for each surface parameter present in the manufacturing process and the best filtering techniques to ensure part quality. The journal bases the surface analysis recommendations on how each surface will affect the overall part function. The only way to truly determine function is to filter and separate form, waviness, and roughness to analyze them independently. After detailed analysis of the parameters, Bhushan concludes that “It is generally not possible to measure all features (all different wavelength domains) at the same time” [10]. Again, we are presented with a science-based, experimental conclusion that deems the nested principle an inappropriate method for analyzing surface geometries.

4.3 Use of the Partitioned Model in Industry

The question arises, if the nested model was adopted as the ASME standard how does industry actually adhere to these practices? The answer simple… they don’t. Based on the NIST toutorial, and the work of Dr. Bhushan and Dr. Malburg, there are rarely cases where a form measurement includes no filtering and inspects all wavelengths. However, the application of filters to assess the resulting form, waviness, *or* roughness of a critical surface is incredibly common. In practice, a surface is broken down and analyzed to determine which component is crucial for the most successful operation. At that point the ideal amount of filtering can be determined to keep production costs down and part quality up.

Given the above discussion of the nesting principle, it is important to see how industry practices form measurement. Do manufacturers and measurement suppliers comply with the nested principle? A literature search was conducted to gather information on the measurement procedures utilized by metrology industry leaders.

Mitutoyo, a leading measurement instrument manufacturer, released their in-house measurement procedure for surface geometries as well as the calibration procedure for their instruments. The text shows strict conformance to the filtering recommendations of ISO 4288 and no mention of ASME Y14.5 or the nested principle in practice. More importantly, before any measurement takes place, they first define whether they are focusing on the primary profile, waviness profile, or roughness profile and apply proper filtering to separate the components [11]. The design significance of measuring these components independently is outlined and deemed necessary for proper part function and manufacturing efficiency. The reliance on filtering and clear separation of surface parameters shows Mitutoyo's adherence to the partitioned model and complete disregard of the nested principle.

Dr. Jim Salsbury, the general manager of corporate metrology for Mitutoyo, recently conducted a presentation focused specifically on the updates of ASME Y14.5 - 2018. His answer to rule s was essentially that following standards are not mandatory and to continue measuring according to your company's plan [12]. Salsbury draws attention to the specific use of filtering for the past 50 years of roundness measurements. In conclusion, Salsbury questions whether Y14.5 gives designers the "necessary tools" to create functional parts [12].

The application of s and the nested principle removes the designer's ability to tolerance form, waviness, and roughness separately, vastly limiting control of surface geometries.

Mahr, another industry leader in measurement instruments, also released their in-house surface finish parameters. Again, several ISO documents, specifically ISO 4288, were cited repeatedly with abundant use of filtering. In their own measurement and calibration procedures they follow the strict wavelength cutoffs shown below in Figure 17. Mahr also defines the engineering significance of separating the waviness and roughness components from the primary profile, or form [13].

Selection of cutoff λ_c

DIN EN ISO 4288, ASME B46.1

Periodic profiles	Nonperiodic profiles		Cutoff	Sampl./ Eval. length
R_{sm} (mm)	R_z (µm)	R_a (µm)	λ_c (mm)	l_r / l_n (mm)
over .013 up to .04	up to .1	up to .02	.08	.08 / .4
over .04 up to .13	over .1 up to .5	over .02 up to .1	.25	.25 / 1.25
over .13 up to .4	over .5 up to 10	over .1 up to 2	.8	.8 / 4
over .4 up to 1.3	over 10 up to 50	over 2 up to 10	2.5	2.5 / 12.5
over 1.3 up to 4	over 50 up to 200	over 10 up to 80	8	8 / 40

Figure 17: Mahr's wavelength cutoff chart for filtering surface measurements [13].

Dr. Mike Mills, the Chief Metrologist at Taylor Hobson, conducted a presentation outlining his thought process on filtering cutoffs when measuring a surface. Mills focused on using the filtering recommendations from the standards, e.g. ISO 4288, as a guideline but exact cutoffs should be determined by taking all aspects of the part into account, specifically the machining process [14]. The main point of the presentation was that manufacturing is becoming so advanced that defining cutoffs should be taken into careful consideration to ensure the best part quality. It is unmistakable that Mills, along with Taylor Hobson, utilizes the partitioned model to assess surface geometries. So much so, that they are focused on processes to more accurately define the cutoff wavelengths between surface components so that they remain separate entities.

CHAPTER 5: SURFACE CONTROLS AND FILTERING IN OTHER STANDARDS

With the addition of rule s, ASME Y14.5 takes a different approach to surface texture controls than all other standards. As previously discussed, Y14.5 has adopted the nested model where the other standards follow the partitioned model when addressing surface finish. This chapter aims to look at how other standards treat surface measurements, specifically the use of filtering and isolation of different wavelengths.

ISO 1101:2017 is a GD&T standard that acts as a "sister standard" to ASME Y14.5 at the international level. Since these standards are so similar, it is interesting to discuss how ISO 1101 treats surfaces in its dimensioning and tolerancing recommendations. International experts recognized that prior to its release, all measurement specifications, specifically filtering settings, were highly biased and relied on the metrologist conducting the measurement. In fact, section A.3.7 states "It was a former practice to rely on common practice amongst metrologists, e.g. in terms of measuring instrument characteristics, sampling density and filter settings to limit the variability of results seen in verification in the absence of explicit filtering specifications. Because different metrologists made different choices, this led to variation in results and therefore ambiguity in the specification. Where such variations were excessive or influenced the function of the workpiece, drawing notes or inspection instructions were typically used to limit the variation. This document introduces specification elements to indicate filtering." [21]. Essentially, ISO decided to attempt to clear the ambiguity involved in filtering settings by introducing detailed specifications and guidelines in ISO 1101. This standard lays out examples, callouts, and specifications in Section 8.2.2.2.1, Annex C, and Annex E respectively.

On the other hand, ASME also recognized this issue when they released the newest revision of Y14.5 in 2018. However instead of laying out their own set of detailed, operation specific specifications, they attempted to clear this ambiguity with the addition of rule s.

ISO 1101 is employed to clear ambiguity and better specify surface measurements. First, the document clarifies that several *recommended* filter specifications are defined in ISO 16610 and there are currently no *default* filter specifications defined in ISO standards [21]. But when filters are used, they should be defined using the specifications given in 1101. Section 8.2.2.2.1 of ISO 1101 describes the proper practice for adding filtering specifications to print tolerances. For example, the section breaks down proper filter dictation on a print, order of filters (e.g. when to use a long-wave pass filter before the short-wave pass filter), specific filter units, nesting index, and many other organizational clarifications for different cases. Section E.2 then displays detailed examples of proper filtering specifications on a print and the associated measurement. Figure 18 below shows a sample of one of the examples located in section E.2.

Figure E.12 shows an example of a straightness specification with a band pass filter using two different filter types. The long-wave pass filter shall be written before the short-wave pass filter. The specification element S indicates that a spline filter is specified. The value 0,08 indicates a 0,08 mm cutoff and because the "-" follows the value, it is a long-wave pass filter, which removes wavelengths shorter than the cutoff value. The specification element CW indicates that a complex wavelet filter is specified. The value 2,5 indicates a 2,5 mm cutoff and because it is preceded by "-" it is a short-wave pass filter, which removes wavelengths longer than the cutoff value. The specification applies to a feature that has been filtered with a 0,08 mm long-wave pass spline filter and a 2,5 mm short-wave pass complex wavelet filter, which together form a band pass filter that retains wavelengths between 0,08 mm and 2,5 mm, effectively making this a type of waviness specification The intersection plane indicator adjacent to the tolerance indicator indicates that the specification applies to line elements parallel to datum C, so each individual filtered line shall be straight within a tolerance zone defined as the space between two lines 0,2 mm apart.

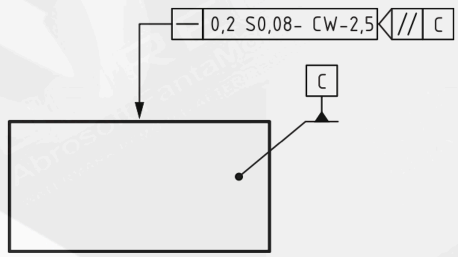

Figure E.12 — Example of a straightness specification with a band pass filter using two different filter types

Figure 18: Example of proper filtering dictation on a print. Image taken from ISO 1101:2017 page 138 [21].

This example describes the addition of filters to isolate wavelengths between 0.08mm and 2.5mm "effectively making this a type of waviness specification" [21]. Effectively, ISO is describing how to isolate a specific wavelength domain so the result can be reported as the waviness of the surface. This is evidence that, by definition, ISO recommends the partitioned model in their GD&T standard. If they were to follow the nested model, there would be no sections describing proper filtering techniques for form measurements because all wavelengths should be included in form measurements. There are examples, similar to the figure above, for almost all instances of form callouts to eliminate any confusion or bias between metrologists when applying filters.

In section C.3 it is pointed out that committees have been trying to decide on a set of final default filter settings that can be used universally across industry for decades. However, differences of opinion have led to no consensus. This standard does not include any set filter specifications in hopes that they will finally be agreed upon in the future. Since these absolute settings cannot be established, the previously discussed sections in ISO 1101 have been added to "provide the means to indicate unambiguous filter information in geometrical requirements" [21]. For now, ISO has delivered tools that can be used to properly define surface texture and control parts based on separable wavelengths. This provides proof that ISO sees the value in the use of the partitioned model when evaluating form, directly opposing rule s.

ISO 4288:1996 is the International standard that states the general values for surface texture filtering if a print does not contain any surface specifications, as they were explained in ISO 1101. ISO 4288 lays out surface texture parameter evaluation rules and procedures in an attempt to create a universal criterion for roughness inspection [9]. This standard provides a guideline for wavelength cutoff values to use when inspecting surface roughness of a part. Table 2 below provides an overview of such recommendations.

Table 2: Wavelength cutoff guideline according to ISO 4288:1996. Image taken from [14].

Periodic Profiles	Non-Periodic Profiles		Cut-off	Sampling Length/ Evaluation Length
Spacing Distance RSm (mm)	Rz (µm)	Ra (µm)	λc (mm)	λc (mm)/L
>0.013-0.04	To 0.1	To 0.02	0.08	0.08/0.4
>0.04-0.13	>0.1-0.5	>0.02-0.1	0.25	0.25/1.25
>0.13-0.4	>0.5-10	>0.1-2	0.8	0.8/4
>0.4-1.3	>10-50	>2-10	2.5	2.5/12.5
>1.3-4.0	>50	>10	8	8/40

These guidelines provide a resource to utilize when no roughness specifications are given on a print, yet an inspection is deemed necessary. The filtering specifications are vital in completing a successful surface texture measurement where roughness is to be separated out. This is an important concept because ISO 4288 deems surface roughness as a separated profile. ISO 4288 cites the GPS Matrix on page 7 where it claims the size, primary profile, waviness profile, roughness profile, and surface defects are all evaluated as separate entities [9]. To obey rule s all of the previously stated profiles would be nested under a single size measurement instead of measured and reported separately via the filtering recommendations provided.

ISO 12181-2 (Geometrical product specifications (GPS) - Roundness) discusses the specification operator for roundness, the probing setup, and the filtering characteristics that go into its measurement. The document claims that no roundness specification is complete without the application of filtering to smooth out noise. Since the result is directly influenced by the type of filter used, it must be clearly specified on the print. ISO 12181-2 states that the complete specification must include the transmission band for the roundness profile [22]. The transmission characteristic is defined using long and short wave-pass filters at specific cutoff frequencies. The long wave-pass attenuation function is defined as:

$$\frac{a_1}{a_o} = e^{-\pi\left(\frac{\alpha f}{f_c}\right)^2}$$

Where $\alpha = \sqrt{\frac{\ln(2)}{\pi}} = 0.4697$, a_o is the amplitude of sine wave undulation before filtering, a_1 is the amplitude of this sine wave undulation after filtering, f_c is the cut-off frequency (in undulations per revolution – UPR) of the longwave-pass filter, and f is the frequency of the sine wave (in undulations per revolution – UPR) [22]. The short wave-pass attenuation function is defined as:

$$\frac{a_2}{a_o} = 1 - e^{-\pi\left(\frac{\alpha \times f}{f_c}\right)^2}$$

Where $\alpha = \sqrt{\frac{\ln(2)}{\pi}} = 0.4697$, a_o is the amplitude of sine wave undulation before filtering, a_2 is the amplitude of this sine wave undulation after filtering, f_c is the cut-off frequency (in undulations per revolution – UPR) of the shortwave-pass filter, and f is the frequency of the sine wave (in undulations per revolution – UPR) [22].

ISO 12181-2 declared that any roundness measurement must have some level of filtering along with the reported cutoff frequency (in UPR). Different frequencies can be used to isolate different wavelength domains so that manufacturing issues (such as ovality, tri-lobing, chatter, etc.) can be diagnosed. These issues would not be detectable if all elements of the surface were to be included in the roundness measurement, as called for in rule s. ISO 12181-2 deems smoothing out smaller wavelengths as necessary in order to produce successful roundness measurements.

Similar to the ISO roundness specifications, ISO 12781-2 (Geometrical Product Specifications (GPS) - Flatness) reviews the specification operator for flatness, the probing setup, and the filtering characteristics that go into its measurement. In the introduction, the document states "At the current state of development, ISO TC 213 has not been able to reach a consensus on defaults for filter UPR, probe tip radius and method of association (reference plane). This means that a flatness specification must explicitly state which values are to be used for these specification operations in order for it to be unique." [23]. Once again, we see a standstill in reporting default filtering settings. In the case of flatness this delay is likely caused by the wide variation of surface sizes associated with flatness tolerances. For example, a 0.8 mm wavelength cutoff was proposed in early drafts of the standard to smooth out the roughness on flatness measurements [3]. This idea points to the direct separation of form (e.g. flatness) from roughness. The 0.8 mm roughness cutoff value, widely used throughout industry, was chosen in hopes of simplifying the flatness measurement process. Without this smoothing, such measurements would include an infinite number of points and no filtering. However, in larger surfaces (such as air foils, exterior automotive components, surface plates, etc.) implementing a 0.8 mm cutoff is still incredibly time consuming and tedious. Further smoothing is necessary to isolate the greater flatness trends on these larger surfaces. For that reason, determining an industry wide default value is difficult. ISO 12781-2 tries to mitigate this issue by adding recommendations of how to implement small wavelength filtering in each flatness measurement.

Even though it has not been explicitly stated, ISO 12781-2 reports a variety of filtering specifications and examples all aimed at separating out the roughness wavelengths. In addition, a note has been added stating “In practice it is unrealistic to achieve comprehensive coverage of the flatness feature given by the theoretical minimum density of points (see Annex B) within an acceptable time span using current technology. Therefore, more limited extraction strategies are employed that give specific rather than general information concerning the deviations from flat form.” [23]. This note is placed directly before all the recommended methods for filtering out small wavelengths (e.g. roughness). Therefore, it can be determined that ISO recommends smoothing out all roughness, or smaller wavelengths, when measuring flatness. This notion is in direct opposition to rule s.

ISO also recognizes that the partitioned model *must* be followed in order to control certain surface characteristics described in their other standard documents. For example, ISO 10110: 2017 Optics and photonics - Preparation of drawings for optical elements and systems - Part 7: Surface imperfections. This document serves to "specify the indication of the level of acceptability of surface imperfections within a test region on individual optical elements and optical assemblies. These include localized surface imperfections, edge chips and long scratches." [29]. In the optical world, miniscule surface imperfections are tightly controlled to ensure proper quality. The acceptance limit of each type of imperfection is defined in ISO 10110. This provides further evidence that ISO strictly follows the partitioned model. ISO presents numerous, independent standards that control form/figure, roughness, and finally surface defects (e.g ISO 10110). Conversely, ASME Y14.5 calls for all of these wavelengths to be assessed as one encompassing surface tolerance.

Lastly, there is an interesting link between three ASME standards with different views on filtering in surface texture measurements. ASME Y14.5 references ASME Y14.5.1-1994 in section 8.4.3 for "Mathematical Definition of Dimensioning and Tolerancing Principles" and ASME B46.1 in section 4.5.21. This is intriguing because both of the other ASME standards referenced in Y14.5 support the partitioned model.

In section 2.1.1 of ASME Y14.5.1 the document addresses "Establishing the Surface Points." This section claims that some form of filtering in necessary to isolate "dimensional features" (e.g. flatness) from the small wavelength noise (e.g. roughness) [24]. It can be concluded from this document that the roughness should be smoothed out when evaluating flatness.

In addition, ASME Y14.5.1 recommends “the use of smoothing functions as defined in ASME B46.1” [24]. Now, when discussing smoothing functions in section 1.2.2, ASME B46.1 introduces the idea of “errors of form” which are described as “widely spaced deviations which are not included in surface texture” [25]. Since this statement proposes that form is not included in surface texture, and surface texture includes waviness and roughness, this section can be understood as identifying three different wavelength domains: form, waviness, and roughness. Essentially, ASME B46.1 claims that roughness and waviness should be smoothed out when measuring flatness. This notion is in direct agreement with the partitioned model.

Therefore, it is apparent that there are three different viewpoints on form measurements, specifically flatness, embedded in the ASME spectrum. Figure 19 below presents a representation of how the viewpoints of the three different standards actually play out in a flatness interpretation.

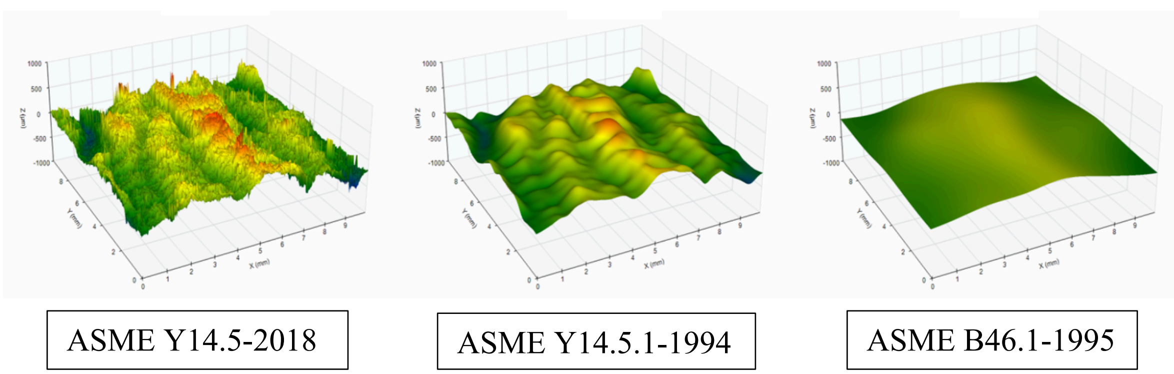

Figure 19: Proper Flatness measurements according to 3 different ASME Standards. Image taken from [3].

The chain of references from one ASME standard to the next promotes confusion on what position ASME is actually taking on surface measurements. First, we have ASME Y14.5 which introduced rule s and supports the nested model, where all elements of a surface should be included in form measurements. Then, ASME Y14.5.1 is referenced, which implies roughness should be smoothed when measuring flatness. Finally, ASME B46.1 is referenced which supports the partitioned model and recommends separation of form, waviness, and roughness.

In its most recent document (Y14.5-2018) ASME released rule s to clear ambiguity in surface measurement. Therefore, it can be assumed that the committee has chosen to adopt the nested model as their final answer to the question: Should form include roughness?

CHAPTER 6: COMPARISON TO GIDEP CMM SHUTDOWN OF 1988

The Government-Industry Data Exchange Program (GIDEP) is a collaborative effort between government entities and industry to promote advances in commerce by sharing information that will improve engineering processes. A GIDEP Alert can be placed by anyone who has a warranted reason to call widespread attention to a specific issue. This system allows American engineering disciplines to work together to mitigate costs as issues arise. Normally, GIDEP Alerts draw attention to a specific OEM part issue or quality concern that can affect other entities. Very few alerts have caught as much attention as the GIDEP Alert placed by Richard Walker (working for Westinghouse Electric Corporation at the time) in September of 1988.

Walker noticed some inconsistencies in certain CMM measurement results. After further investigation, he challenged the software algorithms used to process data in several different CMMs from multiple manufacturers. Instead of isolating a single machine or manufacturer, as typical GIDEP Alerts do, he declared the issue industry wide. The alert claimed "Certain algorithms that on many CMMs are advertised as measuring according to ANSI Y14.5M are calculated incorrectly. The algorithms specified and tested to date are flatness, parallelism, straightness, and perpendicularity. We have found that errors exist on four brands of CMMs, tested thus far. They are capable of stating that the measurement is worse than the actual data father up to an error of 37% and that the measurement is better than the actual data gathered up to an error of 50%" [26]. This alarming error value and inconsistency between measurements raised the concern that CMMs would no longer be considered capable for determining conformance to part specifications and would have to be shut down.

Once Walker discovered this inconsistency, he had to explicitly prove it. He knew without proper evidence CMM manufacturers would argue that repeatability depends on several factors (such as sampling strategy, number of points, probing errors, fixturing errors, etc.) and the errors are not caused by their algorithms. Walker devised a clever plan to isolate and test the algorithms ability to evaluate flatness, parallelism, straightness, and perpendicularity. He selected a specific point sets from various samples that could be solved by graphical methods, without the use of algorithms. This allowed Walker to specifically evaluate the repeatability and accuracy of the CMMs algorithms [27]. This study proved, undoubtably, that the algorithms used to assess these measurement features were incorrect. Walker concluded that the algorithms categorize such measurements into two categories: “Those that reject good parts and those that accept bad parts” [26]. Both of which are unacceptable and lead to a crisis in the metrology world.

In summary, a main issue behind the CMMs algorithms originates from a difference in measurement methodology. At the time of the alert, CMMs used the “least-squares” method for approximating the physical values of features. Meanwhile, the standards and GD&T practices assessed tolerances based on the “minimum zone” method. This caused some CMMs to report *only* the value of the largest deviation (least-squares method) rather than the overall trend of the feature. This resulted in predominant underestimation in the minimum zone of the features, since the least-squares values are always larger. The GIDEP Alert was caused by a difference in *methodology* while rule s represents a difference in *definition*. This notion means that rule s has the potential to cause an even larger, more costly fallout.

To resolve the GIDEP crisis, NIST and ASME began running Round Robin tests to gather their own data and try to identify a solution. Various government agencies worked to end the “shutdown” of their widely used CMMs. While they were creating a long-term solution, the Department of Commerce (in conjunction with NIST and the National Technology Administration) released NISTIR 5651 - Algorithm Testing and Evaluation Program for Coordinate Measuring Systems: Long Range Plan [28]. This was essentially the government’s long-term plan for solving the CMMs algorithm inconsistencies. The document stated that NIST planned to organize a group to specifically design calibration services for data analysis software, such as the CMMs algorithms. Customers would now be able to verify the traceability for their software by having it analyzed and tested by the national lab. This gave CMMs the credibility to be put back in operation as a method for assessing tolerances.

In parallel, ASME formed a group whose sole purpose was to identify key areas in industry that need attention to increase efficiency in the engineering discipline [27]. The group determined that mathematical definitions of tolerances are necessary to avoid measurement ambiguity, as presented by the GIDEP Alert. The traditional method of defining tolerances by written word lead to misinterpretation which caused algorithms to be written with a level of uncertainty. This led to the formation of the ASME Y14.5.1 subcommittee on mathematization of geometric tolerances in January of 1989 [27]. Ultimately, this committee released ASME Y14.5.1M-1994 - Mathematical Definition of Dimensioning and Tolerancing Principles. This document cleared up most of the ambiguity lingering around GD&T practices and the evaluation of callouts. With a better understanding, CMM algorithms were able to be updated and written so that the repeatability and accuracy were improved to the level we know of today.

Through these efforts, the root cause of the problem was able to be identified. The GIDEP Alert was an example of a single effect from a much larger, overarching issue. That is the use of text-based definitions to define mechanical tolerances [27]. The traditional text-based definitions allow ample room for interpretation. With technology advancing continuously and controls becoming tighter, there is no room for bias in how to assess tolerances for conformity. This is what ultimately led to the poor reproducibility of the CMMs algorithms. A hard, yet incredibly valuable, lesson was learned through this crisis. In perfect summary, Mark Nasson of Draper Laboratory stated, “Without the ability to unambiguously specify and assign tolerance controls to mechanical parts, we cannot expect to be able to uniformly verify the adherence of actual parts to those specifications.” [27].

The costs that this crisis incurred throughout the metrology community is the reason this GIDEP Alert remains one of the most popular metrology news stories to this day. This situation provided a great example of what happens when standards do not provide unambiguous content and explicit definitions. Since the metrology world learned such a hard lesson, standards committees should know better than make the same mistake twice. Thus, this begs the question, isn’t rule s an alarmingly similar case of an ambiguous, text-based definition of a tolerance control?

It has been identified that the GIDEP Alert of 1988 was caused by loose, text-based definitions of mechanical tolerances. Rule s shares the exact same characteristics. Again, ASME Y14.5-2018 Section 4.2 Rule (s) states "Unless otherwise specified (UOS), elements of a surface include surface texture and flaws (e.g., burrs and scratches). All elements of a surface shall be within the applicable specified tolerance zone boundaries." [1]. Similar to the pre-crisis tolerance definitions, this rule leaves ample room for biased comprehension. Several questions are left to the metrologist when conducting each individual measurement in accordance with rule s. To name a few: What is the appropriate sample size if the surface has to be measured so precisely? Since, *all elements* of a surface cannot be measured with current technology, how in depth must the measurement be to include small features (such as defects)? What parameters must be met to ensure the measurement instrument is capable to evaluate tolerances? Is there a size limit to including all elements of a surface based on the size of the surface (for example, measuring the straightness of a car door)? Do all measurements need to be performed using scanning methodology instead of single point sampling? All of these details are subject to significant variations based on the opinion of the person conducting the measurement. This can lead to even larger differences in measurement results than those seen in the CMM algorithm study conducted by Walker.

The GIDEP Alert became somewhat of a crisis because it called all CMM evaluated results for flatness, parallelism, straightness, and perpendicularity tolerances into question. As a matter of fact, the Chief Engineer for the Air Force Metrology Program stated that after the GIDEP Alert was released, all of the CMM measurements currently being conducted on aircraft parts were deemed invalid. This caused a huge halt in the labs output. Now each measurement plan had to be evaluated and uncertainty values re-calculated. In simple terms, the CMMs workflow was at a complete halt until proper traceability and calibration procedures could be established with the National Lab (NIST). It is clear that the GIDEP Alert was a precautionary move to prevent accepting bad parts and rejecting good parts. More than 20 years later, rule s raises the same concern with an even larger error.

In the case of the GIDEP Alert, the worst error that was observed is 50% of the peak to valley value [26]. While this is a serious error, rule s has the potential to create an even larger error. For example, let's say cylinder liner has a 4 μm roundness tolerance. If the measurement plan followed rule s than the reported roundness value would have to include all surface defects. Pore depths of 80+ μm are typical values seen in the surface of cylinder liners. Therefore, errors due to rule s can be on the order of hundreds of percent. In comparison, rule s can accept a much larger amount of bad parts and reject a much larger amount of good parts than presented in the GIDEP Alert.

Moreover, rule s is a blanket statement that includes *all* tolerances that rely on surface evaluation. Therefore, rule s represents a difference in definition. For example, in common practice surface measurements have almost always been conducted using filtering as a major proponent in the result. Rule s is now changing the definition of surface tolerances to exclude all filtering in their evaluation. Therefore, it can be concluded that rule s presents an even larger crisis than the GIDEP Alert as it calls for the complete overhaul of a long-standing methodology.

As a reasonable reaction, the GIDEP Alert caused the shutdown of all government CMMs in use at that time until a solution was uncovered. Rule s, on the other hand, has the potential to deem almost all surface evaluation instruments (CMMs, profilometers, structured light systems, CT, to name a few) as incapable since that are unable to capture all elements of a surface by themselves. Since the time of the GIDEP Alert the use of CMMs have increased dramatically. With that being said, even if rule s only caused the shutdown of CMMs, the effects would cause serious problems for metrology-based industries.

This chapter provides a real-life, historical example as to why the addition of rule s can have such a large impact in industry. The impact of the GIDEP Alert was felt for years after the fact and incurred daunting costs. Rule s has the potential to dwarf the costs of the 1988 crisis as it effects a much larger portion of industry.

CHAPTER 7: DISCUSSION IN SUPPORT OF RULE S

To understand the reasoning behind opposing viewpoints on rule s, it is important to first understand how tolerances are developed. Size tolerances can be chosen analytically by the designer, based, for example, on assembly and strength requirements. However, most form and texture tolerances, especially on critical surfaces, stem from previous experiments conducted on prototype parts. The part in question is often tested thoroughly during its specific function then measured with traditional instruments to determine final tolerance limits. Therefore, the existing form and texture tolerances are often the result of metrology-based testing rather than the general idea of "does it fit?" from rule s. Essentially if we applied rule s thinking to these existing tolerances we would get generic, fit based results which could be very different than those resulting from part specific testing and operational history. This different thought process when applying tolerances could lead to very different performance of manufactured components.

On the other hand, the "designer" (who in this work will represent any person working in the drafting discipline assigning part tolerances on a print) specifically assigns tolerances so that the mating parts will fit together "perfectly." A perfect fit can be defined as the case where all in-tolerance parts are guaranteed to assemble. In their case, the nested methodology behind rule s is the only model that allows them to successfully create a print. They are responsible for the first step in the life cycle of manufacturing a new or re-designed part. Effectively, they provide controls that the part must meet until the controls are improved (via in house testing, reverse engineering, field failures, etc.). In the part design stage, any miniscule surface imperfection, such as a nodule or burr, will keep from an ideal fit. Therefore, for the designer, a surface tolerance must include all elements of a surface.

7.1 Drafting Outlook vs. Metrology Outlook

The current generation of Y14.5 primarily addresses the control of fit. Therefore, all notions of function (for example sealing, sliding, and noise/vibration) are essentially based on fit. It is important to note that the function of fit is foundational to GD&T. Control over how surfaces interact is vital to successful part design.

Designers assign tolerances so that their assemblies fit together perfectly after all manufacturing processes are complete. This mindset provides a goal, or standard, for the manufacturing team to reach when actually producing the part. Within the factory, at the stage where the freshly designed part is being produced, is when rule s thrives. Many of those involved in that stage of the part life cycle are working to ensure the parts fit together perfectly when they leave the factory doors. Quality control techniques are consistently in play to confirm no out of tolerance parts are being sent to the customer. All of this effort is put towards releasing a part that conforms to the customers specifications.

This is where the disconnect takes place between the designer and the metrologist. The designer is working to produce tolerances, often using the nested model, to create the new part with the perfect fit. On the other hand, the metrologist is working to create a measurement plan to quantify the parts, often using the partitioned model. These two divisions within the factory follow completely different methodologies while trying to accomplish the same goal. Of course, this is the case for most of the manufacturing community. There is much more to the process of manufacturing a part, but this birds-eye view isolates the key components that apply to this work.

After the designer creates an “ideal” part, the metrologist works in accordance with other engineering units to refine the tolerances to ensure an acceptable function (how things will slide, roll, seal, etc.). This is where the final tolerances mostly come from. There is normally a comprehensive testing period where the fit-based tolerances are improved to become function-based tolerances that produce a final, effective part.

For generations this relationship has evolved and worked in harmony. Both the designer and the metrologist know how to generate the necessary results to produce successful parts. The designer assigns the tolerances and trusts the metrologists enough to create the proper measurement plan to ensure conformance. Meanwhile, the metrologist trusts the designer to present effective tolerance controls. It is important to note that this relationship becomes more difficult with further distributed supply chains. For example, a US based designer can't have as effective communication with a manufacturer in another country, as compared to the designer and manufacturer operating under the same roof.

Nonetheless, before rule s, both units were able to follow the principle that suited their job description the best. Now with the addition of rule s, one principle has been selected as the default that should be followed throughout the part life cycle of the manufacturing process. This throws the dynamic between the metrologist and the designer off balance.

Under rule s, all functions involved in part production are required to follow the nested principle, unless specified otherwise on the print. The nested principle works only when releasing the first iteration of print. In this stage tolerances are only based on an ideal fit. However, when it comes time to adapt these tolerances to allow for proper function, rule s presents a huge issue. Engineers and metrologists can no longer control part surfaces with separate wavelength domains or include filters to isolate a specific surface trend. Adherence to the nested principle dampens the ability to control a part based on its specific task.

Conversely, there are many cases where the inclusion of *all elements* of a surface within a tolerance zone will work from start to finish of part production. These are the cases where the surface wavelength domains are clearly discernable (e.g. size is much greater than form, which is much greater than waviness, which is much greater than roughness). This mostly presents itself when the surface texture of the part needs to be incredibly smooth, down to the roughness level. For example, fuel injector components, medical implants, prosthetics, bearing components, etc. In these cases, the nested principle works because the surface roughness is tightly controlled and is so miniscule that it will rarely affect the much larger form/size tolerance. In these common cases the nested principle works for the designer and the metrologist because the roughness tolerance is much smaller than the waviness tolerance, which is much smaller than the form/size tolerance. Each wavelength domain is controlled, yet has minimal, if any, impact on other.

These cases provide valid support for the addition of rule s. For parts with tightly controlled, smooth surfaces the nested model will successfully carry though its life cycle. Here, rule s clears all ambiguity involved in determining what size/form tolerances actually include in their control. This can be very valuable to mitigate any confusion in the manufacturing process. However, what about the parts where the wavelength domains are starting to overlap, or those where the surface roughness tolerance is greater than its form tolerance, as discussed in chapter 3.2.

There is also the case where parts simply don’t need a controlled surface roughness. Their function doesn’t require any tight fit and any burrs, or imperfections of that nature, will remove themselves during assembly. These “non-critical” parts make up a large part of manufacturing. They operate as a key component to the world economy, the balance between cost and quality. This drives competition in the marketplace and ensures that technology keeps advancing to provide the customer the highest quality part at the lowest cost. In this case, quality parts can be produced without any smaller wavelength evaluation. Adhering to rule s would force manufacturers of these parts to radically increase their surface inspection protocols, therefore dramatically increasing the price. This represents an example of why a *functional surface* is so important to distinguish. Therefore, a blanket statement that applies to all surfaces is counterproductive to the advancement of technology.

7.2 Design Intent

It would be foolish to claim that *all* drafting personnel are attempting to control every element of a part surface when they assign tolerances. Hundreds of years of successful engineering provides evidence that designers are more than capable of consistently releasing higher quality parts. Therefore, designers are commonly tasked with creating parts that have increasingly complex functions. In these cases, they modify their thought process to factor in the final function and control the part based on the specific *design intent.*

Design intent is effectively the practice of keeping the distinct, overall function of a part in mind when assigning tolerances or controls to a print. Design intent is a widely used notion in industry that aids the designer to control a part based on its purpose so that it does not require much revision when it advances to the testing phase. This is the concept that allows for the overall function of a part to be taken into consideration when assigning tolerances. A good understanding of design intent has given those in the design function the ability to treat each part individually and control it according to its unique needs. This open mindedness has allowed for continuous advancement in manufacturing.

The design stage of a new parts life cycle is often a race to get the part into production as soon as possible. Modifications are likely to occur in the prototype phase where designs can be solidified to ensure part quality. However, this trial and error process is very costly to manufacturers, so it is beneficial to minimize the time spent in the prototype phase as much as possible. This is where a skilled designer is advantageous. With design intent in mind, parts can be controlled properly within the design phase to mitigate the need for a lengthy trial and error period.

Experienced, successful, designers are typically very familiar with the design intent when tolerancing a part. These veterans have been taught the best practices and processes to design a successful part by their predecessors and through their own experiences. They follow the GD&T standards as a foundation of their work but take every project on a case to case basis, employing their experience to properly control parts, because engineering is rarely black and white. This leaves enough room for a skilled designer's creativity and knowledge to present a successful print, being that each part presents itself with a unique set of issues that must be carefully thought through to produce proper tolerances. However, until the most recent release of the ASME GD&T standard (Y14.5) there was nothing in the standards that limited the designer's capability to control surfaces differently based on the part function. As a matter of fact, before the release of Y14.5-2018 there was no ASME standard that outlined how to control surfaces differently. Therefore, it can be understood that the old problem (pre Y14.5-2018) was that there was *no default* for surface controls and the current problem (post Y14.5-2018) is that there is a *bad default* for surface controls. Rule s presents a limit when attempting to control surfaces properly in the design stage of a part lifecycle.

If the next generation of designers is taught to follow the GD&T standard as a foundation for their work, they will inevitably be required to follow rule s and the nested principle. This will limit the design freedom present in current successful design divisions that allows for a streamlined process from design to production. When it comes to assigning surface tolerances, the adoption of rule s takes away much of a designer's freedom and room for judgement calls based on experience. A major tool at a designer's disposal is the ability to control part surfaces at different levels, or wavelength domains. With the addition of rule s, designers are now forced to include even the smallest wavelengths in their tolerances which can cause much higher costs in the prototype phase. s can potentially diminish the design community's success being that it limits the practice of controlling a part with design intent in mind.

CHAPTER 8: MULTI-INSTRUMENT SURFACE EXPERIMENT

8.1 Experiment Overview

The experimental portion of this thesis serves to provide further insight on how rule s plays out in actual surfaces and their measurement. To analyze the effects of measuring according to rule s across a broad range of common scenarios, this study utilized 3 different instruments along with 2 common parts with different surface characteristics. This Multi-Instrument study will show that the nested principle doesn't have too much of an impact *if* the amplitudes of the part surface become smaller as each scale becomes smaller (i.e. size >> form >> roughness >> defects). Figure 20 below provides a visual representation of the circumstance that must be present for the nested model to succeed. For the nested model to work, each smaller parameter must be within the tolerance zone of the proceeding, larger parameter.

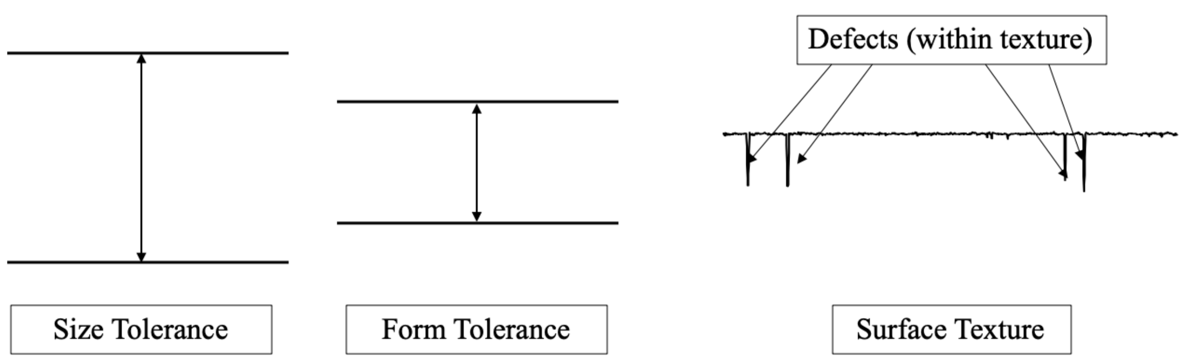

Figure 20: Visual representation of the circumstance where the nested model succeeds.

The instruments used to evaluate the surface were selected because they are the three most popular and widely used tools for measurements throughout industry. A Zeiss Prismo CMM, Mahr tactile surface profilometer, and ZYGO NextVIEW Scanning White Light Interferometer were chosen to represent the three main divisions of surface measurement.

The two surfaces were carefully chosen to represent common cases in manufacturing where rule s will work and where it will break down. The first surface represents the case where a parts surface texture is purposely designed to be larger than the required form control. A brake rotor was chosen to represent this case where rule s will breakdown in the part evaluation process. A brake rotor needs a very rough surface texture coupled with a tight form control to function properly. Figure 21 below shows the brake rotor that was used in this experiment.

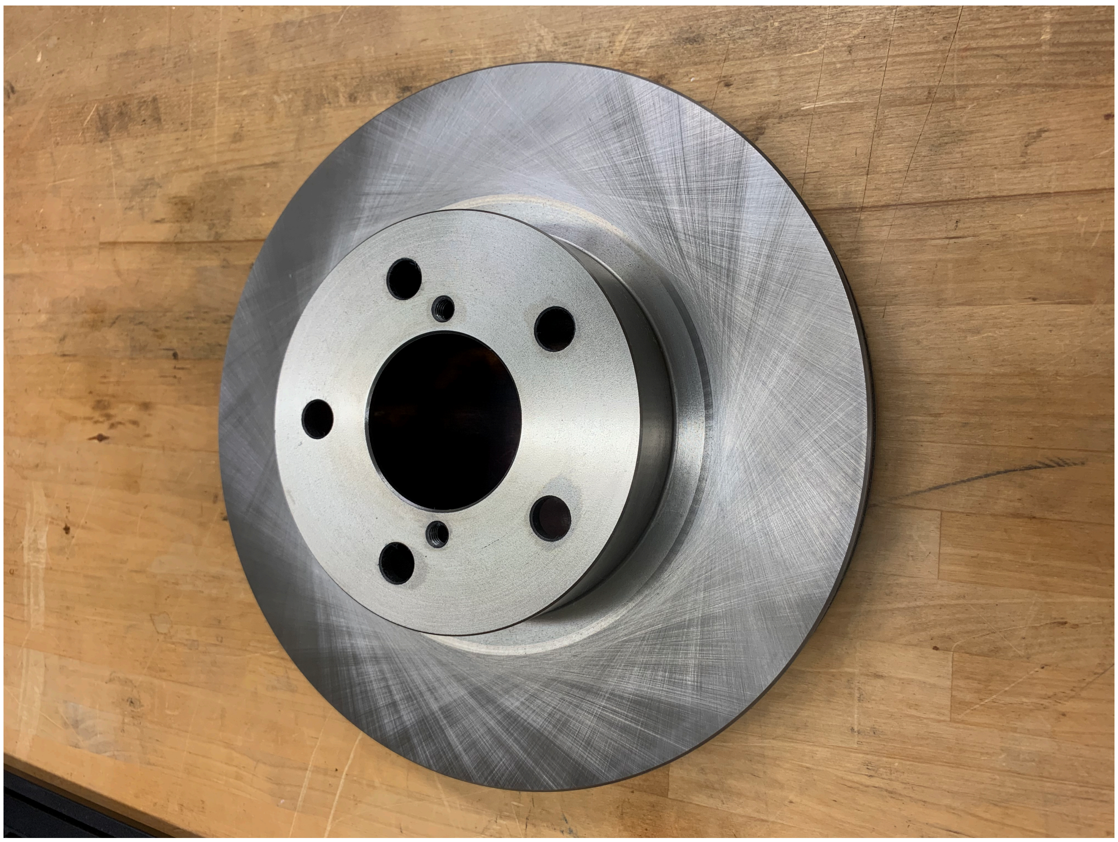

Figure 21: Image of the brake rotor used in this experiment.

The second surface represents the case where size is much greater than form, form is much greater than roughness, and roughness is greater than surface defects. A piston pin was chosen to represent this type of part where rule s will hold through its manufacturing lifecycle. A piston pin must have a controlled, smooth surface, along with a tight form tolerance to fit and function properly. Figure 22 below shows the piston pin that was used in this experiment.

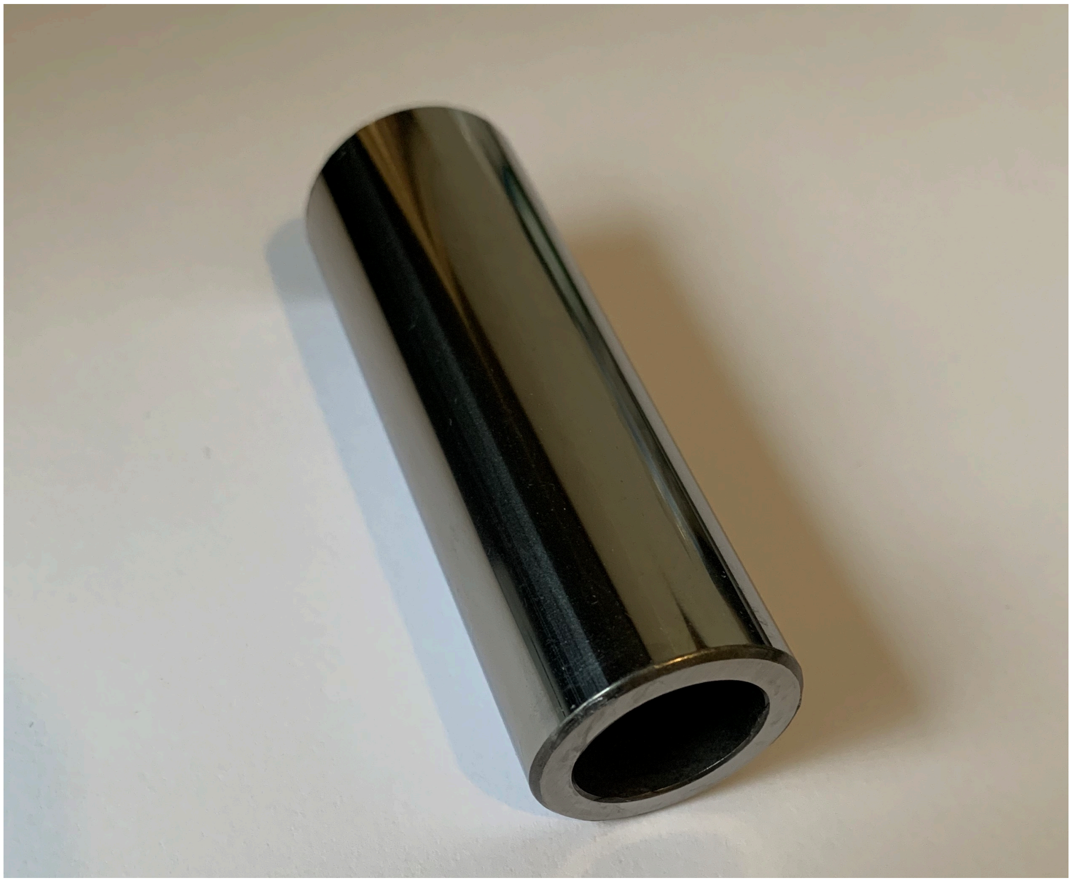

Figure 22: Image of the piston pin used in this experiment.

Table 3 below shows the experiment specifications for the surface evaluation of the brake rotor.

Table 3: Experiment specifications for the surface evaluation of the brake rotor.

Instrument	Instrument Specifications	Evaluation Procedure
Zeiss Prismo CMM	3mm diameter ruby stylus tip with 0.1mm point spacing	Measure 3 different locations (180° apart) on the surface of the rotor using continuous contact scanning. Take full length traces radially to report straightness and any attainable surface roughness/waviness. Then scan a 50mm x 50mm area on the surface of the rotor (using grid scanning methodology with 1mm spacing between lines) to report flatness.
Mahr Tactile Surface Profilometer	2 µm radius diamond stylus tip with 0.5 µm point spacing	Measure 3 different locations (180° apart) around the surface of the rotor. Take full length, radial traces to analyze the surface texture.
ZYGO NextVIEW Scanning White Light Interferometer	10x objective giving a 0.83 µm pixel size with a 1024 x 1024 pixel frame	Measure 3 different locations around the surface of the rotor. Each measurement will consist of a 5-frame x 5-frame stitch at different rotational locations (180° apart) with increasing radial distance between measurements.

Table 4 below shows the experiment specifications for the surface evaluation of the piston pin.

Table 4: Experiment specifications for the surface evaluation of the piston pin.

Instrument	**Instrument Specifications**	**Evaluation Procedure**
Zeiss Prismo CMM	3mm diameter ruby stylus tip with 0.1mm point spacing	Measure 3 different rotational orientations using continuous contact scanning. Take full length traces axially to report straightness and any attainable surface roughness/waviness.
Mahr Tactile Surface Profilometer	2 µm radius diamond stylus tip with 0.5 µm point spacing	Measure 3 different rotational orientations around the surface of the pin. Take full length, axial traces to analyze the surface texture.
ZYGO NextVIEW Scanning White Light Interferometer	10x objective giving a 0.83 µm pixel size with a 1024 x 1024 pixel frame	Measure 3 different locations around the surface of the pin. Each measurement will consist of a 3-frame x 3-frame stitch at different rotational locations with a spread between them along the axes of the cylinder.

The raw data from these experiments was extracted and analyzed using Digital Metrology's Omnisurf3D (for the CMM and ZYGO measurements) and Omnisurf2D software (for the CMM and Mahr measurements).

8.2 Brake Rotor Measurement Results

The measurement results from the brake rotor were just as expected. The surface texture was very rough at all measurement locations while the filtered form result (flatness) was small. After the measurement data from the brake rotor was analyzed, a single measurement was taken from each instrument and shown below. The filtering specifications used along with the measurement results are displayed on each image.

In each of the following Omnisurf3D images the abbreviations for the results are as follows: *St* is the total deviation in the data set (e.g. the highest peak to the lowest valley), *Sq* is the standard deviation of the data set, *Sp* is the highest peak in the data set, and *Sv* is the lowest valley in the data set. In each of the following Omnisurf2D images the abbreviations for the results are as follows: *Pt* is the total deviation in the data set (e.g. the highest peak to the lowest valley), *Pq* is the standard deviation of the data set, *Pp* is the highest peak in the data set, and *Pv* is the lowest valley in the data set.

Figure 23 below provides a visual representation of the CMM data from the 50mm x 50mm scanned area. The CMM picked up a few peaks across the surface of the rotor. As previously discussed, most of the peaks and valleys will be missed due to the heavy mechanical filtering effects encountered with the 3mm stylus tip along with the sparse sampling of the CMM program. It is shown below that the total peak to valley deviation of the brake rotor reported by the CMM is 9.994 µm.

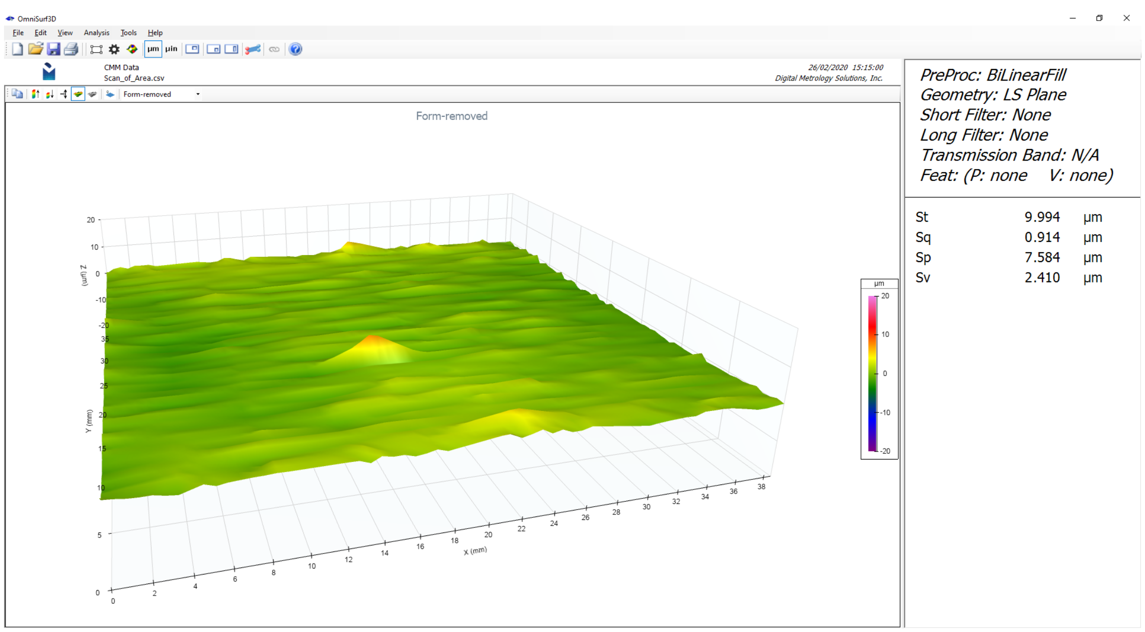

Figure 23: Characterization of the scanned area of the brake rotor surface using the Zeiss Prismo CMM. Image was created using Omnisurf3D software.

Figure 24 below provides a representation of the underside of the measured surface area from the same CMM data shown in the previous image. It was noted that the CMM did not report any prominent valleys (such as pores or grooves caused by the turning operation during manufacturing).

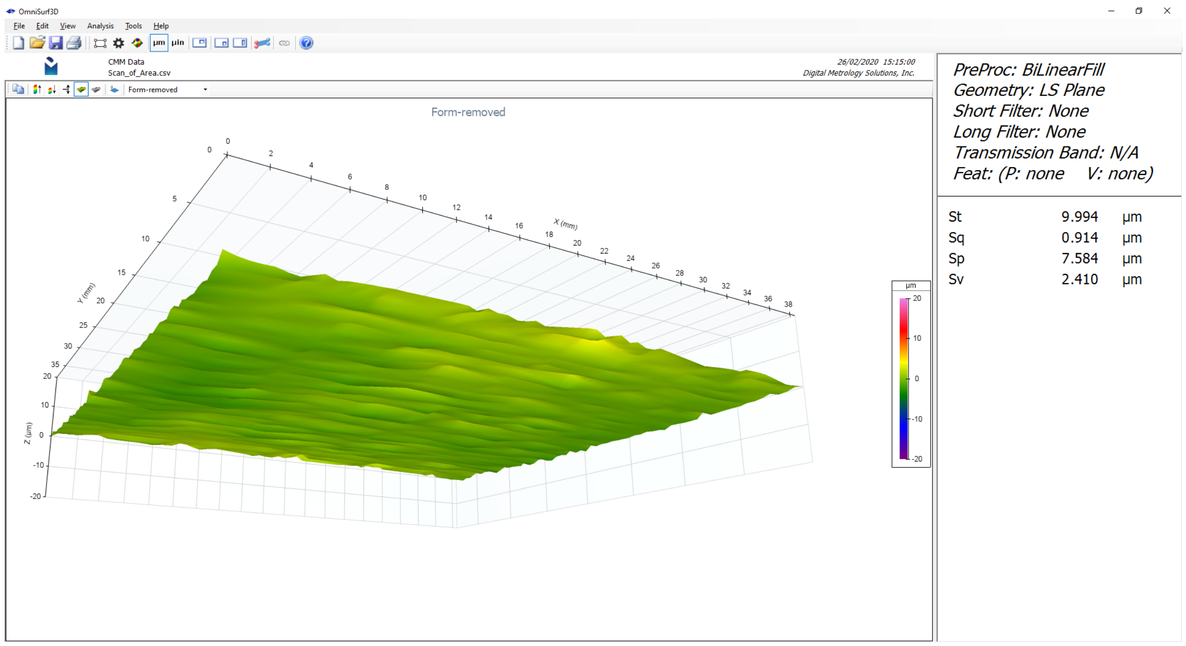

Figure 24: Characterization of the underside of the scanned area of the brake rotor surface using the Zeiss Prismo CMM. Image was created using Omnisurf3D software.

Figure 25 below provides the profile of a radial trace on the brake rotor's surface from the data acquired with the Mahr profilometer. It is shown below that the total peak to valley deviation of the brake rotor reported by the profilometer is 21.579 µm.

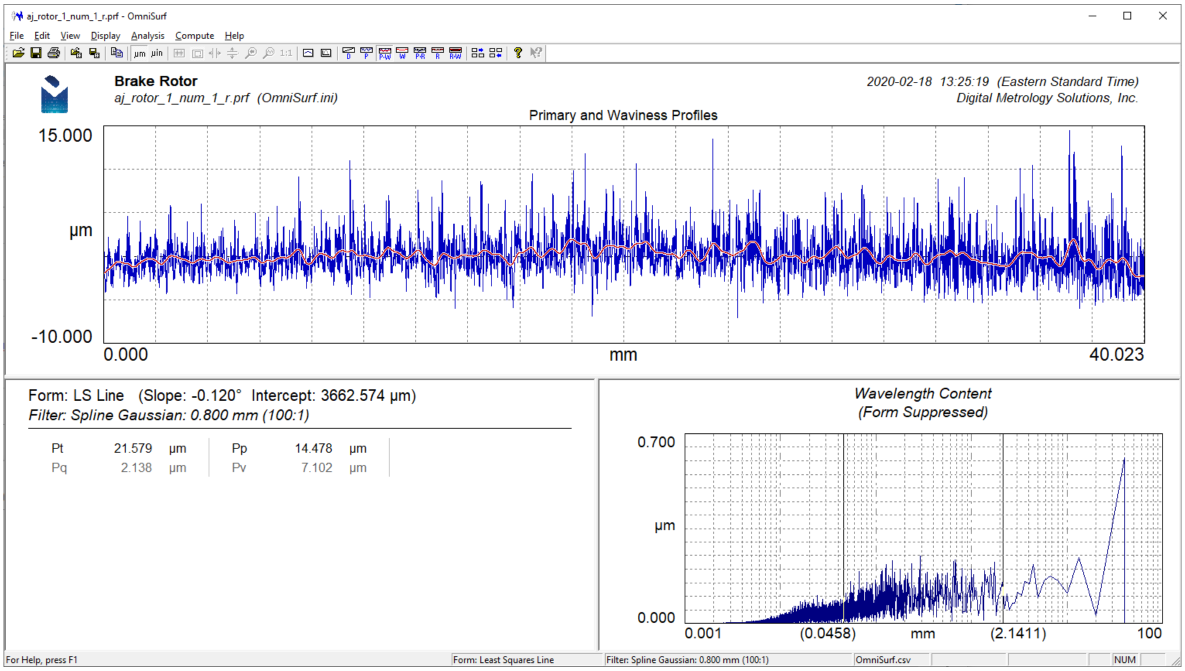

Figure 25: Profile of a radial surface trace of the brake rotor using the Mahr Profilometer. Image was created using Omnisurf2D software.

Figure 26 below provides a representation of a 5-frame x 5-frame stich of the brake rotor's surface from the data acquired with the ZYGO NextVIEW scanning white light interferometer. This areal data, without additional filtering, shows a higher concentration of tall peaks. It is shown below that the total peak to valley deviation of the brake rotor reported by the ZYGO NextVIEW is 39.891 µm.

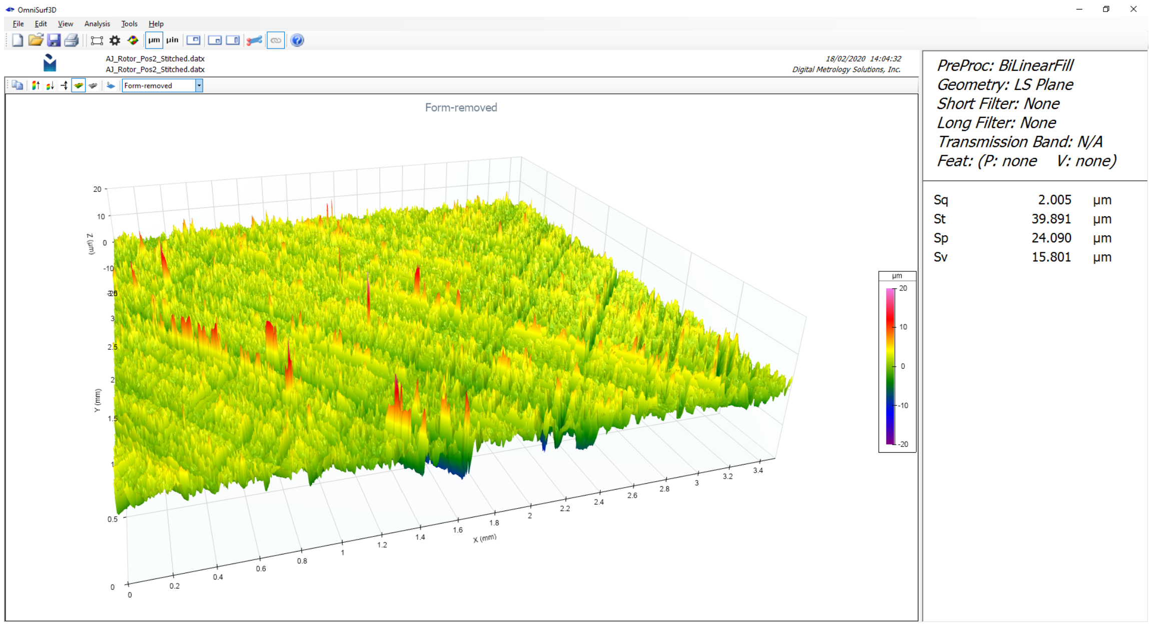

Figure 26: Characterization of a measured area of the brake rotor surface using the ZYGO NextVIEW Scanning White Light Interferometer. Image was created using Omnisurf3D software.

Figure 27 below provides a representation of the underside of the above surface area. It is shown that there are clear pores and valleys reported in this analysis. It is shown below that there were pores present on the surface that reached depths of 15.801 µm.

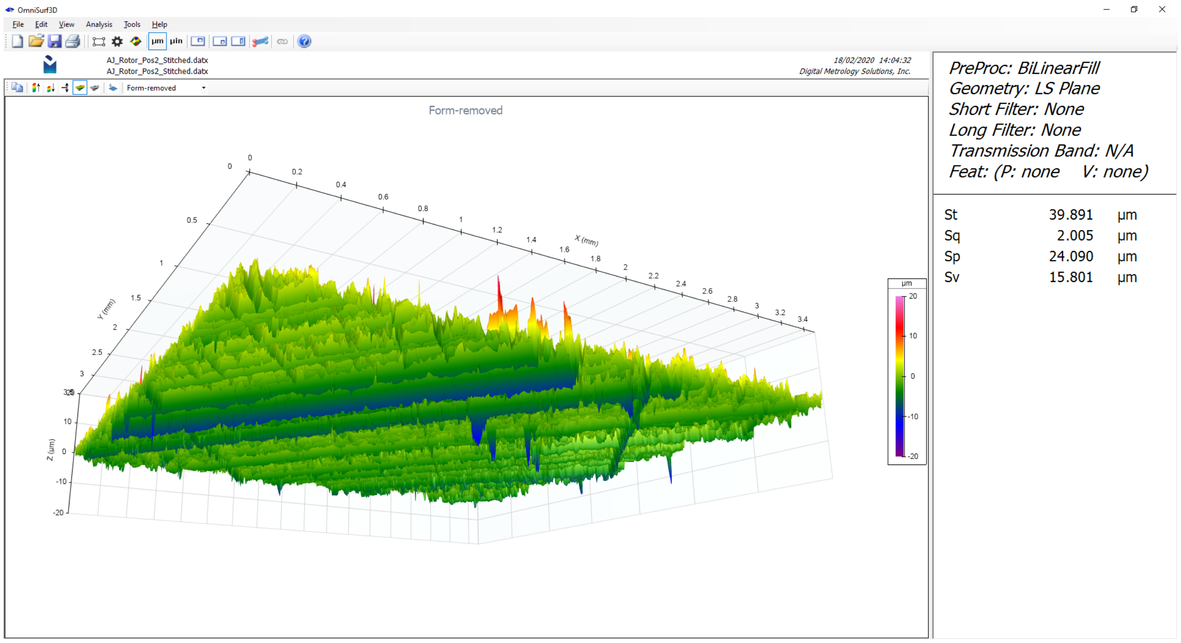

Figure 27: Characterization of the underside of a measured area of the brake rotor surface using the ZYGO NextVIEW Scanning White Light Interferometer. Image was created using Omnisurf3D software.

8.3 Piston Pin Measurement Results

The measurement results from the piston pin were also as expected. The surface texture of the pin is small as compared to the size and form (e.g. roundness) tolerance. In this case, including all elements of the surface within the larger form control will work because the roughness should be so small that it has no effect on the larger tolerance. After the measurement data from the piston pin was analyzed, a single measurement was taken from each instrument and shown below. The filtering specifications used along with the measurement results are shown on each image.

Figure 28 below shows the resulting roundness of the piston pin using the Zeiss Prismo CMM. The data was filtered according to the ASME B89.3.1 roundness standard specification. ASME B89.3.1 also has its own filtering requirements, similar to the ASME Standards discussed in Figure 19. This measurement was pushing the accuracy limits of the

CMM however it provides a good representation of the pin's overall shape. It is shown below that the roundness value reported by the CMM is 0.580 µm.

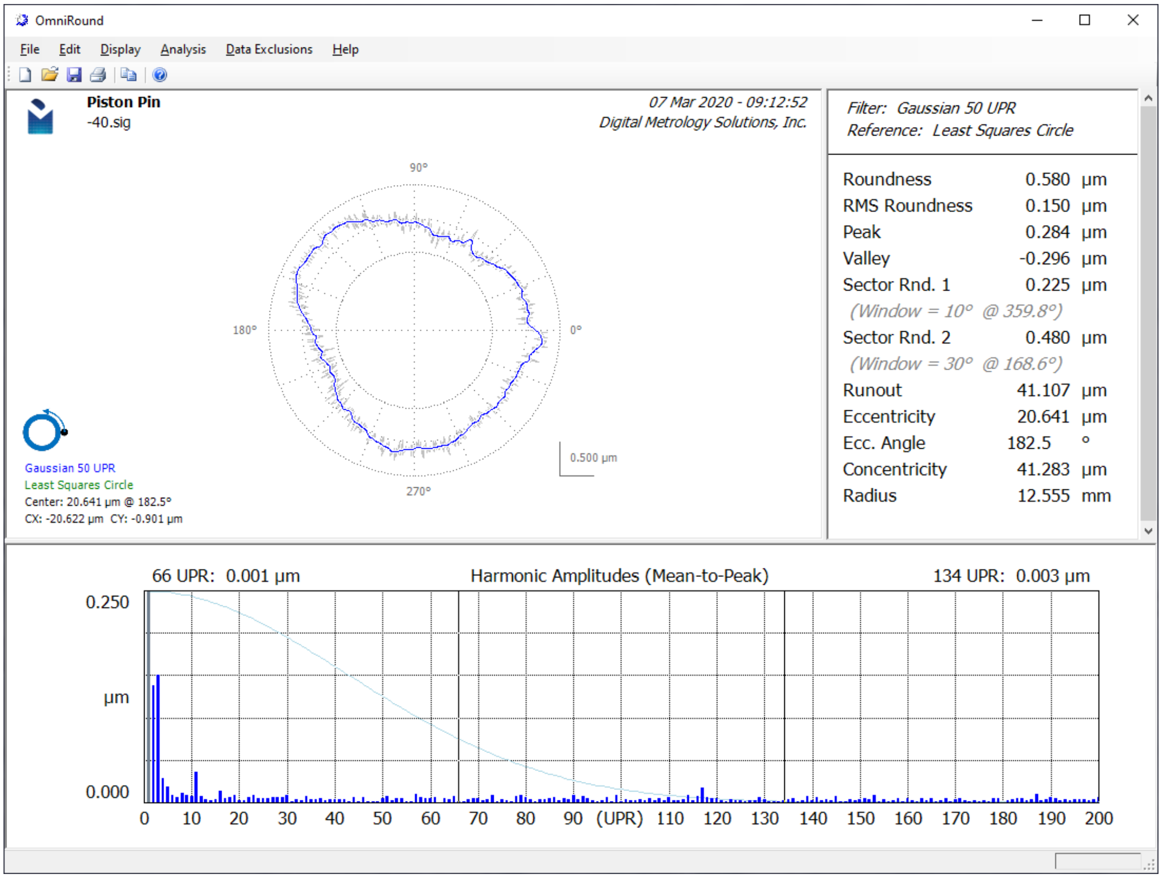

Figure 28: Roundness of the piston pin using the Zeiss Prismo CMM. Image was created using Omnisurf2D software.

Figure 29 below provides a profile of an axial trace of the piston pin's surface from the data acquired with the Mahr tactile profilometer. It is shown below that the total peak to valley deviation of the piston pin reported by the profilometer is 2.004 µm.

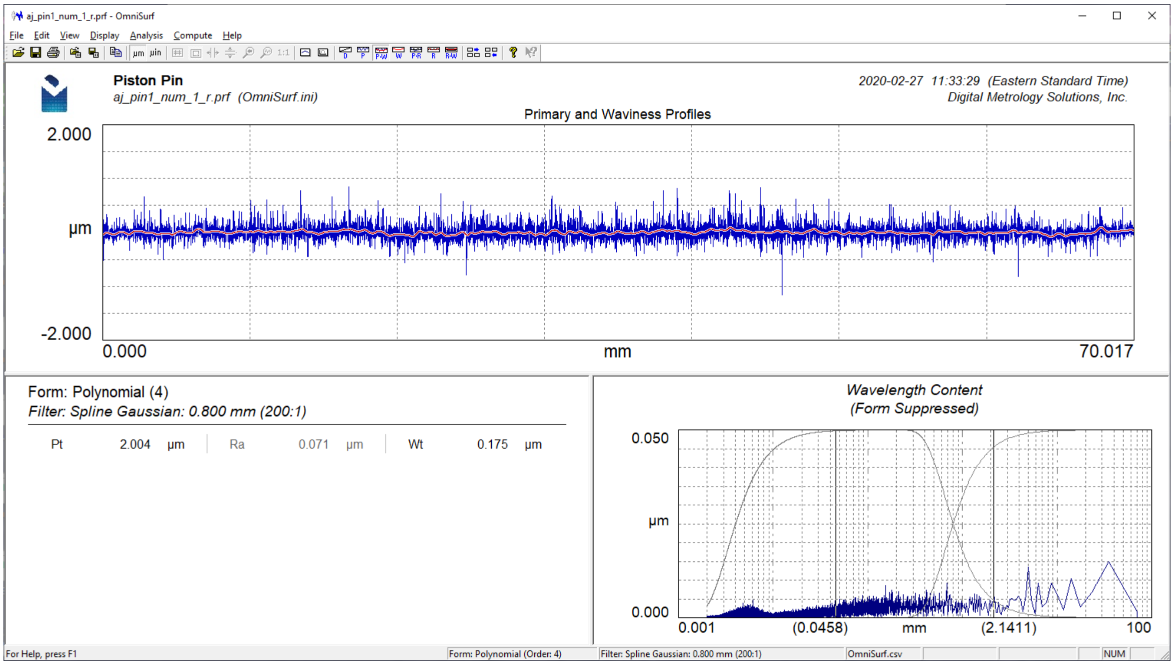

Figure 29: Profile of a full axial surface trace of the piston pin using the Mahr Profilometer. Image was created using Omnisurf2D software.

Figure 30 below provides a representation of the raw data acquired in a 3-frame x 3-frame stich of the piston pin's surface with the ZYGO NextVIEW scanning white light interferometer. It is clearly shown that the surface is tightly controlled in both form and surface texture parameters.

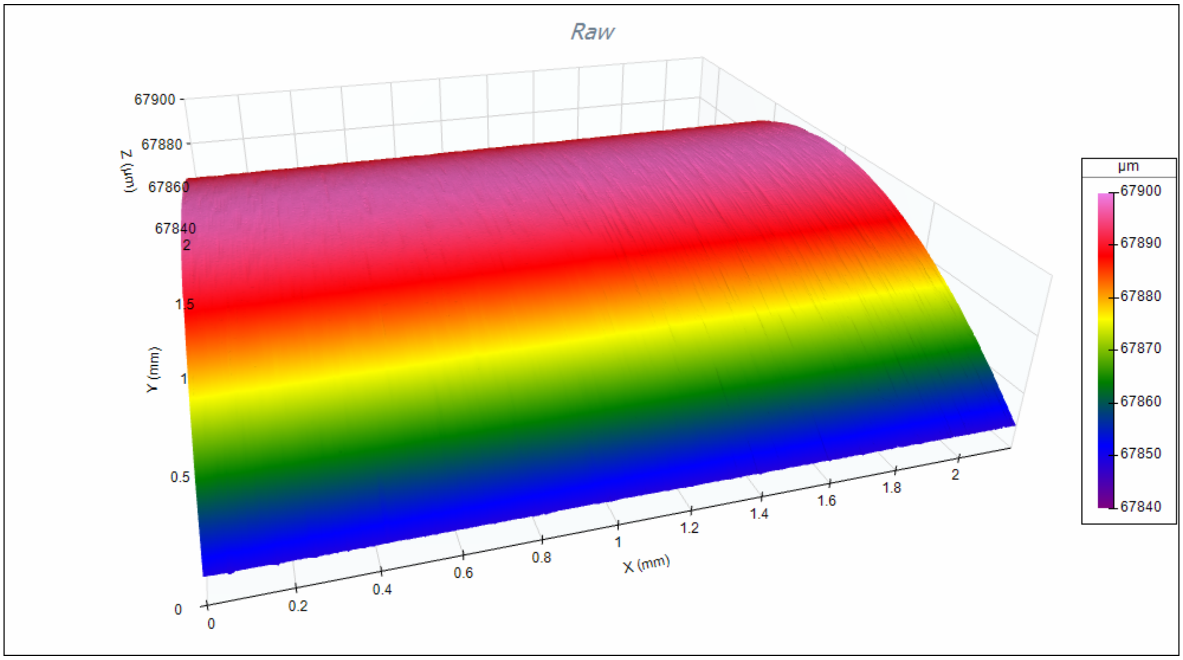

Figure 30: Characterization of the raw data from a 3-frame x 3-frame measurement of the piston pin using the ZYGO NextVIEW Scanning White Light Interferometer. Image was created using Omnisurf3D software.

Figure 31 below provides a representation of a 3-frame x 3-frame stich of the piston pin's surface, with the cylindrical geometry removed, from the data acquired with the ZYGO NextVIEW scanning white light interferometer. The surface texture is clearly much more controlled than that of the brake rotor. It is shown below that the total peak to valley deviation of the piston pin reported by the ZYGO NextVIEW is 1.377 µm.

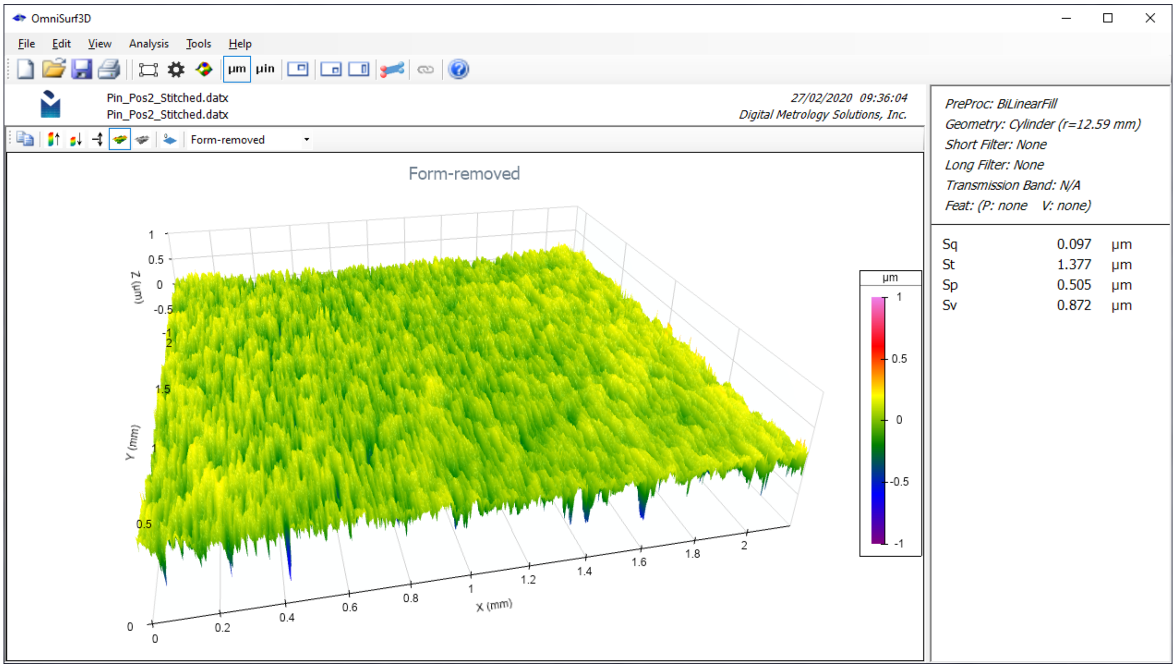

Figure 31: Characterization of a 3-frame x 3-frame surface area of the piston pin using the ZYGO NextVIEW Scanning White Light Interferometer with form removed. Image was created using Omnisurf3D software.

8.4 Experiment Conclusions

In both parts the mechanical filtering effects of the CMM are significant when attempting to evaluate small amplitudes, such as surface texture. It was determined that the CMM is useful for the evaluation of reasonable form tolerances but is not the correct instrument for evaluating surface texture. However, if the overall surface trend is the only critical surface control for proper part function, such as the flatness of the brake rotor, then the CMM provides an efficient instrument for the task. The Mahr profilometer provided a more accurate representation of surface texture, however it still encountered some mechanical filtering effects when evaluating surfaces with large amounts of roughness. This was revealed when the profilometer was unable to report the deep valleys and pores in the brake rotor's surface. Also, the sampling size if the profilometer is much smaller than the ZYGO as it only reports a single, narrow trace at a time. The ZYGO was able to report the large peaks and valleys measured in the brake rotor being that it is not limited by the reach of a stylus tip. Therefore, it was concluded that the ZYGO provided the most reasonable representation of the "true" surface texture for the purpose of this work. However, the ZYGO has a very small measuring area and is impractical for the measurement of waviness or form.

The brake rotor experienced an increasing level of peak to valley deviation with each increase of instrument resolution. The CMM reported a 9.994 μm deviation, the profilometer reported a 21.579 μm deviation and the interferometer reported a 39.891 μm deviation. If we were to assume the CMM value was used as flatness result and the interferometer value was the surface texture result, rule s would cause a drastic failure. Rule s states that the surface texture and defects must be included in the overall form tolerance. Therefore, if the flatness tolerance was proposed to be 10 μm the part would fail significantly because the roughness was on the order of 40 μm. The brake rotor is specifically designed with high roughness and tightly controlled flatness so that it can function properly. Moreover, many of the highest peaks would be removed as soon as the brake pad touches the surface of the rotor. Also, the deep valleys are not even touched by the brake pad. Therefore, both the high peaks and low valleys are not related to the function of braking and can be considered negligible. This experiment proves that almost all brake rotors would fail inspection if adhering to rule s.

The peak to valley deviations seen in the surface of the piston pin were significantly smaller than the brake rotor. The profilometer reported a 2.004 μm deviation and the interferometer reported a 1.377 μm deviation. The form tolerance (e.g. roundness) on a piston pin is typically on the order of 5 μm and size tolerance (e.g. diameter) is typically on the order of 20 μm. It was shown in this experiment that the roughness value is much smaller than the 5 μm form tolerance. With that being said, rule s provides a reasonable evaluation criterion for this part. Rule s calls for surface texture and defects to be included in the form tolerance. Therefore, adhering to rule s will have no negative impact on the inspection of piston pins because there should be minimal small amplitude deviations. These roughness domain deviations should be easily encompassed in the overall form tolerance. The surface texture of piston pins is specifically designed to be minimal in comparison to the form. Thus, if the surface texture was larger than the form tolerance the part would correctly be deemed a failure. This experiment proves that in these cases, where parts are designed similar to the piston pin, rule s can be a valuable addition to the standards community.

The issue at hand is that rule s works for some designs but significantly increases manufacturing costs on others. This blanket statement has proven to fail when evaluating parts with purposely rough surfaces and tight form controls. However, it provides a great way to clear ambiguity when evaluating parts with surface texture much smaller than its form tolerance. This experiment provides evidence for both cases. Even though rule s has been proven to function perfectly as an unambiguous standard for some surface measurements, it creates a large room for error in others. Therefore, it was concluded from these experiments that rule s should be amended to include guidance on how to evaluate parts, such as brake rotors or cylinder bores (described in chapter 3.2), where roughness needs to be greater than form for proper part function.

CHAPTER 9: INTERVIEWS AND SURVEYS

9.1 Survey Questions

Several industry experts were interviewed to gain insight regarding the impact and implications of rule s. Each interviewee represents a different sector in industry as they each come from a specific manufacturing background. This careful selection of candidates allowed for a complete, unbiased collection of opinions. This survey serves to include all possible areas that could be affected by rule s.

Furthermore, the questions for the interview were also carefully selected to provide balanced feedback on how rule s can impact the different divisions within industry. To remain consistent, each interviewee was asked the same set of questions, presented in Appendix A.

The survey questions were purposely laid out in this order to capture the essence of how each interviewee thinks rule s will impact their work, for better or for worse. The first four questions gather some background information on what division of industry the candidate represents and their typical work. Questions 5-12 determine how that candidate, and their organization, controls surface texture in their work. Question 13-14 introduces the idea of including all elements of a surface in a size/form measurement. Questions 15-16 then collect the candidate's opinions on how the inclusion of all elements could impact their work, if it is not practiced already. Questions 17-18 present the issue that rule s creates when evaluating additive surfaces and gathers the candidate's opinion on a solution. Questions 19-21 are the key section of the survey that directly assess the candidate's opinion on how rule s can impact their work along with what changes they plan to make to adhere to rule s, if any.

These series of questions serve to directly correlate back to the problem statement of this thesis. This survey effectively represents foundational questions that justify the motivation behind this work. Exploring the feedback from the vastly experienced sample group provided great support when presenting a conclusion on whether form (e.g. roundness, straightness, flatness, cylindricity etc.) should include all elements of a surface.

9.2 Interviewee Backgrounds

Nine industry professionals, who are each regarded as credible experts in their respective field, were interviewed for this chapter. As previously stated, the interviewees were carefully selected so that an opinion from all parties that will be impacted by rule s can be voiced. This sample group provides an unbiased collection of ideas on the best method for surface evaluation (e.g. the separable or nested model) at this time.

The following list provides background information on the nine candidates that were interviewed. This information is vital because it is important to understand which section of industry the interviewee represents before analyzing their opinions on the addition of rule s. Different divisions (such as drafting, OEM, quality, metrology, standards member, etc.) have their own, unique outlooks on surface measurement.

1. Mark Malburg [30]: Owner of Digital Metrology Solutions and creator of "Omnisurf" surface evaluation software. Malburg has a Doctoral Degree with a focus of surface metrology and is widely respected as an expert on surface geometries and metrology software development. He consults with numerous companies, across all manufacturing disciplines, as well as teaches about all facets of surface characteristics, measurement, and evaluation.

2. Scott Ledger [31]: Previously worked for the sales department of Mitutoyo and Zeiss as a surface measurement product specialist where he spent years providing the correct instrument for the customer’s needs. Ledger is now the corporate metrology lab manager at Cummins where he creates measurement plans, reviews measurement results, programs machines, and teaches best practices for various measurement methods. He has decades of experience in the metrology world and has focused on the evaluation of surface geometries.
3. Brian Vogel [32]: Worked in the drafting department at Cummins where he designed and created master CAD Models. Vogel led the design team responsible for creating the cylinder head and block for one of Cummins main production engines. He comes from a background of hands-on testing and manufacturing where he has assembled, disassembled, and reverse engineered the parts he has designed. Vogel represents the drafting outlook of the GD&T standards community.
4. Ken Bergler [33]: Former owner of the metrology specialist company Advanced Consulting & Engineering (ACE) that was acquired by Renishaw in 2014. Bergler is a practiced industrial metrologist and expert in CMM services, programming, calibration, and measurement plans as they relate to Y14.5. He is now a leader in the CMM division of Renishaw where he designs/produces CAD models for part holding fixtures and creates and tests programs for CMMs. He verifies other entities parts as well as conducts internal testing to better improve Renishaw's hardware and software.
5. Carl Musolff [34]: Works in research and development as a tribology and materials expert holding multiple degrees in metallurgical engineering. Musolff focuses on how surfaces interact and function with one another (e.g. friction and durability) and has

developed many surface specifications (material, heat treatment, inspection). He works mainly in the roughness/waviness domains and has a vast understanding of material defects (cracks, pores, etc.). Musolff's work includes failure analysis involving inspection (visual, dimensional, surface), metallurgical testing, mechanical testing, and functional testing as well as developing specification limits and inspection methods.

6. John Acosta [35]: Spent over 30 years as a machinist and CNC programmer where he learned CAD and spent time exclusively in drafting. He has also spent time writing CMM programs and studying the underlying GD&T principles. Acosta now works as a respected GD&T trainer where he teaches GD&T on a "more than fundamental" level. Essentially, he works to better define the relationship between design and measurement. Acosta has worked in all aspects of manufacturing and has collected GD&T knowledge from decades of experience.
7. Alex Krulikowski [36]: Led the Dimensional Engineering department at GM and spent his career focused on studying GD&T. Krulikowski now runs a GD&T training and consulting company and is actively involved in GD&T standardization. His work includes teaching GD&T, consulting on dimensional management issues, serving as an expert witness in court cases involving the interpretation of drawings, developing standards related to GD&T, as well as writing books and developing courses related to GD&T. Over his career, Krulikowski has been exposed to surfaces of all shapes and sizes across almost every facet of manufacturing.
8. Larry Bergquist [37]: Spent his career in the metrology engineering field for large, international manufacturing entities. Bergquist currently works for John Deere as a

staff engineer in product development but also functions as a consultant to other units, specifically metrology. He also focuses on ASME standards development for the company, ensuring prints meet company/industry standards. Bergquist serves as an expert on the integration of ASME standards into the actual quality control/part validation processes of large manufacturing companies.

9. Cory Leland [37]: Works as a principle engineer in the metrology department for John Deere. Leland works closely with Larry Bergquist and functions as an expert in industrial metrology. He focuses on enterprise strategy and setting company standards on various metrology approaches (e.g. measurement plans, evaluation procedures, etc.). He was included as a metrology specific representative in an interview with Larry Bergquist.

9.3 Survey Responses

The industry experts responded to the survey with great enthusiasm as most organizations are just now being made aware of this issue. The questions were formulated to allow each candidate to form their own opinion on how rule s will impact their work. The survey responses included a variety of different viewpoints based on the interviewees experience in their specific field. It is important to note that there were valid arguments for and against rule s at the beginning of the survey. However, the conclusion amongst the sample group was a unanimous, unmistakable rejection of rule s.

It was immediately clear how perspectives of the nested principle were based on what background the candidates came from. As expected, those involved mainly in part design/drafting followed the nested principle and focused mainly on theoretical fit. They reported that assuming defects and surface texture are included in a form tolerance is standard practice. However, there are special cases where the domains are treated separately due to prior knowledge, past failures, testing, etc. This presents a gray area in design where form tolerances are *assumed* to include all smaller wavelength domains in the original application of the tolerance, but the form tolerance is actually *evaluated* by filtering out the smaller domains. Therefore, it was interpreted that the design community functions by using the nested model, but the metrology community functions by using the separated model.

On the other hand, those involved in evaluating tolerances and creating measurement plans strictly followed the separable model and focused on overall function. This group reported that surface texture and defects should be evaluated separately from a form tolerance. When evaluating a form tolerance, the smaller wavelengths are almost always filtered out, or if necessary, have their own tolerance. All candidates claimed to have some type of plan in place if a defect happened to be discovered during evaluation. As a matter of fact, all respondents stated that their organizations have an individual specification specifically for defects. In most cases, the defect will be documented and reported, then the part will be re-measured in a different location. This opposing methodology in tolerancing proves that manufacturing is rather fluid, and each section of industry has evolved in their thought process to produce the best final product.

Despite the opposing viewpoints on the inclusion of defects and texture in form measurements, all experts agreed on where tolerances actually come from. It is noted that tolerances are originally theoretical, but they must be fine-tuned when the part goes through testing/validation. The common case where tolerances on older versions of a part have been synthesized over its years of use was frequently noted in the interviews. Unfortunately, many tolerances were said to come from hard lessons learned. These tolerances were formed when part failures were analyzed. Therefore, it was concluded that part tolerances are mainly finalized via measured/experimental results, not theoretical values.

When it comes to evaluating surface texture (e.g. Is texture considered "defect free" in the evaluation process?) the responses were again split. The design community all considered surface texture to be "defect free" when they assign a tolerance. However, they are aware if a defect is found, it will be documented and reported as a separate entity. It was further explained that a general, usually large, surface texture tolerance (typically an Ra value) is called out in the title block to control the non-critical part surfaces. However, in most parts there is at least one critical surface that has its own surface geometry specifications to ensure proper function. The fact that all interviewees made this point is fundamental because it proves that control of critical surfaces requires a separable model.

The most interesting aspect of all the responses was the fact that every interviewee claimed to use filtering in each domain. Specifically, the lower level "noise" from the roughness domain is almost always filtered out when evaluating form tolerances. When asked their opinion on whether a form tolerance on a critical surface should include surface texture/defects, the results were even more shocking. The answers were all strongly against the inclusion of smaller domains in a form tolerance. Even those who represent the design community understood that these wavelengths would likely be filtered out, mostly via outlier elimination, in practical measurement plans. This is a shift from the previous responses where including texture/defects in form tolerances was a clear gray area with no definite answer.

The experts were then asked about how the inclusion of all surface texture/defects in the evaluation of form/size tolerances would impact their organization. Most candidates stated that this was simply impossible as their organizations do not have the capability to do so. The others stated it could be theoretically possible, but highly improbable in a production environment. The group was in complete agreement that an attempt to implement this type of evaluation criteria would be an economic disaster for their organization. One interviewee even stated, “The costs would be infinite, we cannot stich areas any larger than a square inch for roughness alone.”

When asked about the impact of evaluating additive manufactured surface parameters using the nested model, there was no concrete answer. Many claimed it would simply be impossible. The remaining responses were more reserved. They claimed that additive manufacturing still needs much more experimentation before it can be used in a production environment. The consensus was that no organization currently has the capability to accurately evaluate all elements of these surfaces. However, it is clear that there is strong competition in industry to be the first entity to present a reasonable evaluation specification.

When asked if it would be beneficial to decouple form/geometry from surface texture and surface texture from defects on a print, the response was a unanimous yes. All candidates recognized that there is a manufacturing need to separate the domains as this practice helps to better control surfaces for specific designs. It was stated that “All 3 areas have their own purpose and modes of correction. To have everything lumped together as one callout makes it more difficult to not only troubleshoot, but to define specific traits of a feature.” This notion was universally stated in some form between all candidates. One interviewee even responded, “ABSOLUTELY! I recommend that my customers add a note on all drawings (or in a document referenced on the drawings) to override Rule S from Y14.5.”

Finally, the sample group was asked how they plan to measure form tolerances now that Y14.5-2018 is published. Every response showed strong opposition the adoption of rule s in industry. The candidates all agreed that “we will continue to measure how we always have: separating form from defects and texture because that is the best we can do with the tools we have. The financial and practical ramifications are justification enough to continue with filtering.” Every organization represented in this survey has been incredibly successful in their business, there is no reason to completely revamp their evaluation procedures if they are successful and continue to improve. The responses were all worded in a politically correct manner, but the implication was that rule s will likely be ignored in their work. One candidate even specified, “Since this is an impossible requirement to verify, I recommend overriding rule s on all drawings.”

One candidate summed up the survey with a powerful note. “This is not an important topic in my organization because it probably hasn’t even been recognized through the company that this has been changed and even if it has people won't really grasp what it means. They don’t think about the ramifications of the statement. Since it is so impractical the company probably won't even consider it. From a design aspect, complying with Y14.5, they think they are already following this principle so why try to change?” This conclusion was inferred from all of the survey responses and speaks volumes to the longevity of rule s in industry.

In conclusion, the survey results were as clear as possible. Every industry entity represented in this survey agreed that rule s, and the nested principle, is a highly unrealistic and impractical notion to implement on all parts. The sample group unanimously claimed that the rule would have to be ignored in their work because it is impossible to comply with it. It was made clear that the major reason the separable principle holds so much value over the nested principle is practicality. It was stated that "Using the nested principle in a standard is essentially trying to write a specification where the true limits are unknown." It is very hard to come up with a specification where there is really no way to quantify it. The uncertainty would have to be incredibly large. Therefore, the survey results provide further proof that rule s must be amended to be able to be accepted in industry.

9.4 Results of additional surveys relating to Rule S

While these surveys don't exactly focus on the addition of rule s, they provide insight on the industry wide understanding of the relation between surface texture/defects and surface tolerances. They focus on collecting opinions on how the smaller wavelength domains (roughness and surface defects) should impact larger surface controls (form).

The first survey was conducted by Alex Krulikowski (interviewed above) and focused on the interpretation of ASME Y14.5 – 2009 [38]. While this thesis is focused on the 2018 release of ASME Y14.5, the 2009 release included a less direct statement to recommend the inclusion of all elements in a size/form tolerance. Krulikowskis survey effectively gathered opinions on how professionals from all sections of industry evaluate form/size tolerances. This survey sought to determine whether industry practice the nested model or the partitioned model.

In the 2009 release of ASME Y14.5, the committee took a step towards adopting the nested principle by stating "the actual surface or line elements must be within the specified tolerance zone" [38]. This statement was widely overlooked as it is indirect and can be interpreted differently based on the readers understanding. The reader could interpret "the actual surface or line elements" as all elements or the resulting profile that is created after filtering operations. These two interpretations could lead to vastly different measurement results. Noticing this ambiguity, Krulikowski sought to gauge how the added rule was understood by different divisions in manufacturing (e.g. metrology, drafting, design, quality, etc.).

Krulikowski's survey is very interesting because of the volume of credible feedback he was able to collect. The survey results included responses from 261 industry professionals from the United States, India, and the United Kingdom [38]. From this group, 59% represented the automotive industry, 10% represented aerospace, 4% represented medical, and 24% identified as other. Also, 72% represented the design/engineering function, 15% represented quality/inspection, 5% represented manufacturing, and 8% identified as other. It should be noted that a majority of the respondents work primarily in the GD&T design community. An identical series of questions were sent out to each candidate to assess their understanding of the rule added to Y14.5-2009. Analyzing the results of this survey can provide a greater understanding of how the adoption of the nested principle in rule s will play out throughout industry.

The results showed that a majority understood the rule as an adoption of the nested principle. As a matter of fact, the majority of interviewees (72%) interpreted "the actual surface or line elements must be within the specified tolerance zone" as all types of surface deviations must be included when verifying a profile tolerance [38]. This proves that most of the sample group understood that ASME Y14.5 – 2009 was recommending the nested principle. However, Y14.5 2009 does not call for the inclusion of all elements, specifically surface defects, in surface tolerances, as rule s does in its 2018 counterpart. Also, it is likely that the full extent of the nested principle was not completely understood. For example, the sample group might not be aware that the nested principle does not accept any form of filtering in surface evaluation. It is important to recognize that the survey only seeks to gauge how the sample population interprets the added rule, not how they plan to incorporate it into their work. As a matter of fact, there is no question that identifies if the rule will change the way surfaces are evaluated, or if it will even be accepted, in the interviewees work. Therefore, it can be concluded that most industry professionals understand that ASME Y14.5 recommends the nested principle, but we have no information on how they plan to incorporate this principle into their work.

The second survey was conducted by Mark Malburg, (also interviewed above). This questionnaire focused on how surface defects (pits, pores, nodules, dings, dents, cracks, etc.) are treated in surface measurements [39]. While ASME Y14.5 – 2018, or any standards for that matter, were not included in the survey, the questions aligned directly with the understanding of the nested principle. To expand, the questions were aimed at gauging the understanding of how different entities in industry handle defects in their texture, waviness, form, and size measurement results. Essentially, the underlying motivation was to get a better grasp on whether industry utilizes a nested model or a separated model in surface measurements.

This survey is important to mention in this work because it includes a sample size of credible industry professionals, from different roles and backgrounds. The sample group included 4 who represent the manufacturing/quality function, 14 who represent design/product engineering, and 9 who represent metrology/gaging [39]. Also, the sample group contained representatives from the automotive, aerospace, firearms, gaging, and bearing industries. It is clear that this survey provides an unbiased collection of opinions as it includes views from all different sectors of industry. Therefore, this survey also provides valuable information that can be used in providing a conclusion to the longevity of s and the nested principle.

The results showed that almost all of the represented organizations make a distinction between surface texture and surface defects. Furthermore, it was determined that most defects are called out individually instead of assumed to be captured in surface texture controls. Many of the organizations utilize visual inspections, or similar methods, to assess surface defects. This is largely due to the fact that many "deep" surface defects (such as pores, cracks, scratches, etc.) are not able to be captured in surface texture measurement methods due to filtering (e.g. mechanical filtering). Interestingly, around 45% of the group then stated that defects are considered part of form tolerances in their organization. However, this is only for the cases where the defects are large enough to present themselves after software and mechanical filtering was applied. A majority of the time the defects are not even noticed in form measurements because CMMs, the most widely used instrument, rarely pick up defects, such as porosity, pits, or scratches.

When asked what action is taken when surface texture measurement encounters a defect (such as a pit, crack, ding, dent or pore) the group almost all agreed that it would not be included in the texture result [39]. They would either exclude the data, filter it out, or step over and remeasure. The defect would still be marked, and proper entities would be notified to investigate, but it would not affect the surface texture tolerance. The group was then asked for their *opinions* on whether surface defects should be included in surface texture measurements. Almost all agreed that defects should be evaluated separately as "surface texture parameters are not useful for the description of surface defects" [39]. When asked their opinions on whether surface defects should be included in form measurements the answers again aligned with the separable model. Most of the group does not think defects should be included in form tolerances. Again, it is extensively stated that defects should have their own specific evaluation process. Including the rare surface defect in form measurements comes down to a game of statistics. It is most important to determine if the surface defect impedes part function or not. The group argues that in most cases it does not, therefore it can be ignored to avoid a waste of time and money evaluating a surface with no significance [39].

CHAPTER 10: THE EFFECT OF RULE S ON ADDITIVE MANUFACTURING

Additive manufacturing (also known as 3D Printing) is rapidly gaining popularity in the manufacturing community. It is consistently receiving attention as possibly the next big breakthrough in manufacturing technology. This widespread publicity formulates strong competition within industry to be the first entity to incorporate additive manufacturing into their repertoire of production methods. Articles such as “5 Unstoppable Industries Using Additive Manufacturing” [40], “Additive Manufacturing: A Breakthrough Technology for Manufacturing” [41], and “Behind the Breakthrough: Getting to Push-to-Print for Additive Manufacturing” [42] represent just a few examples among the plethora of media coverage feeding the hype behind the additive manufacturing movement. These articles demonstrate how all the publicity leads to massive investments in research from numerous industrial entities to be the first to master the process.

It has been shown through these articles that industry is working tirelessly to fine tune additive manufacturing in a production environment so that it takes its place as the next major technological breakthrough. Being that the work of this thesis is focused on assessing the longevity of rule s in industry, it is important to look at its implications on the next generation of manufacturing technology.

Additive manufacturing can provide substantial benefit to industry. This technology allows parts to be produced with complicated geometrical features, that are not possible with current processes, with less overhead and less scrap costs. While this seems to be very beneficial to the manufacturing community, it comes with a significant drawback: a relatively rough surface texture. Figure 32 below shows a SEM image of a typical additive surface. These images help to gain a better understanding of the actual surface topography present in typical additive manufactured surfaces.

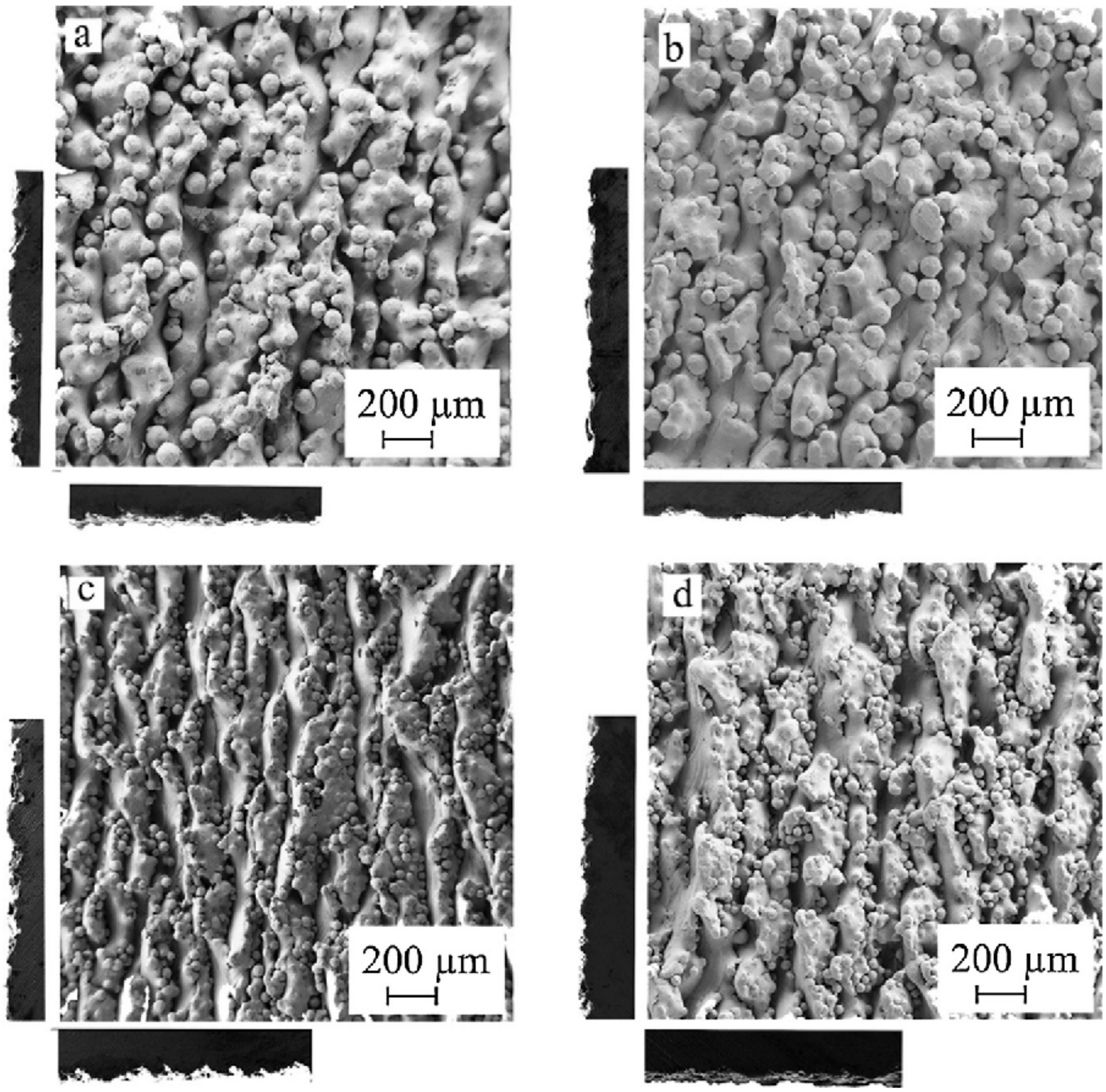

Figure 32: SEM images of a metal additive manufactured surface. "(a) Built with 45–100 m powder and 70 m layer thickness, (b) Built with 45–100 m powder and 50 m layer thickness, (c) Built with 25–45 m powder and 70 m layer thickness, (d) Built with 25–45 m powder and 50 m layer thickness" [43]. Image taken from Figure 2 of [43].

Figure 33 below provides an example of a 3D surface trace of another additive manufactured surface. This areal representation provides further, quantifiable information on the complex surface topography of an additive surface. This image was taken using a ZYGO ZeGage 3D Optical Surface Profiler and analyzed with Omnisurf3D software.

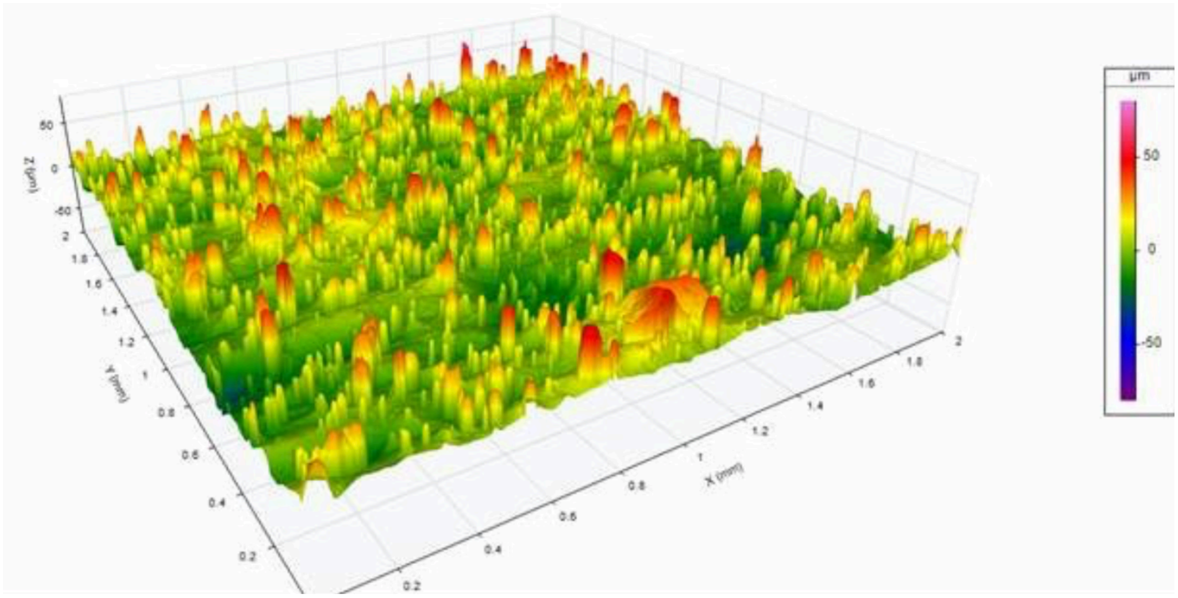

Figure 33: Example of a 3D surface trace of an Additive Manufactured surface [44].

It is clear from this image that the surface texture varies up to around 60 µm almost uniformly across the surface. This type of high magnitude variation makes surface controls very difficult to implement without proper filtering. As a matter of fact, additive surfaces generally see peak to valley deviations on the order of 50 µm even in the most advanced operations [43] [44]. This high level of surface roughness poses a complicated issue when it comes to classifying additive manufactured parts.

Since the surface texture of these parts are so poor it is important to understand how current measurement methods are attempting to quantify these surfaces. It is also vital to understand how metrologists are trying to assess additive manufactured part tolerances.

To gain a better understanding of this issue, a study was conducted to determine the effect rough additive manufactured surfaces has on typical dimensional measurement methods (including tactile, optical, and X-Ray computed tomography methods) [45]. Specifically, different filtering and measurement techniques (such as probe diameter, stylus length/weight, probing force/direction, scanning speed, etc.) were tested to determine the best practice for evaluating additive manufactured part tolerances.

It is known that the rougher the surface texture the larger the impact mechanical filtering and low pass filtering has on tactile and optical measurement techniques respectively. Figure 34 below is a graphical representation of the data analyzed in this study to assess how the high roughness of additive manufactured surfaces effects dimensional measurement instruments.

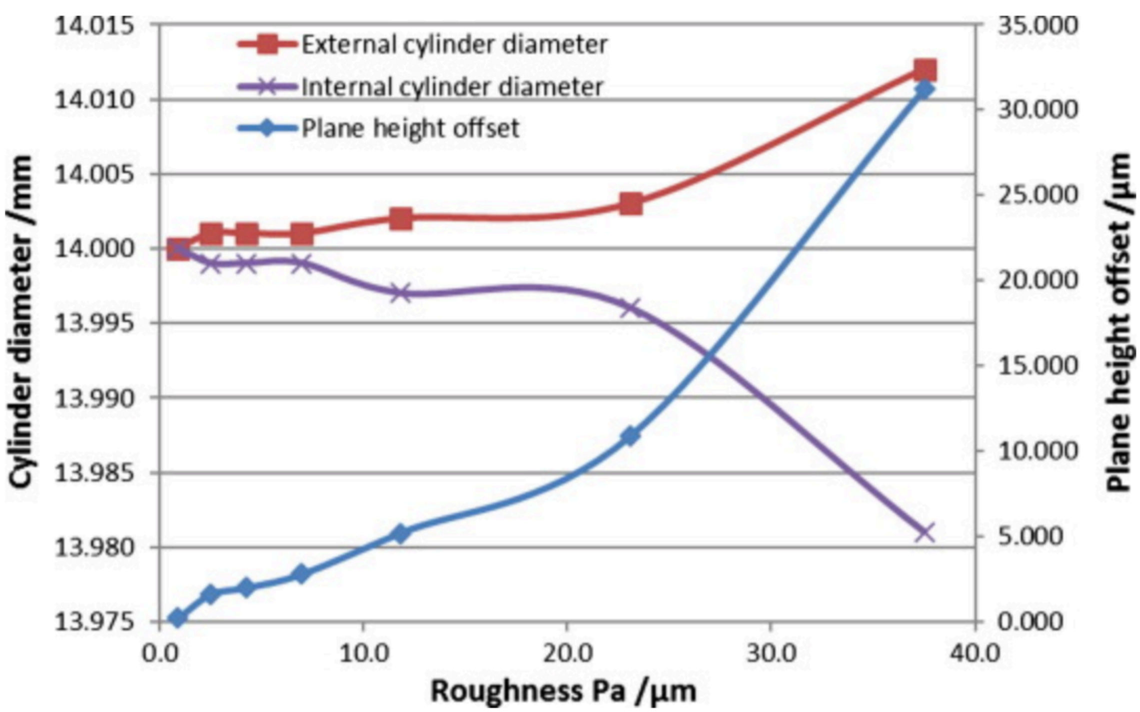

Figure 34: Effect of high roughness additive manufactured surfaces on measurement instruments. Image taken from [45].

From this experiment, it was determined that rough additive manufactured surfaces have a large impact on the accuracy of both optical and tactile instruments. The figure above presented a 10 µm variation in external cylinder diameter, a 20 µm variation in internal cylinder diameter, and a 35 µm variation in plane height offset with roughness increasing from 0 – 40 Pa/μm using a tactile system. However, the group then focused on how to best minimize these negative effects. Further experimentation discovered that the morphological method can be employed to minimize the effects of mechanical filtering seen in evaluation of form controls [45].

In this study, special attention was paid to tactile instruments since they are much more commonly used in industry to evaluate tolerances, due to common misconception that they provide a higher level of accuracy and traceability at a reduced cost when compared to other methods. It was discovered that while smaller probe sizes lead to a more accurate representation of the true surface texture, there is no tactile instrument in existence that can measure the true magnitude of additive manufactured surfaces. For example, it is impossible to reach the true depth of surface pores with any instrument currently in production. This plays out in the mechanical filtering error. In simple terms, the mechanical filtering errors presents itself when tactile instruments "round" or "smooth" the true depth of valleys since the probe tip cannot travel the full distance. Figure 35 below provides an example of how a tactile surface measurement actually plays out.

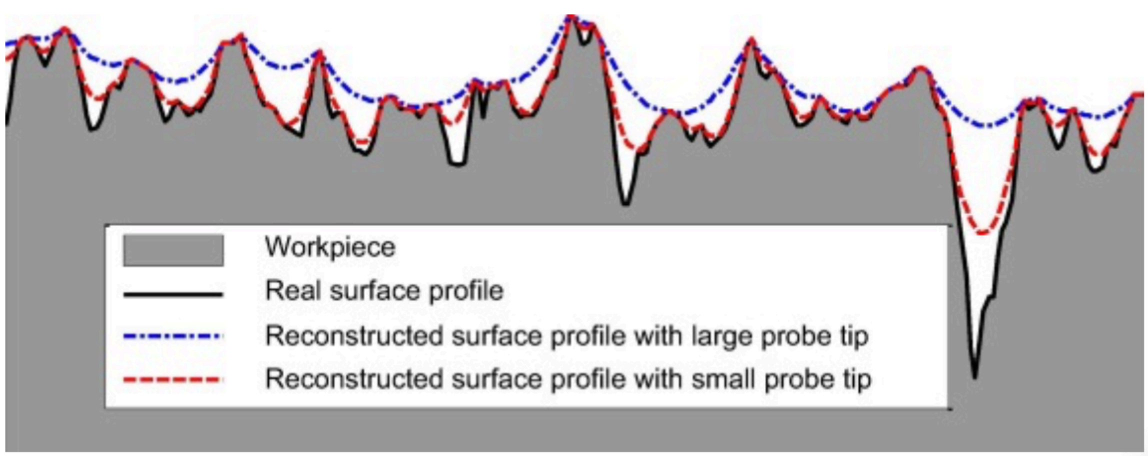

Figure 35: Depiction of how a tactile instrument evaluates the profile of a surface. Image taken from [45].

The figure above shows how mechanical filtering is amplified with increasing probe tip size. It is important to understand that tactile systems report the *best attainable* profile of a surface, not the *real* profile. The figure above clarifies that the profile of a surface given in a measurement result is an estimation of the real profile using mathematical filtering. Filtering allows the trend of the surface to be reported, and in most cases that is more than enough to evaluate a form tolerance (such as roundness, straightness, flatness, cylindricity etc.).

A key takeaway from this work is the importance of filtering when providing a measurement result of an additive manufactured part. While measurement of additive surfaces was not able to be perfected, the study produced a best practice for evaluating form controls of such surfaces. A major component in this best practice was the addition of morphological compensation to minimize the effects of mechanical filtering on such rough surfaces and simply improve the repeatability. As previously discussed, rule s calls for no filtering when reporting measurement results. It is then understood that the highest peak or lowest valley of an additive manufactured surface must be included in the result. If that were the case, the measurement of additive surface profiles would go from difficult to near impossible. Without filtering the evaluation of these surfaces would require immense amounts of point cloud data. This high volume of data is incredibly hard to handle and incurs serious time commitments and costs. Also, without filtering, the recommended morphological compensation method would be invalid. Therefore, the mechanical filtering effects would be maximized. This would increase the uncertainty of all tactile systems to the point where they would have to be considered unqualified for surface measurements. In addition, the slope measurement of optical instruments is limited. Therefore, it can be concluded that the near vertical parts of the surface lumps can't be measured with non-tactile means either. Without the use of filtering, form tolerances would need to be increased dramatically to be able to accept the large deviations/imperfections seen in additive surfaces.

Another group conducted a study to specifically assess the capability of surface texture metrology on additive manufactured parts [43]. ISO standards were utilized to create a measurement plan and determine the exact measurement specifications necessary to provide the most accurate result. All measurement parameters were documented and explained in detail, specifically the heavy reliance on high and low pass filtering, so that the experiment can be duplicated in the future. To isolate the surface topography of the part, the form was removed by subtracting the least squares mean plane then the special frequencies were filtered out using high and low pass filters. Filtering cutoffs were taken from the recommended values reported in ISO 4288. The work also covered a wide array of past and present research on the characterization of surface texture in additive manufacturing.

The study focused on verifying modern methods that would allow for accurate characterization of additive surfaces. Most of these methods included a form of post processing (such as vibro-finishing or grit blasting) coupled with a form of data analysis (such as Wolf pruning) [43]. Without this type of processing, it was shown to be incredibly difficult to analyze the underlying surface because of the amount of “noise” in the original data. Figure 36 below shows an example of measurement data that was synthesized using post processing techniques to gather a “purer” representation of the surface.

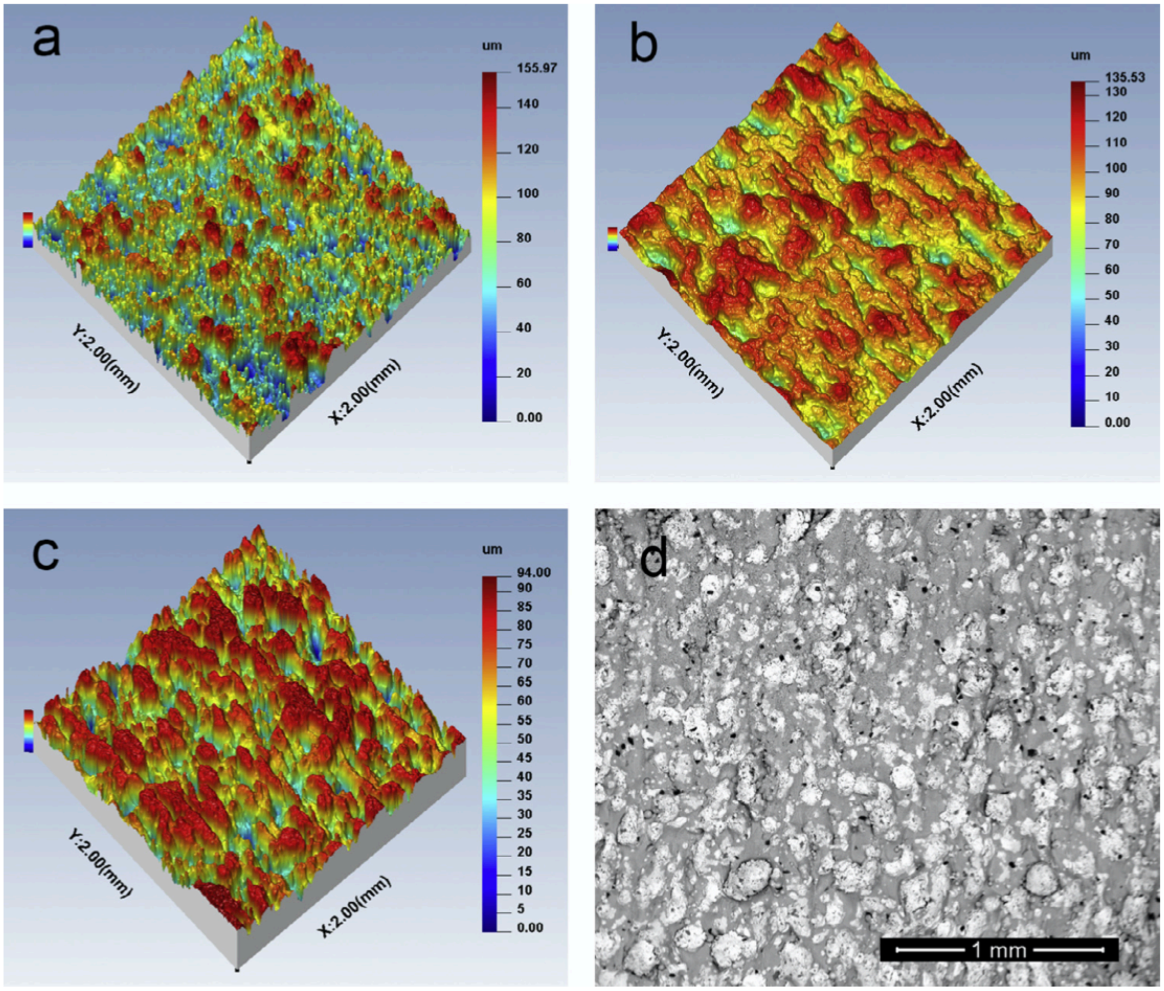

Figure 36: Comparison of surface topography data before and after post processing operations. Image taken from [43].

In this experiment, the raw surface (without post processing) is shown in image a. The sample was then post processed using bead blasting (image b) and vibro-finishing (image c) coupled with a high and low pass and Gaussian filtering to remove the unwanted noise in the data. Images a-c are data representations using color height maps from areal measurement instruments and image d is an SEM image of the post bead blasted surface [43]. Without post processing (image a) the surface topography data is difficult to analyze and distinguish between key characteristics. Post processing (images b-c) allows for a sharper distinction of "true" deviations with a lower volume of data per measurement. This is potentially the beginning of a solution for a credible evaluation procedure of additive surfaces. It is clear from this experiment that some form of post processing is necessary to produce a data set this is both manageable and quantifiable.

This study covered almost all aspects involved in characterizing additive surfaces and presented several important conclusions. It is specified that quantification of additive surfaces is still in beginning stages. However, the it is important to recognize that the characterization of these surfaces "is mostly based on computing ISO 4287 texture parameters on profiles" [43]. Effectively, these surfaces are so complex that it is necessary to have a complete understanding of the surface texture before any measurements can be made to evaluate form. It is also stated that "ISO 25178-2 feature parameters, which could help a great deal at isolating surface areas of interest, have not been explored in the literature on surface metrology for AM" [45]. Essentially, in order to have the ability to characterize these surfaces, more work needs to be done in the roughness domain.

In conclusion, it was determined that additive manufacturing may be incredibly valuable in industry, but their rough surfaces present many challenges in the metrology community. The ability to produce credible measurement results of such surfaces has yet to be achieved. Nonetheless, there is a multitude of ongoing research aimed at defining a reasonable process to accomplish this goal. No matter the outcome, it is obvious that a substantial amount of filtering must take place to clear the large amount of noise so an overall profile can be determined. This evaluation process must be proven and accepted in standards to be able to evaluate form tolerances of these surfaces with any credibility. This study has proven that even when measuring in the roughness domain the data is far too abundant and complex to assess in its pure, unfiltered state.

It is evident that when an appropriate evaluation process of additive surfaces is presented, it will be physically impossible to include "all elements" of the surface in the measurement result. The immense amount of data required to analyze roughness alone presents a challenge in true quantification. When it comes to evaluating the overreaching form tolerances according to rule s, the inclusion of all wavelengths will overwhelm any measurement lab. Therefore, it can be concluded that rule s is inapplicable when evaluating additive surfaces.

CHAPTER 11: CONCLUSIONS

ASME Y14.5-2018 Section 4.2 Rule (s) states "Unless otherwise specified (UOS), elements of a surface include surface texture and flaws (e.g., burrs and scratches). All elements of a surface shall be within the applicable specified tolerance zone boundaries." [1]. This work sought to explore the repercussions that the addition of rule s to ASME Y14.5 could present throughout manufacturing. The technical and economic challenges that rule s presents were discussed in detail. Also, the advantages and disadvantages of adopting the "nested" model over the "partitioned" model were analyzed to determine the most beneficial principle throughout industry. A foundation of knowledge was presented in this work in hopes that this issue will be brought to light, and a change can be made before any significant consequences present themselves.

This work provided a detailed breakdown of how following rule s will play out in actual surface evaluation procedures. The implications of including surface texture/defects in size/form tolerances (referred to as the nested model in this work) on current measurement equipment, designs with specific intent, and industry finances were examined with credible support. The definition of a surface presented in rule s was compared to several other standards as well as the GIDEP Alert of 1988. It was discovered that there was little support for the nested principle in other standards. This issue also had parallels with the CMM shutdown of 1988, possibly prompting an even more extreme reaction. The reasoning for and against rule s was then examined and it was apparent that the costs seemed to outweigh the benefits. A multi-instrument surface experiment was performed on a surface that complied with the nested model from rule s as well as a surface that was not well-suited to rule s. It was found that on the unfavorable surface the adoption of rule s would cause very significant increases in cost and potential degradation of function. A series of interviews were then conducted to collect credible industry opinions on the addition of rule s throughout all divisions in industry. The results of both the experiment and survey strongly opposed the addition of rule s. Finally, the effect that rule s can have on additive manufacturing was examined. It was determined that the adoption of rule s would make the evaluation of additive surfaces impossible. The information provided in this thesis delivers enough evidence so that a conclusion can be made regarding the longevity of rule s in industry.

It was concluded that rule s is an unsuitable addition to Y14.5 and should be amended to clear the ambiguity. Most importantly, the measurement uncertainty is indeterminable when evaluating surfaces in accordance with rule s. The inability to determine uncertainty calls the results from all surface measurement equipment into question. Rule s states “all elements of a surface shall be within the applicable specified tolerance zone boundaries" [1] and since the true bottom of a crack or pore cannot be quantified with any current instrument, the measurand cannot be assessed. If the measurand cannot be assessed and calibrated, the measurement uncertainty cannot be determined. For this reason, it was determined that the addition of rule s would cause all current measuring instruments, specifically CMMs, to be considered ineligible for part evaluation.

Furthermore, it was deemed nearly impossible to measure most workpieces according to rule s with the technology currently at our disposal. Even if the rule was to be interpreted as measuring to the best capability with the tools currently at our disposal, the inclusion of smaller amplitudes (roughness/defects) in larger (size/form) tolerances is highly impractical.

It was revealed that a majority of industry is not aware of the addition of rule s and those who are have no intent on completely changing their evaluation procedures to accommodate it. Especially with the very high costs that present themselves when any organization attempts to adopt rule s. It was also discovered that surface tolerances throughout manufacturing are mainly finalized via measured/experimental results (e.g. testing based on part function) instead of theoretical values that are aimed at "perfect fit" as called for in rule s. Therefore, adopting rule s limits an organizations ability properly control their parts. In conclusion, it is evident that most organizations will simply ignore rule s or create a footnote that states the provided measurements are not compliant with rule s. It is unmistakable that the adoption of a defective principle by our nations GD&T standard is an irrational gesture.

However, the real problem presents itself when customers start questioning, or even rejecting, measurement results as they are not in compliance with ASME Y14.5. It has been shown that it is impossible, or highly improbable, to measure according to rule s. Yet, many manufacturers claim to be ASME compliant. The effort for manufacturers to remain ASME compliant, such as updating their entire surface evaluation criteria, can generate serious financial implications. With that being said, it is recommended that rule s be amended before a serious crisis presents itself.

Luckily, there are entities within ASME, such as the Joint Advisory Committee (JAC), currently focused on providing a resolution to the rule s issue. The JAC-2 was recently formed with the main goal of finding a solution to the complications presented by rule s. JAC-2 states that it will work to "harmonize B46, B89 and Y14 standards by proposing solutions to reduce ambiguities and complications resulting from the default of Y14.5 Section 4.1(s) and measurements. This will promote clear expectations and understanding of standard practices in the area of interactions between specification and measurement." [46] This group of experienced professionals will hopefully propose a solution to the ambiguity presented by rule s before any negative impacts present themselves in the manufacturing community.

The recommendation from this work is that rule s be modified to adopt the partitioned model instead of the nested model when evaluating surface geometries. That includes making a distinction between evaluating larger wavelength domains (such as size and form) and smaller wavelength domains (such as roughness) on critical surfaces. Furthermore, ASME should specify that the use of appropriate filtering in surface measurements is not only accepted but encouraged. It should also be specified that surface defects should not be included in surface measurements and evaluated independently. These additions will serve to clear the current ambiguity present in rule s. If rule s is not resolved in a timely manner, it can potentially invoke serious financial implications throughout all detachments of industry.

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APPENDIX: LIST OF SURVEY QUESTIONS

1. What is your specific position in the engineering field? (Metrologist, Product Development, Drafting, etc.)
2. How often do you work specifically with the measurement data of parts (or artifacts)? Daily? Weekly? Monthly? Rarely? Never?
3. What is an example of your day to day work? (CAD Modeling, Machining, Drafting, Measuring, testing, etc.)
4. In general, what size surfaces do you deal with on a daily basis?
5. Does your organization include surface defects in form tolerances such as straightness, roundness, flatness, cylindricity, etc.?
6. Does your organization include surface defects in surface texture (for example roughness)?
7. If a defect is encountered during a form measurement (roundness, straightness, flatness, etc.) what do you do?
8. In your experience, are form tolerances based on theoretical tolerances (e.g. tolerance stack ups) or actual measured/experimental results?
9. In your organization is the surface texture assumed to be "defect free" in the evaluation process, e.g. are surface defects considered negligible?
10. In your organization is surface texture called out on a per feature basis (critical surfaces) or in the title block on a print?
11. Does your organization have an individual specification defining the limits of surface defects?

12. Is there any smoothing/filtering used to remove surface waviness and roughness when evaluating form tolerances from a print?
13. Given a form tolerance on a critical surface should the measurement plan include surface texture as part of said form tolerance?
14. Given a form tolerance on a critical surface should the measurement plan include surface defects as part of said form tolerance?
15. If it was determined that all surface defects must be included when reporting form tolerances, does your organization have the capability (equipment, personnel, resources, etc.) of producing these measurements?
16. How would the inclusion of these defects affect measurement cost and turnaround time (since surface roughness is almost always determined by sampling a small subset of the surface)?
17. Is your organization involved or pursuing additive manufacturing technologies?
18. Now that additive manufacturing is becoming a popular manufacturing tool, how would you measure their form tolerances since their surfaces are notoriously rough (commonly seeing +/- 50μm peaks and valleys)?
19. Would it be beneficial to decouple form/geometry from surface texture and surface texture from defects on a print?
20. How do you plan to measure form tolerances now that Y14.5-2018 is published (which states "Unless otherwise specified (UOS), elements of a surface include surface texture and flaws (e.g., burrs and scratches). All elements of a surface shall be within the applicable specified tolerance zone boundaries.") ?
21. Is this an important topic to your organization? Why?