Cylinder Bore Honing

"Tool Change Analysis"

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i. Abstract

The Dundee Engine Plant has known warranty issues with high oil consumption that have not been diagnosed with a known root cause. One possibility lies within the cylinder bore finish and the associated quality. Analysis on cylinder bore finish using profilometer readings, fax film and microscopic analysis was performed. The results produced showed a trend of better surface finish, clearer crosshatch angles and less smearing with a newer and softer honing stone. However, making this tool change would cost the Dundee plant $187,200 more annually than what we are already paying. Only qualitative data can be drawn from fax film analysis. Further investigation for a cost/benefit analysis must be obtained to make a definitive stance on the argument. The data depicted in this report helps to reinforce cylinder bore surface quality in relation to the hardness of the tool as a likely root cause and gives a more thorough analysis on tool hardness comparison and wear of each tool over time.

iv. Introduction

The Tiger Shark Engine has the second highest warranty issues targeted for oil consumption in the company, Dundee Engine Plant being in 3rd for the issue. The piston pack and cylinder bore are two primary parts in the combustion engine that contribute to high oil consumption. On top of that, these cylinder bores have also had continual issues with torn and folded metal. It is predicted that torn and folded metal (TFM) and a non-plateau finish for cylinder bores will cause the piston, as it breaks in around that uneven surface, to begin to wear at an accelerated rate and will also cause the engine to retain less oil. The excess wear at the beginning of the piston packs life could potentially cause more chips and gaps in the piston rings or light vertical scratches on the cylinder bore, resulting in excessive pathways for oil to travel through – ergo possibly leading to high oil consumption.

Part of the solution in diagnosing a root cause to oil consumption required an analysis of cylinder bore honing quality. Fax filming, profilometer reading, and topographical research was done on 20 sample parts (every 15 of 300 parts for both the base tool and the after tool change tool, both at the beginning and middle of each tools life) to acquire potential root causes and analyze the cost/benefit to changing the current tools to a softer finish honing tool. It was hypothesized that the softer after tool change tool would wear at a quicker rate than the harder base tool by about 85,000 blocks. This meaning the after tool change tool is expected to hone 85,000 less blocks than the base tool. Since the base tool is harder, it is predicted that the roughness of the tool is causing the undesired smearing (or TFM) and that changing to a softer tool will allow optimal crosshatch angles and surface quality with less smearing. Because these tools cost approximately the same amount, it is predicted that the after tool change tool will be more costly as it will need to be replaced more often (since it will wear quicker).

The wear rate of each tool and the consistency in quality throughout the tools life was also analyzed as a secondary theme. It is predicted that both tools will wear quicker at the beginning of their lives then plateau out to wear at a steadier rate.

v. Background

This report discusses the physical cylinder bore (including crosshatch angles and torn and folded metal), quantitative values associated with the cylinder bore (Rk, Rz, etc.), fax filming, and wear factor values. It is important to understand these items in order to better understand the data. This report does not include warranty, dyno, or SEM (electron microscope) data in relation to the connecting oil consumption issue.

The cylinder bores are part of the cylinder block on a combustion engine. Here we will be studying the 4 cylinder Tiger Shark engine. The bores have a grey cast iron coating that is embedded into the aluminum block. The bore refers specifically to the cylinder (diameter) in which the piston travels. Because oil is cast up from the crankshaft directly to the bore, the surface of the cylinder bores is directly related to oil consumption in that the surface finish allows oil to flow a certain way throughout the bore and into the combustion chamber. The crosshatch angle and surface finish of the bore determine how much oil flows through. In order to establish oil flow that is not too heavy and not too light as to starve the engine, the honing tools will carve out the crosshatch between 30-50 degrees. Crosshatch angles allow the oil to maneuver within the valleys, or depths, of the indents as opposed to traveling straight up the bore or, if horizontal scratches, traveling little to not at all.

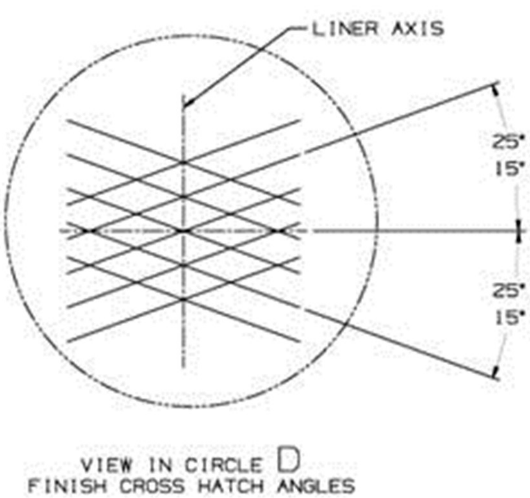


Figure 1 - Cylinder Bore Definition and Crosshatch Angles

As shown in Figure 1 above, the crosshatch angles are located on the surface inside the bores as indents made from the honing process. The crosshatch angles should ideally have clear crosshatch pattern, angles between 30-50 degrees, and no signs of smearing or disruption within the pattern. One issue that can occur is that the crosshatch topography will appear smeared or have unclear crosshatch angles. In cases of TFM, the crosshatch angles will be hard to decipher.

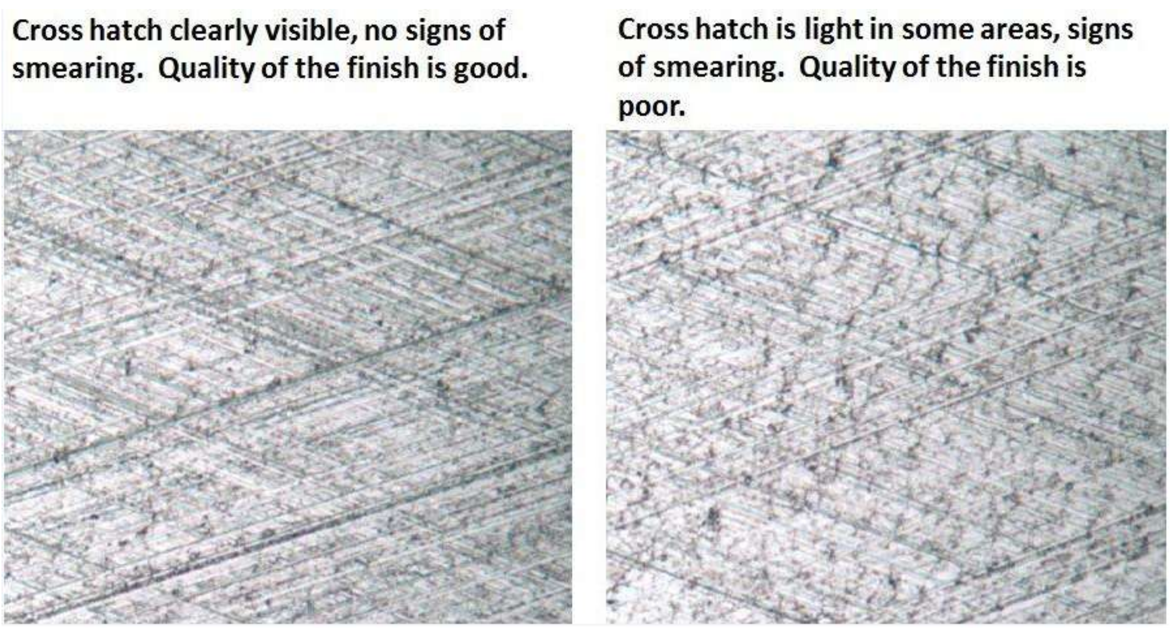


Figure 2 - Example of Good/Bad Comparison for TFM & Crosshatch

The cylinder bores are honed at the Dundee Engine Plant in three stations: rough hone, semi-finish hone, and finish hone. For each of the three stations there are two honing spindles per station that hone separate bores; paradigm spindle six is located at the finish hone station and hones bores three and four while spindle five does the same thing at the finish station but instead hones bores one and two. The honing tools are drawn in and out of the fixed block in a vertical up and down motion while simultaneously rotating inside the bore to create the crosshatch finish.

The honing tool is comprised of multiple diamond coated honing stones. Inside the tool, there is a hydraulically controlled pin that pushes down to force the circumference of the tool to expand outward as the diamond coated stones wear.

Figure 3 - Gehring Honing Tool Example

The resultant values that can be taken from the surface finish of the bores with a profilometer reading are Rz, Rk, Rpk, Rvk, and Mr2. They are described below:

- Rz – “maximum height of profile.”
- Rk – “core roughness depth, depth of roughness core profile.”
- Rpk – “reduced peak height; average height of peaks above roughness core profile.”
- Rvk – “reduced valley depths; average depth of valleys through roughness core profile.”
- Mr2 – “material portion 2; level in percent; for intersection line separating valleys from profile.”

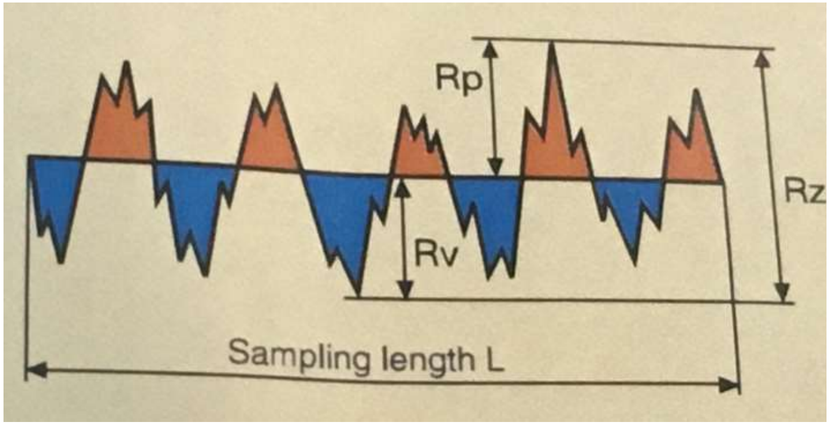


Figure 4 - Rz Value Example [1]

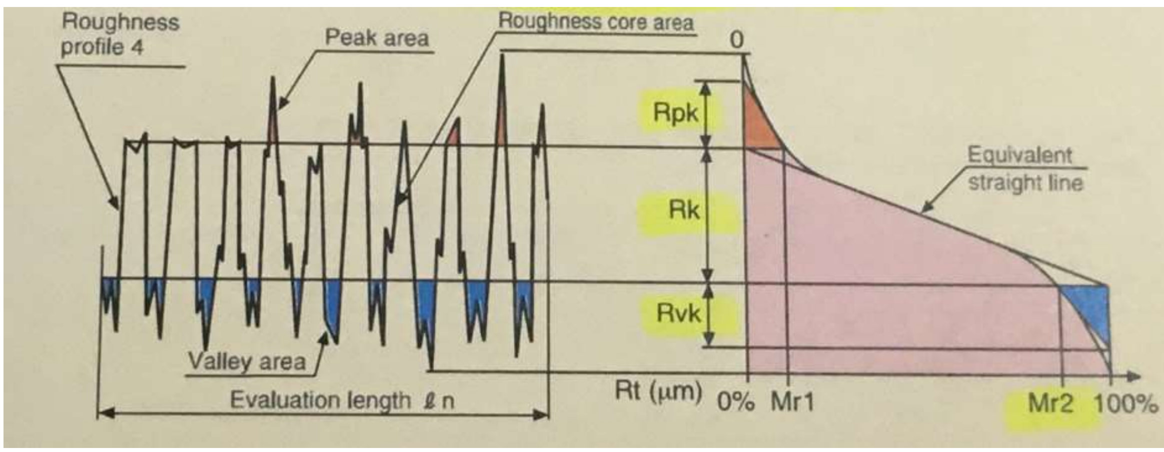


Figure 5 - Rk, Rpk, Rvk, Mr2 Examples [1]

Figures 4 and 5 are a visual representation of the cross-section of a cylinder bore. The values listed above give better insight as to how rough the cylinder bore really is; these values must be within a certain speculation (differs between items) in order to be considered acceptable. A preferable finish is a plateau finish because it allows the pistons to do less work when they break in. A plateau finish is as it sounds – all the benefits of the oil retaining valleys with a top 'plateau' finish that contacts the piston or piston rings.

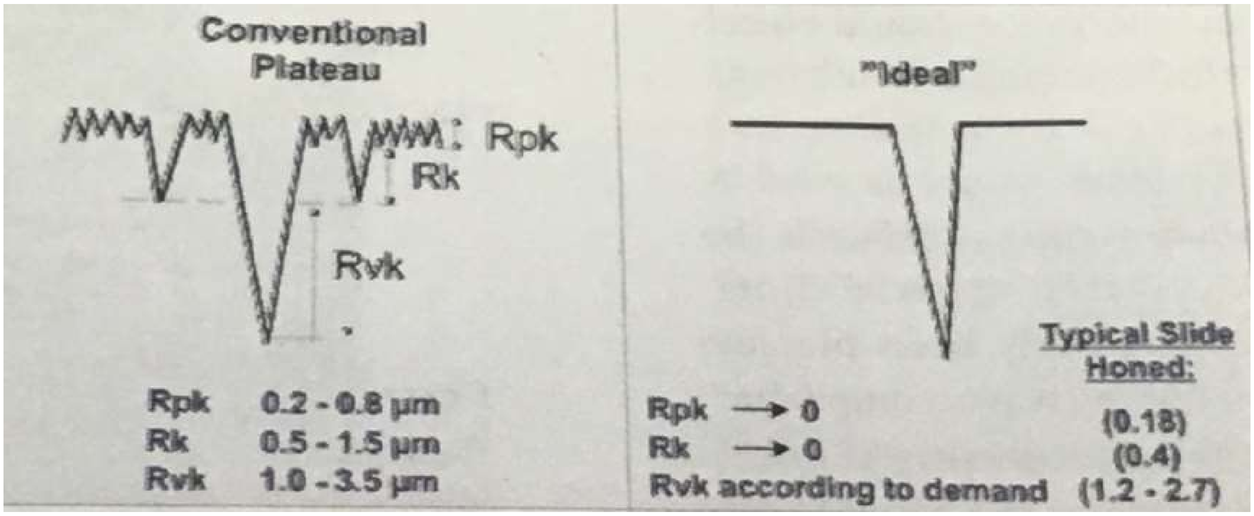


Figure 6 - Plateau Honing Ideal [2]

Figure 6 resembles ideally what the cross section of a cylinder bore should look like: higher rvk than rpk values, consistency in finish, deep valleys with an almost flat contact area, and little to no signs of open pores, TFM, or smearing.

Fax filming is a more qualitative method to obtain data. The images obtained from fax films are very ambiguous in that they can give a visual quality comparison, but no actual numbers or percent TFM can be determined from fax films alone. Fax film is produced in long thin rolls and is also known as acetate paper. Acetone is lightly sprayed on the desired surface and the film is placed on top. A chemical reaction takes place that imprints the cylinder bore surface pattern into the fax film. The fax film cleanly peels off so that it can be analyzed under a microscope (more details on procedure attached separately). Once the fax films have been taken, and microscope images are produced, the images are not only checked for proper and visible crosshatch angle but also topographical signs of smearing or TFM as mentioned and pictured above (Figure 2).

Another item of consideration is wear factor. Wear factor determines tool life, namely it juxtaposes how many cycles (cylinder blocks run) the tool can last per 1mm of tool. The wear factor is simply a ratio between tool thickness used and recorded number of parts produced, to put it more wholesomely (more description in calculations).

Reference Table for Each Set of Samples	
Samples 301-320	Base Tool - Beginning of Life
Samples 1-20	Base Tool - Mid-Life
Samples 101-120	After Tool Change Tool - Beginning of Life
Samples 201-220	After Tool Change Tool - Mid-Life

Figure 7 - Reference Chart: Color Coordination

Within this report, the data recorded is color coordinated into four sets of data: base tool at the beginning of its life, base tool at the middle of its life, after tool change tool at the beginning of its life, and after tool change tool towards the middle of its life. The colors associated with each set and sample numbers are listed in Figure 7 for reference.

vi. Procedure

Specifics on the fax film and microscope analysis procedure are attached separately. Two honing tools, from OP 140C in the South at Dundee Engine Plant at finishing spindles five and six (station nine), were analyzed in comparison to each other to see which produced better honing finish quality on the Tiger Shark engine. The two tools in this report are labeled as the "Base Honing Tool," which is the tool that had been implemented in the Dundee Plant originally and has harder honing stones, and “After Tool Change Honing Tool,” which is the variable tool that has a softer honing stone and will hypothetically give the bores better finish quality.

To check for consistency in tool wear and between the two tools themselves, 20 blocks were pulled directly from the bore honing line for analysis. The 20 blocks were determined by pulling every 15th part of 300 parts off the line for each tool. Since 20 blocks were pulled towards the beginning of the after tool change tools life (about 100 parts in), it was decided to check for consistency later on after about 3,000 cycles. 20 additional blocks were hence pulled off for re-analyzation of the tool towards the middle of the tools life. This same concept was applied to the base tool.

The mentality behind the investigation was to more thoroughly check the beginning, middle, and end blocks in all sets rather than spend tremendous amounts of time checking all 80 parts for every test. If the first couple blocks checked seemed consistent with each other, it was to be assumed that the blocks following them were similar as well. The middle 10th and 11th parts as well as the 19th and 20th parts were checked for consistency in all four sets of data. Whereas all 20 parts per trial were checked with a profilometer reading, only six of each set of 20 were checked in more bore positions with the profilometer, had fax film analysis, and had wear factor readings which were taken on 4 of the 20 parts (beginning, middle and end).

vii. Results

The results found, as pictured below in Figure 8, conclude that the quality of the cylinder bores produced by the base tools had noticeable torn and folded metal with unclear crosshatch. This is compared to the after tool change tool (Figure 9) that, with reverse set on the machine, has less torn and folded metal but the Rz and Rk values are consistently out of speculation.

Figure 8 - Fax Film Comparison: Base Tool Mid-Life

In Figure 8, the “Tiger Shark Quality” box looks closer in comparison to the “Poor Quality” box. This is because the “Tiger Shark Quality” picture has unclear crosshatch angles and smeared looking consistency. Note that the Tiger Shark image is at 40x magnification and the magnification of the good and poor quality pictures are unknown. This is solely qualitative data, any attempt at quantitative data via fax films must be paired side by side to SEM pictures, dyno tests or other similar methods.

Figure 9 - Fax Film Comparison: Tool Change Mid-Life

In comparison to Figure 8, the “Tiger Shark Quality – Tool Change” image is of better quality. Notice it looks closer in correlation to the “Good Quality” image. The crosshatch angles can be more easily spotted and there appears to be less smearing though not perfect. Discretion must be advised in comparing pictures as it is sometimes better analyzed by a professional; in this investigation, we will assume caution with the “Tiger Shark Quality – Tool Change” image as it seems sharper, but may be too sharp for piston rings and may not be the desired quality. A better comparison is seen through the profilometer scans and readings (described later on).

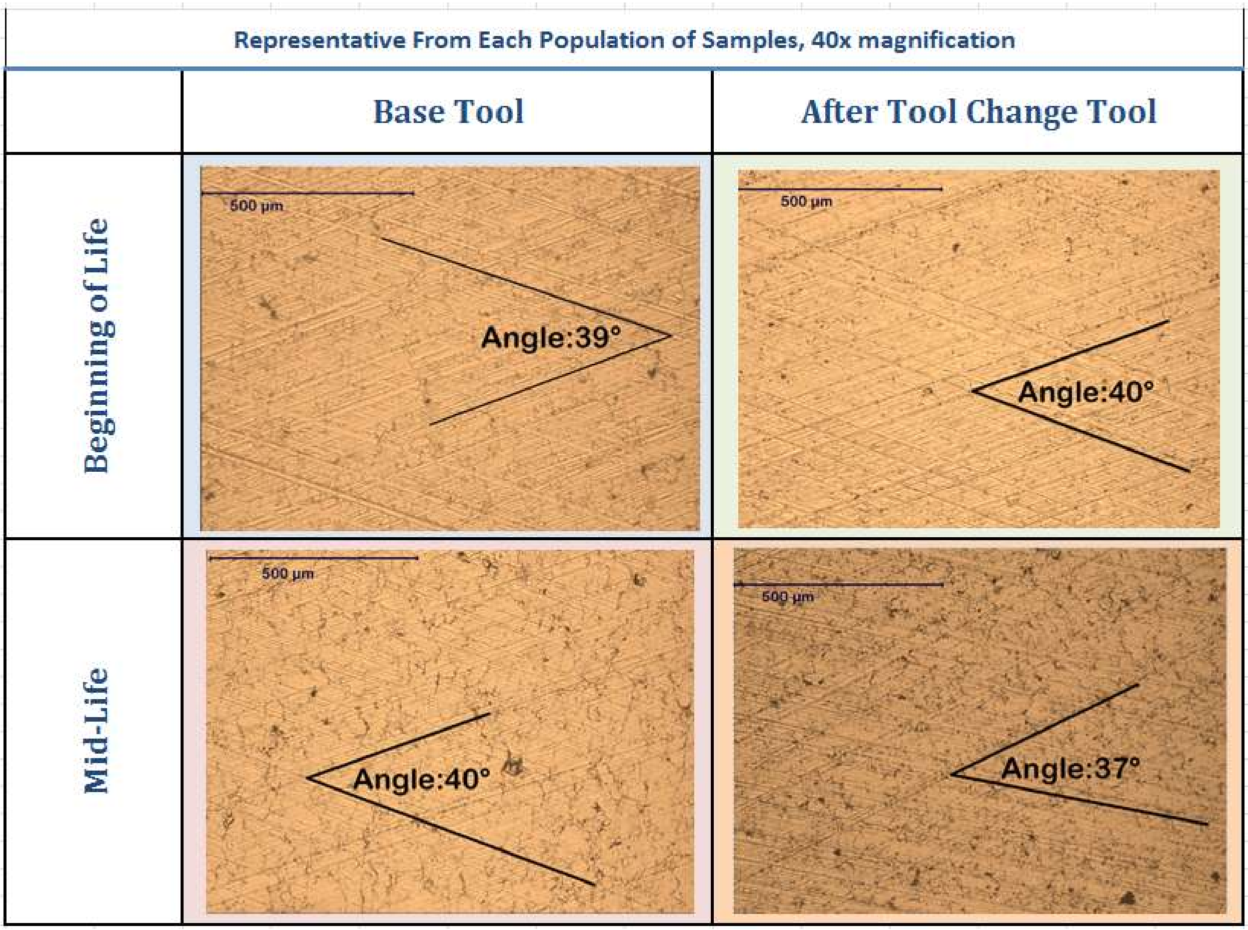


Figure 10 - Fax Film Comparison: All Sets

Figure 10 compares all four sets of data with each other: the beginning and middle of each tools life in relation to the base and after tool changes tools. The results produced by the middle of each tools life is important to observe as it is representative of the average quality that the tool will give. As shown in Figure 10, the base tool starts out looking clear and has clear cross hatch angles then wears and produces lower quality over time with more smearing and less clear cross hatch angles. From fax films alone, the after tool change tool appears to have better and more consistent quality in that the cross hatch angles and images themselves are sharp and clear both at the beginning and middle of the tools life.

The camera images taken directly of the bore reiterate the same conclusion – the bore quality appears to be sharper and has less smearing with bores honed with the after tool change tool. This is seen topographically in Figure 11 and Figure 12 below:

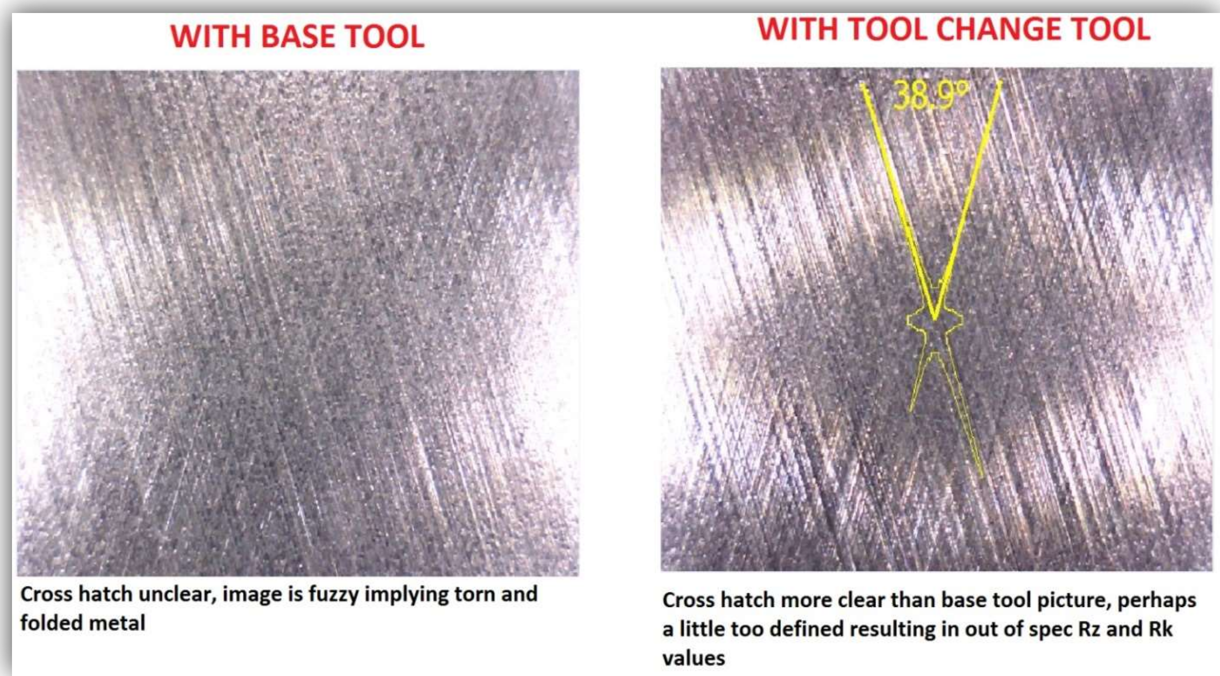


Figure 11 - Camera Images of Bore, Mid-Life Tools

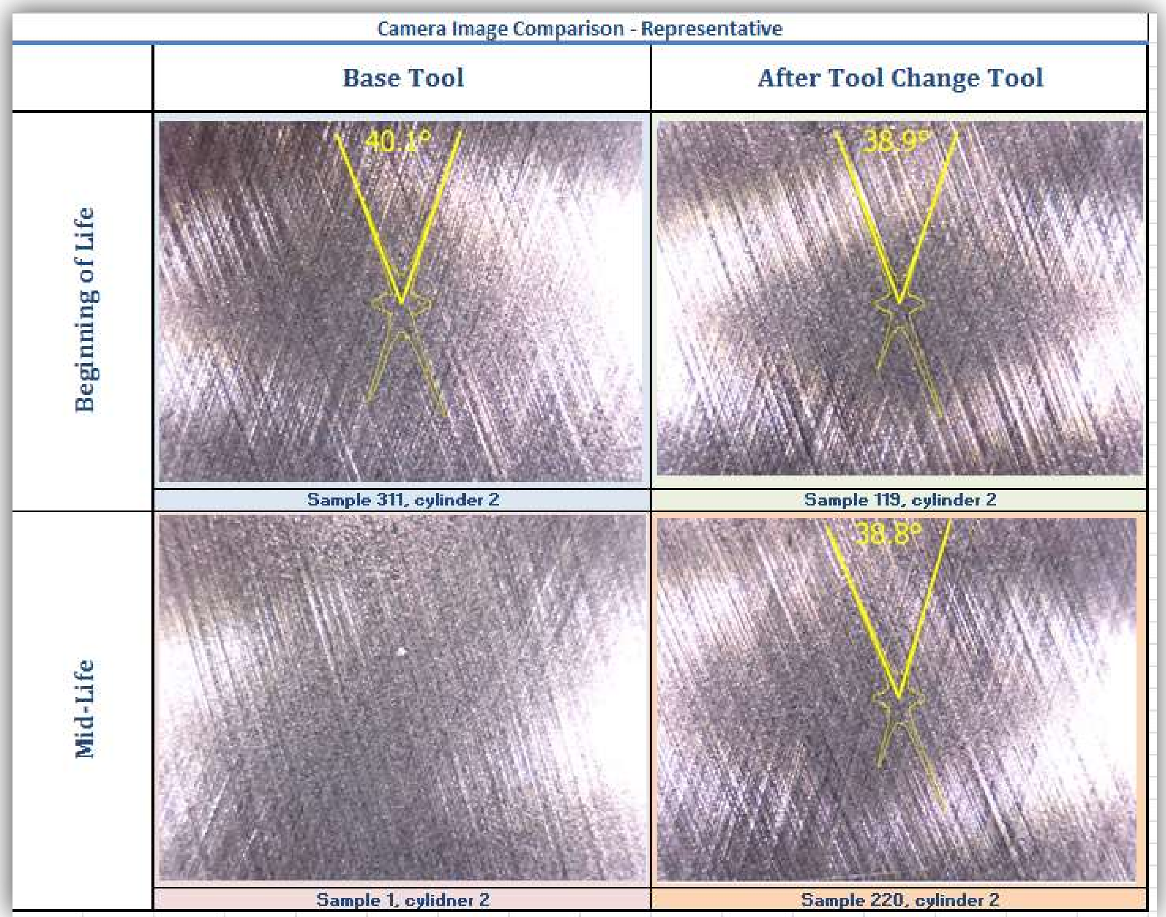


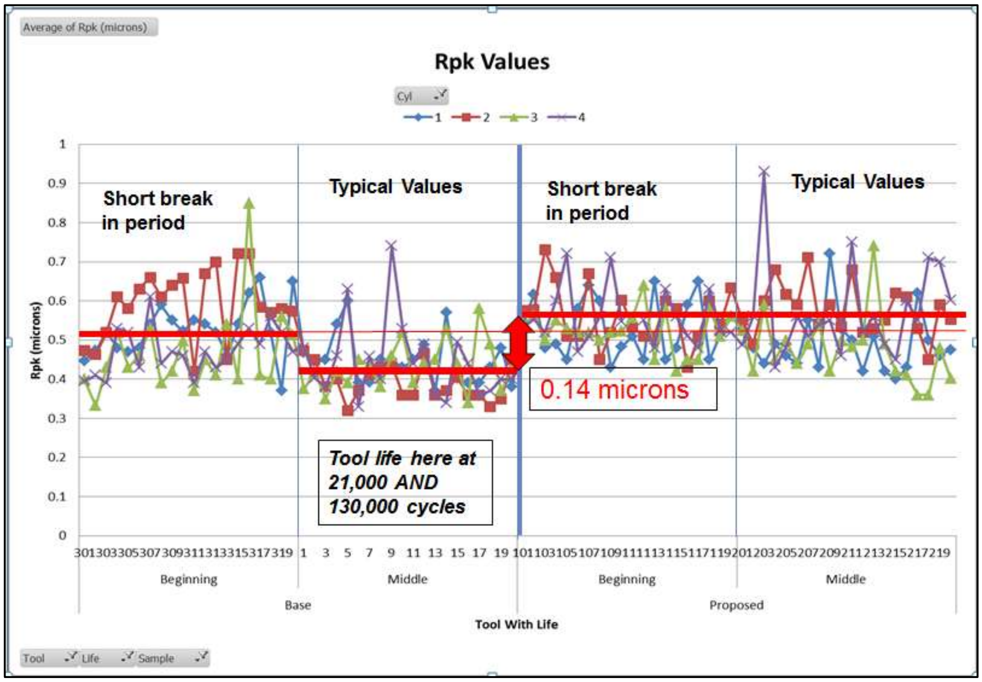
Figure 12 - Camera Images: Representative of All Sets

The Rz and Rk value trends differed between the two tools but were fairly consistent within each similar honing tool over time. Figure 13-15 depicts the comparison between the base and proposed tool during the entirety of their lives. The Rpk, Rvk, Rz, and Rk values of the bores after the tool change are higher in comparison overall to the values of the bores from the base tool. The trend is continuous over all of the roughness values that the base tool depreciates in quality and roughness over time while the proposed tool keeps a consistently rough quality.

Rpk and rvk values are crucial to piston wear and oil flow (Figures 14 and 15). Rpk refers to the peak height whereas rvk refers to the valley depths. The peaks will collide with the piston as it is shoved into the bores and when the engine starts to run. The peak heights determine how much the piston rings will end up wearing down in the initial engine break-in period. Extra wear on the rings can cause small gaps or dents in the piston that allow excess oil to pass through into the combustion chamber. The valleys, or how deep the indents are in the crosshatch, determine how much oil is retained in the cylinder bore during operation. The deeper the valleys, or higher the rvk values are, determine how lubricated the piston is. Typically the more lubricated the bore is, the less friction there is between the piston rings and bore, meaning the engine doesn't have to do as much work and can run more efficiently.

The Rk values in Figure 14 are interesting in that spindle five seems to operate differently than spindle six. Spindle five hones bore's one and two, while spindle six hones bore's three and four. The red and blue data values associated with bores one and two are consistently higher and closer together than the green and purple data values. This confirms some small discrepancies within the machine settings. Mr2 values were continuous and within specification (Figure 15).

Totaling up the average increase in roughness, the proposed tool generates an average 0.6-1 micron increase. This concludes that the surface finish is measurably rougher due to the proposed tool. This is a good peak finish, not a plateau finish.



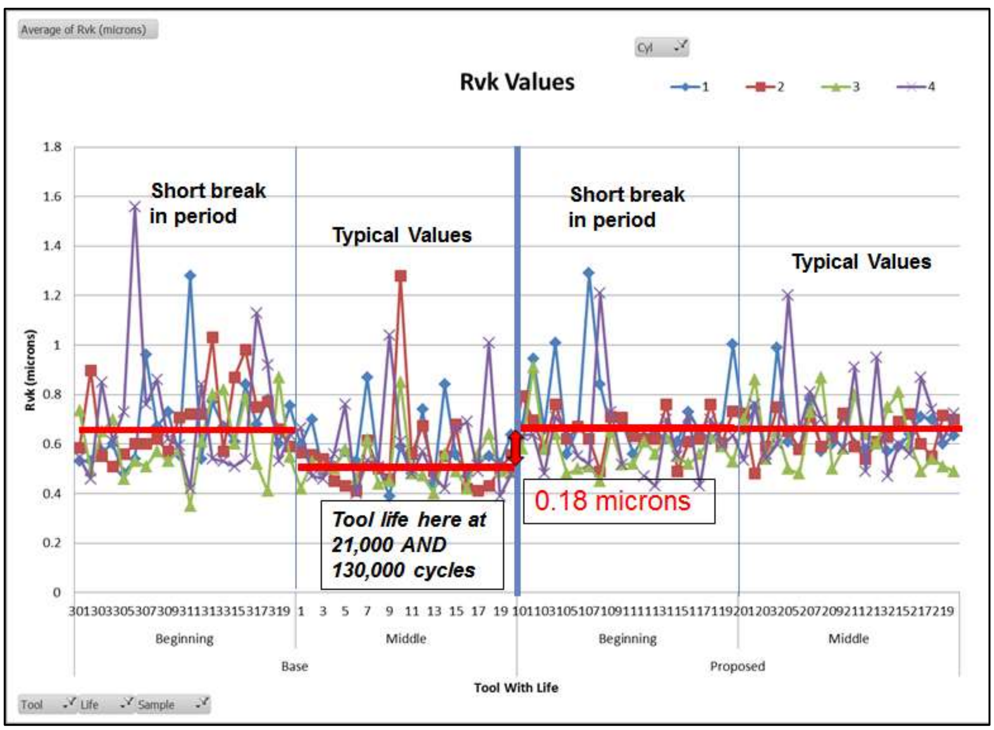
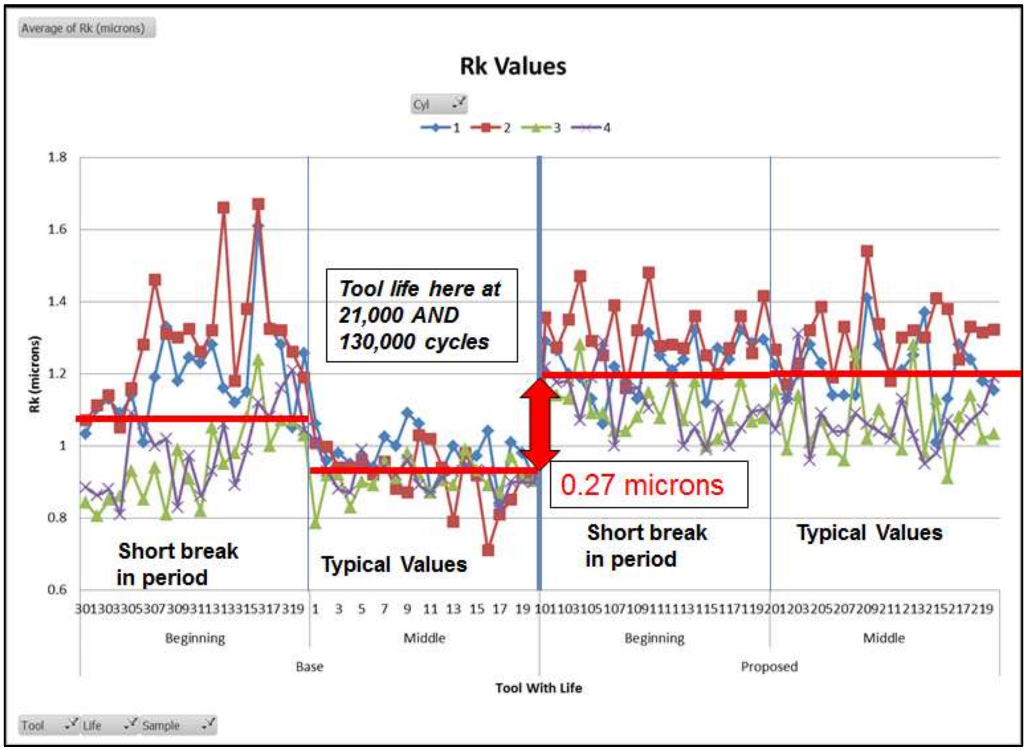


Figure 13 – Rpk and Rvk Value Comparison



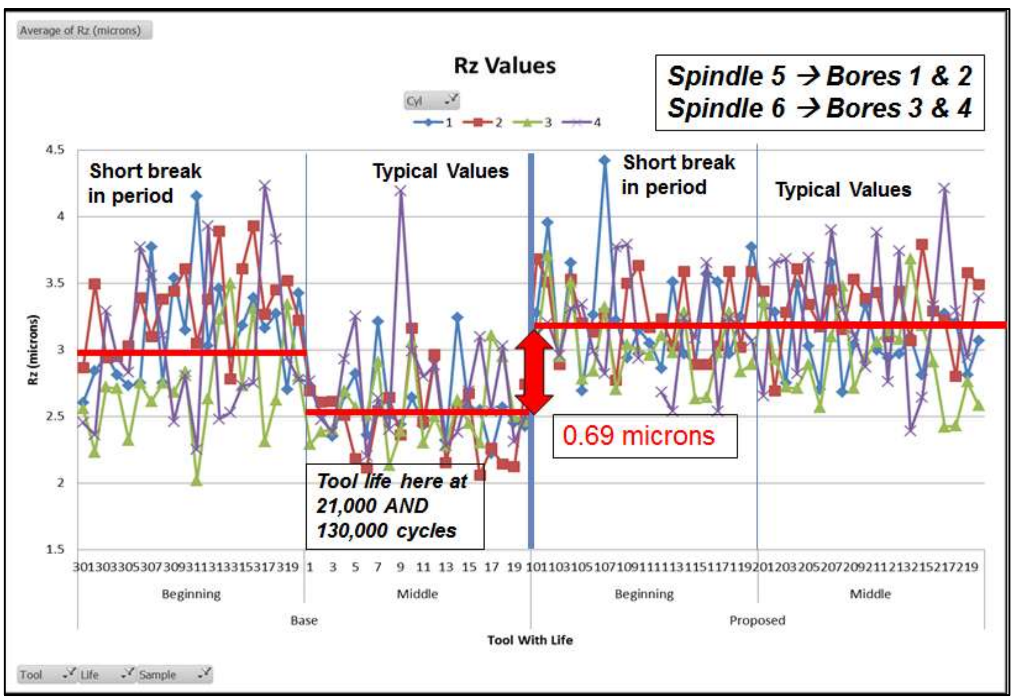


Figure 14 – Rk and Rz Values

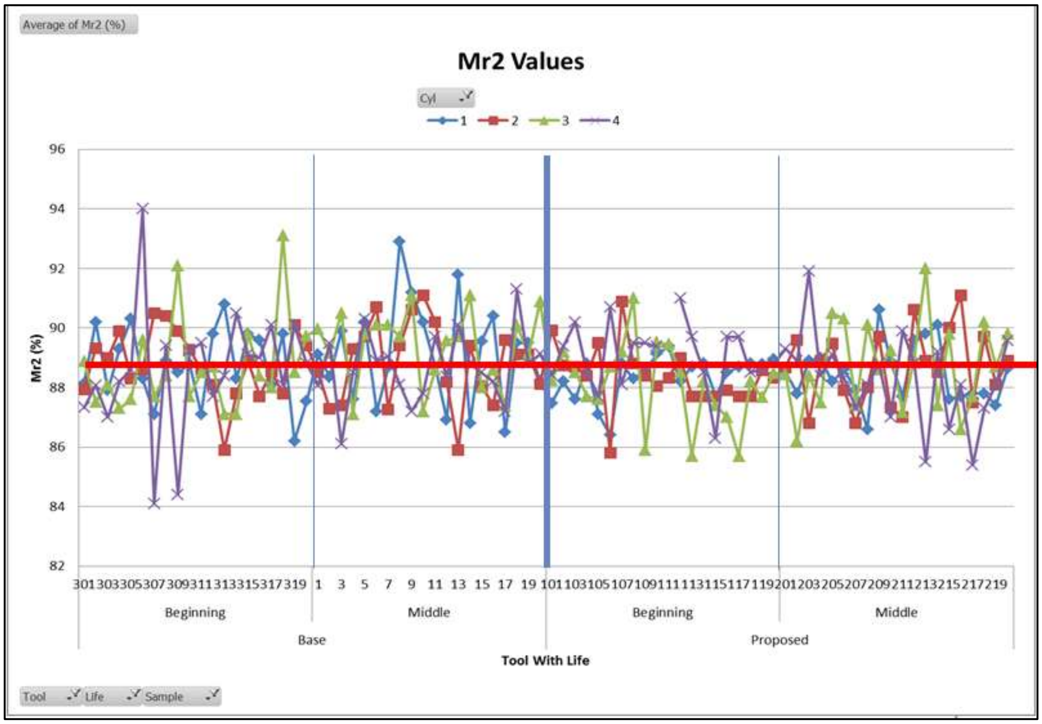


Figure 15 – Mr2 Values

Increase in ALL values

- Greater roughness average

$$0.14\ (Rpk\ microns) + 0.18\ (Rvk\ microns) + 0.27\ (Rk\ microns) = 0.6\ micron\ increase$$

- 1 micron total increase

$$0.69\ (Rz\ microns) + 0.27\ (Rk\ microns) = 0.96\ micron\ increase$$

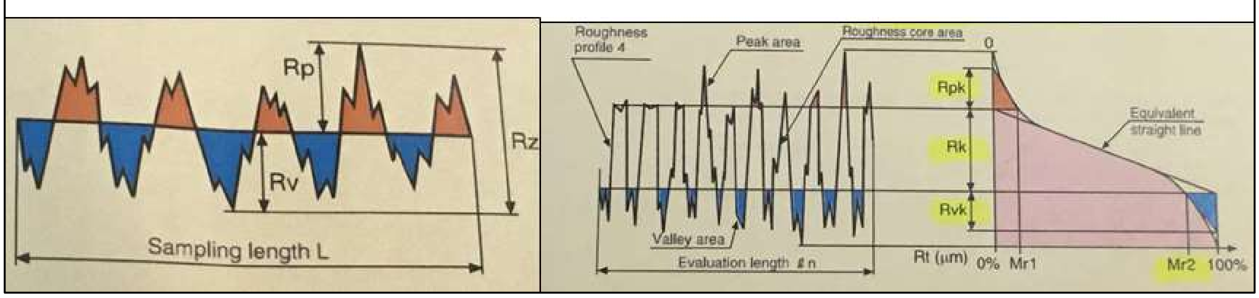


Figure 16 - Analysis

The wear factor for each spindle was taken as well. The base honing tools (spindles five and six) towards the middle of their life have a tool life of approximately 180,000 cycles whereas the after tool change honing tools have a tool life of about 10,000-20,000 cycles towards their mid-life. As pictured in Figure 17, both of the tools predict a quicker wear rate and shorter tool life at the beginning of their lives than towards the middle or end of the tools lives. This is proven in that, for each tool, the beginning of the life predicts the tool to last a smaller number of cycles then increases the predicted number of total cycles it can hone over time. This is typical for Gehring tools. From this data it can be inferred that overall the base honing tool lasts much longer than the after tool change tool; however, the base tool produces lower quality visually than the after tool change tool [argument further analyzed below].

The word “cycles,” in this context, refers to how many individual bores the tool can presumably hone. To get the number of *blocks* the tool can hone, simply divide the tool life depicted here by two (since each tool hones two cylinders per block).

BASE TOOL - BEGINNING OF LIFE:

	Spdl 1	Spdl 2	Spdl 3	Spdl 4	Spdl 5	Spdl 6	AVG
Wear rate: # cycles/mm	60,358.7	147,421.6	71,503.4	34,160.0	7,982.6	3,435.0	54,151.9
Tool Life (# cycles)	181,076	515,976	250,262	119,560	23,948	10,455	152,456

BASE TOOL MID-LIFE:

	Spdl 1	Spdl 2	Spdl 3	Spdl 4	Spdl 5	Spdl 6	AVG
Wear rate: # cycles/mm	60,236.2	204,960.8	101,729.0	45,963.4	59,657.0	65,677.8	89,704.0
Tool Life (# cycles)	180,709	614,882	305,187	137,890	178,971	197,033	269,112

AFTER TOOL CHANGE - BEGINNING OF LIFE:

	Spdl 1	Spdl 2	Spdl 3	Spdl 4	Spdl 5	Spdl 6	AVG
Wear rate: # cycles/mm	60,315	206,277	102,142	53,045	1,876	1,706	70,893
Tool Life (# cycles)	180,944	618,832	306,426	159,134	5,629	5,118	212,680

AFTER TOOL CHANGE - MID LIFE:

	Spdl 1	Spdl 2	Spdl 3	Spdl 4	Spdl 5	Spdl 6	AVG
Wear rate: # cycles/mm	42,123	202,843	101,599	63,920	3,028	6,174	69,948
Tool Life (# cycles)	126,370	608,530	304,798	191,760	9,083	18,522	209,844

Figure 17 - Wear Rate Comparison Data

Each tool costs approximately $1,300. If the old tool only had to be replaced after it had run 180,000 cycles and the new tool has to be replaced after around 10,000 cycles, then there is an annual

13 times increase (explained in calculations – Equation 3) in how much we spend on tools at the Dundee plant alone. That equates to the Dundee Engine Plant spending $62,400 more per year than we already do (explained in calculations – Equation 4). This comes out to 33 cents more per engine produced.

As demonstrated in Figure 18 and Figure 19, both the after tool change tool and base tool wear quicker at the beginning of their lives than after they have had a few days to break in.

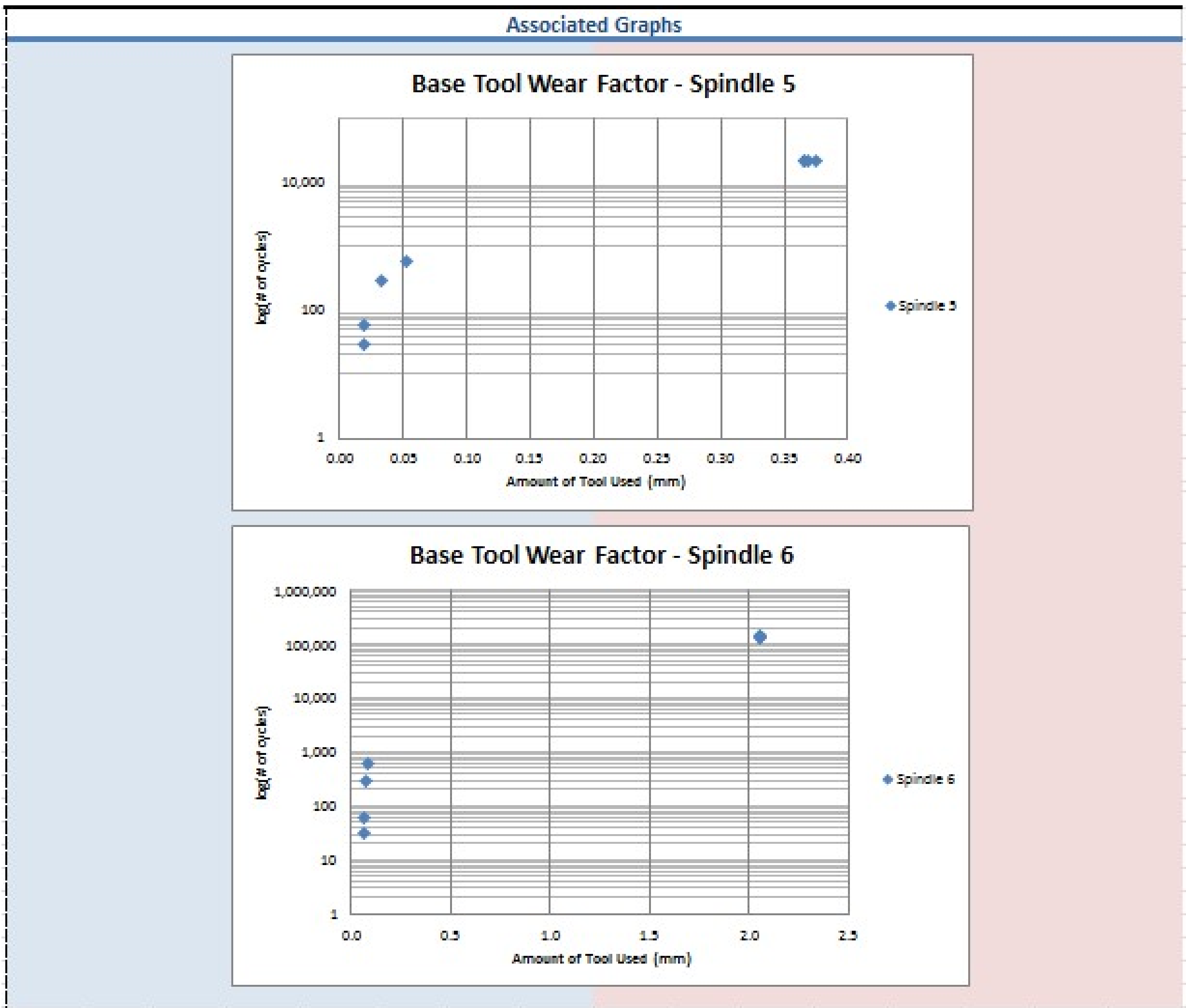


Figure 18 - Wear Factor Graph, Consistency in Wear for Base Tool

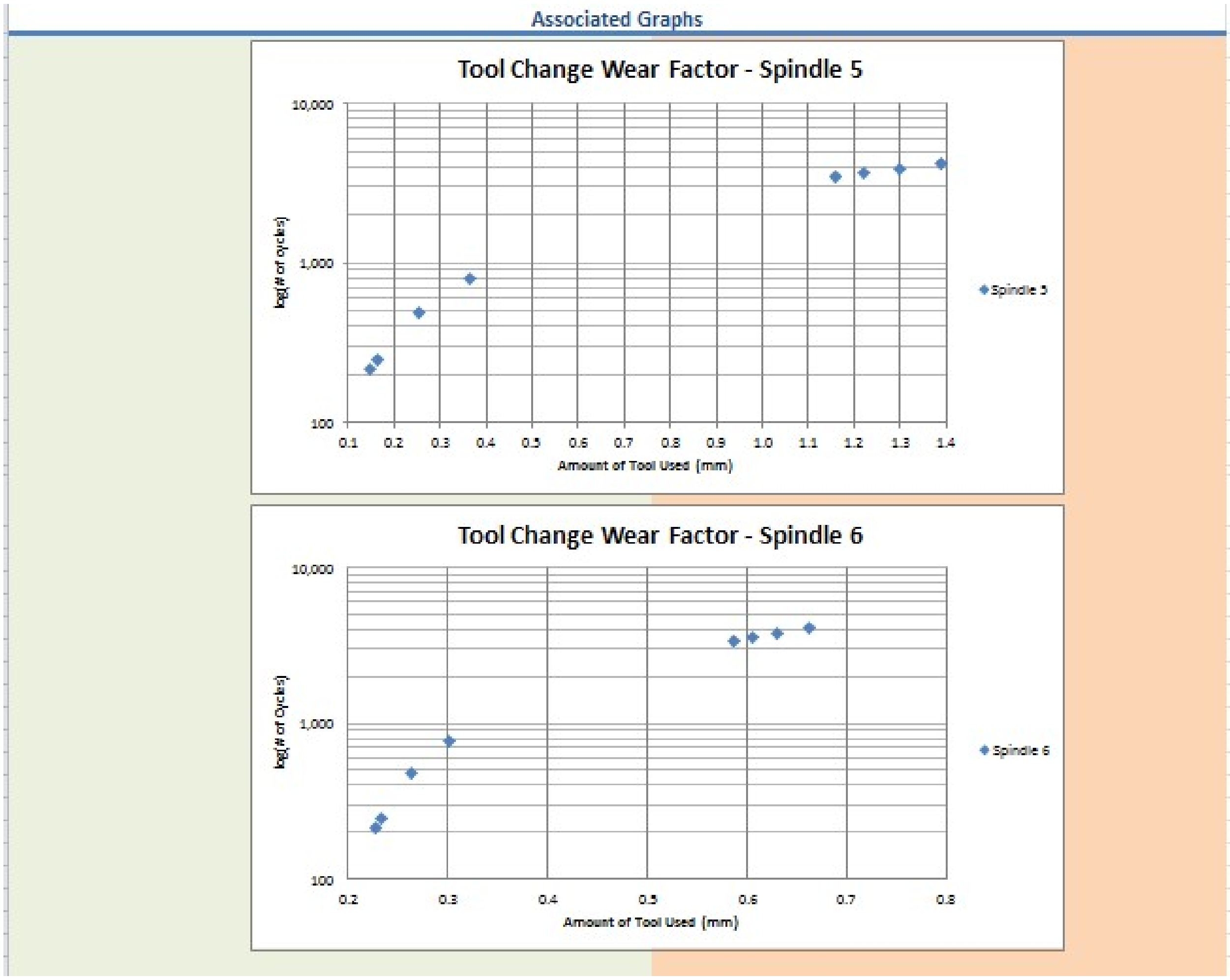


Figure 19 - Wear Factor Graph, Consistency in Wear for Tool Change

A logarithmic graph is shown to better reiterate that the tool wears faster when it is first installed on the machine than when it is has been broken in. The slope of the graph appears to start steeper and plateau out past 1,000 cycles into its life.

Figures 18 and 19 show that the after tool change tool wears very quickly compared to the base tool. This is shown in that the plateau values for the after tool change graphs (Figure 19) approach 0.8mm-1.4mm of tool used (of the 3mm total amount of tool) while on the y-axis only approaching about 10,000 cycles. That means that the after tool change tool has already used about a third to a half of its life within the first 10,000 cycles (or 5,000 blocks) performed. This is compared to Figure 18 where the base tool exceeds performing 100,000 cycles while still having ample amounts of tooling left.

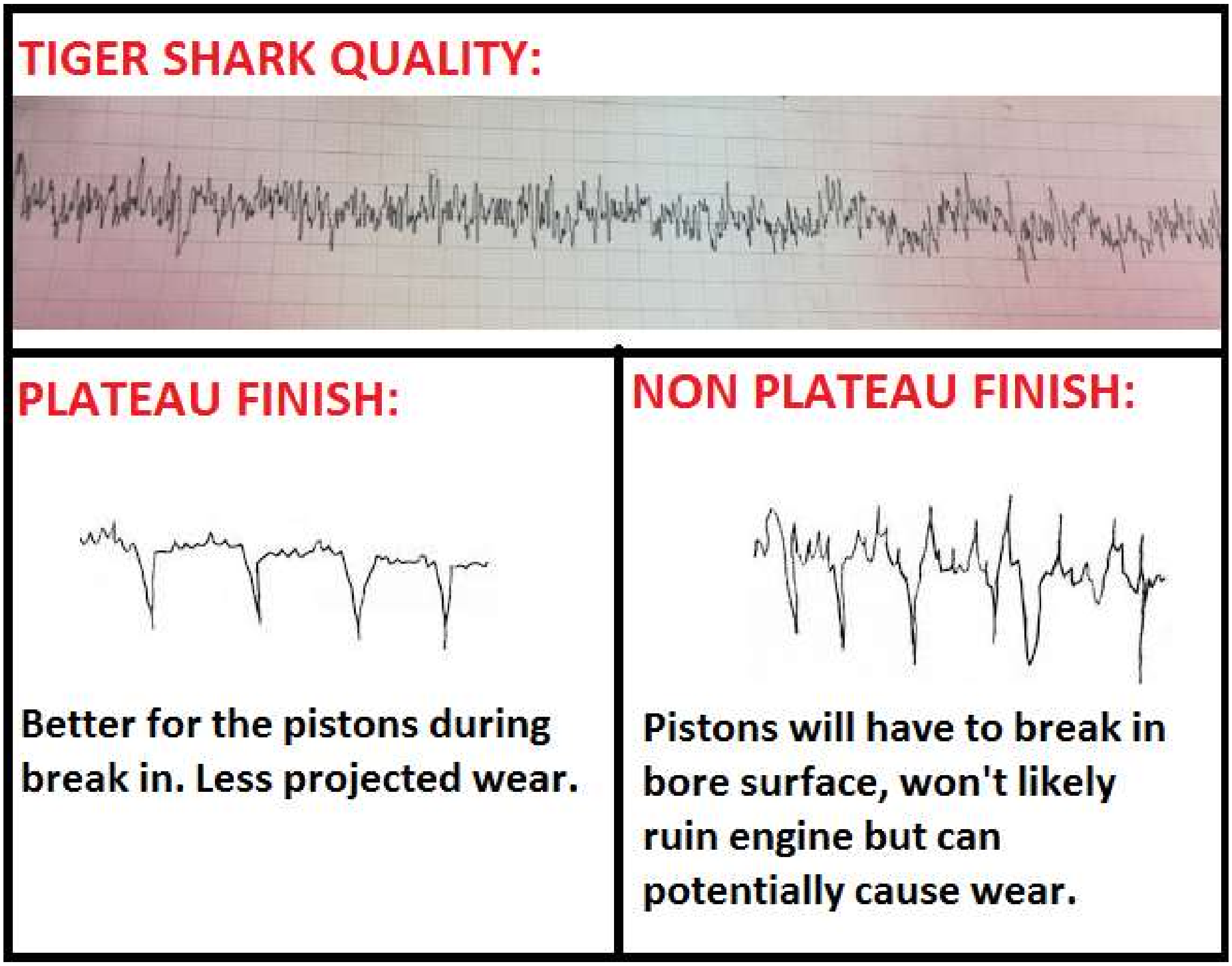


Figure 20 - Surface Finish [3]

Figure 20 reproduces a surface scan on the bores (the cross section of a cylinder bore). The Tiger Shark finish is considered a non-plateau finish. Although a plateau finish is more preferred, it seems from Figure 20 that the valleys are not so deep that excessive oil would be consumed from surface finish alone. The peaks are rough so the piston will end up doing work to break them down, but not likely so much as to create excessive damage. Below are the details associated with the graphical representation of the surface finish.

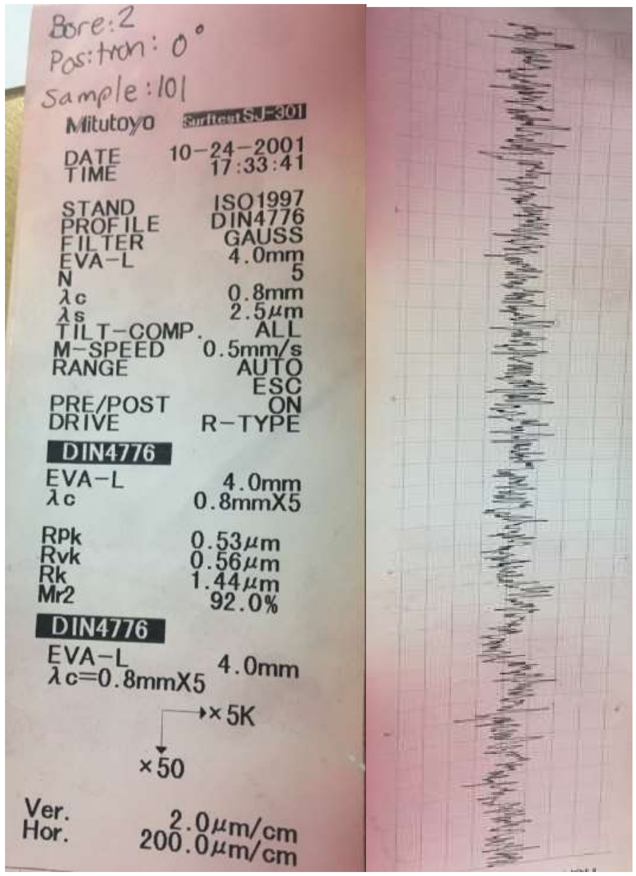


Figure 21 - Profilometer Surface Finish Sample - Tool Change Beginning of Life

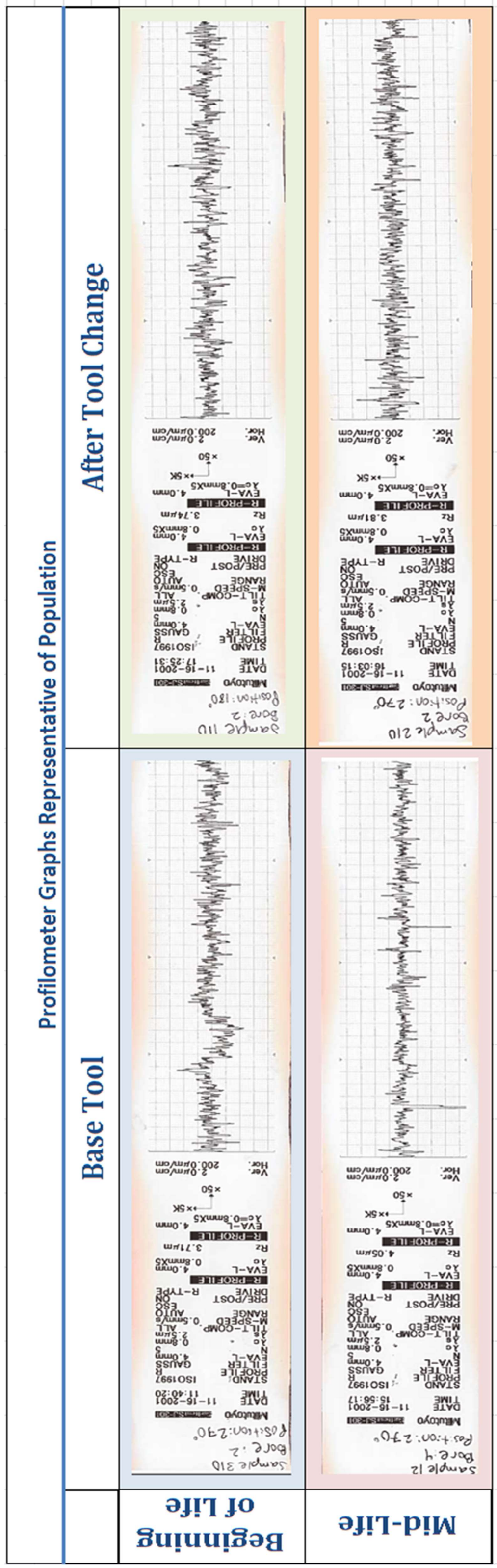


Figure 22 - Profilometer Scans Comparison

Figure 22 compares all four representative sets with one another: quality produced by the base and after tool change tool at the beginning and middle of their lives. The peaks point towards the words "Base Tool" and "After Tool Change" while the valleys are pointed the other way. In both instances, the beginning of the tools life produces a more jagged quality with deeper valleys and higher peaks than the middle of the tools life. Comparatively, the base tool appears to maintain lower Rk values throughout its life than the after tool change tool; this is also proven from Figure 13. This potentially implies that the quality the base tool produces doesn't allow the engine to retain as much oil as the after tool change tool does. This is assumed because the valleys are shallower in the images from the base tool.

viii. Calculations

Three primary equations were used to gather the data listed above in results: wear factor, tool life, and numerical value calculations for the briefly mentioned cost increase expectation for proceeding with tool change.

Wear factor = $\frac{Number\ of\ cycles\ tool\ has\ run}{3mm - X\ mm\ of\ tool\ used}$
Example: Wear Factor (Sample 1 Spindle 6) = $\frac{134{,}455\ cycles}{3\ mm - 0.95070\ mm} = 65{,}610\ cycles/mm$

Equation 1 – Wear Factor

Tool Life = $(Wear\ Factor) * (3\ mm\ of\ Total\ Tooling)$
Example: Tool Life (Sample 1 Spindle 6) = $65{,}610\frac{cycles}{mm} * 3\ mm = 196{,}830\ cycles$

Equation 2 – Tool Life

Annual Increase in Cost = $\frac{\left(13\frac{after\ tool\ chang\quad chang}{6mo}\right)*\left(2\,\frac{6\ mon\ periods}{yr}\right)*(2\ tools)}{(2\,\frac{base\ tool\ chnges}{yr})*2\ tools}$ = 13x increase spending/year

Equation 3 – Annual Increase in Cost

Additional Annual Cost = $\left[13\ *\left(\$5{,}200\,\frac{on\ base\ tool}{yr}\right)\right]-\$5{,}200\,\frac{1}{yr}=\$62{,}400\ addtl./year$

Equation 4 – Additional Annual Cost

Additional Cost Per Block = $\frac{\$62{,}400\frac{more}{yr}}{184{,}000\frac{blocks}{yr}}=33\,\frac{cents\ more}{block}$

Equation 5 – Additional Cost Per Block

Equation 3 assumes that the base tool wears time wise in about six months. This is based on its wear factor and how many blocks the plant has produced in six month, for the base tool it is about a one to one ratio (can hone 90,000 blocks total per tool, plant has made 92,000 blocks in six months). Comparatively, the after tool change tool wears completely after honing about 7,000 blocks. There is about a 13 times increase in how often the tool would need to be changed in six months. The relationship between this quantity and how much more would be spent per year remains to give a 13 times increase in spending per year total.

The annual increase in cost is calculated for all tools that would be affected by this change. The total annual additional cost (Equation 4) is simply determined by taking how much on average is spent on tools per year($\$1{,}300*2\ tool\,\frac{changes}{year}*2\ tools=\$5{,}200$) multiplied by the annual increase in cost factor (13), then subtracting the amount that is typically spent on tools to get the total additional cost spent. The additional cost per block (Equation 5) is taken by dividing how much more money is spent annually by the total number of blocks produced per year (which is about 184,000 blocks).

xi. Errors and Potential Improvements

Errors in the fax film process include only taking each fax film once instead of twice (the first time the fax film is taken it typically cleans the bore better) and not utilizing an entirely sterile environment where the films were cut. Other errors include potential human contact discrepancies via debris, oil, or dirt getting on the microscope, profilometer, and fax film.

Three more pieces of information that must be collected to make a better stance of this data in relation to warranty loss in oil consumption are SEM (electron microscope) testing, dyno testing for emissions, and obtaining warranty values. The data in this report will help back the case that cylinder bore finish texture is a potential root cause in high oil consumption, but no exact value can be drawn or measured to determine the cost/benefit in following through with this tool change. General trends and factual data can be obtained from this report, but comparing how much is lost in warranty compared to how effective this tool is battling those numbers cannot be determined from this data alone.

In solving for the big picture, there are a myriad of factors that can cause high oil consumption in an engine. Oil consumption can be related to the cylinder bores, piston pack, and other such oil related engine parts. In the cylinder bore honing process alone there are numerous factors that can contribute to poor surface finish such as tool pressure, feed rate, number of strokes, etc. Any and all factors can be analyzed as well as performing a design of experiment (DOE) to determine an exact root cause.

Another likely potential that is being looked at is bore distortion properties. When the cylinder bore heats up, the Tiger Shark blocks transform from a nearly perfect cylinder to more of an hour glass appearance. The piston pack is also being considered as a potential root cause.

x. Conclusion

The results obtained from this investigation prove the hypothesis correct that the newer softer tool generates better surface finish quality, clearer crosshatch angles, and less smearing. The new tools also, as predicted, wear down at a much quicker rate than the base honing tools and would cost Dundee Engine Plant $64,200 more annually than what we are already paying, or 33 cents more per block. The new honing stones change in how quickly they wear over time in that they wear faster at the beginning of the tools life than towards the end. Further investigations must be made in order to take a definitive stance on cost/benefit and whether or not this company investment to change to the new tool would produce sufficient change. The data depicted in this report helps to reinforce cylinder bore surface quality in relation to the hardness of tool as a potential root cause, though it is more likely that the bulk of the oil loss is coming from other sources in the engine such as bore distortion.

Appendicies

Appendix A: Profilometer Graphs

Sample number, bore number, and position on the bore (in degrees) are labeled at the top of each profilometer graph. Here, “vertical” refers to the shorter axis that is nine centimeters wide (pictured here horizontally) and vice versa for the “horizontal” reference that is 40 centimeters wide.

Sample 1
Bore 3
Position: 0°

Mitutoyo Surftest SJ-301

DATE 11-16-2001
TIME 15:35:47

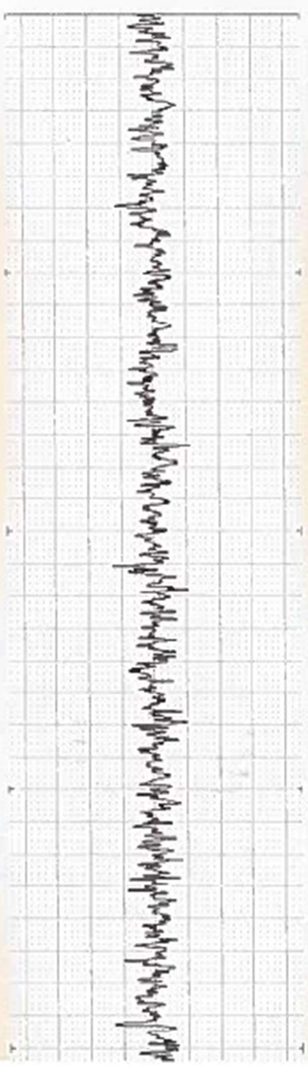
STAND ISO1997
PROFILE R
FILTER GAUSS
EVA-L 4.0mm
N 5
λc 0.8mm
λs 2.5μm
TILT-COMP. ALL
M-SPEED 0.5mm/s
RANGE AUTO
ESC
PRE/POST ON
DRIVE R-TYPE

R-PROFILE
EVA-L 4.0mm
λc 0.8mmX5

Rz 2.29μm

R-PROFILE
EVA-L 4.0mm
λc=0.8mmX5
×5K
×50

Ver. 2.0μm/cm
Hor. 200.0μm/cm



Sample 12
Bore: 4
Position: 270°

Mitutoyo Surftest SJ-301

DATE 11-16-2001
TIME 15:56:17

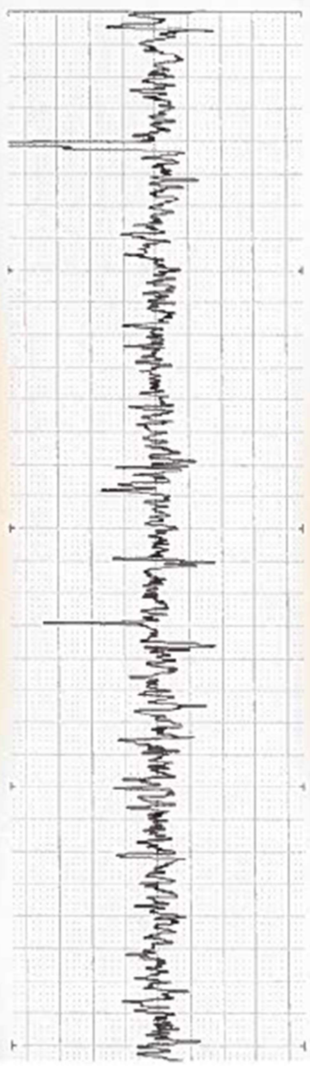
STAND ISO1997
PROFILE R
FILTER GAUSS
EVA-L 4.0mm
N 5
λc 0.8mm
λs 2.5μm
TILT-COMP. ALL
M-SPEED 0.5mm/s
RANGE AUTO
ESC
PRE/POST ON
DRIVE R-TYPE

R-PROFILE
EVA-L 4.0mm
λc 0.8mmX5

Rz 4.05μm

R-PROFILE
EVA-L 4.0mm
λc=0.8mmX5
×5K
×50

Ver. 2.0μm/cm
Hor. 200.0μm/cm



Sample 20
Bore: 1
Position: 0°

Mitutoyo Surftest SJ-301

DATE 11-15-2001
TIME 18:19:20

STAND ISO1997
PROFILE R
FILTER GAUSS
EVA-L 4.0mm
N 5
λc 0.8mm
λs 2.5μm
TILT-COMP. ALL
M-SPEED 0.5mm/s
RANGE AUTO
ESC
PRE/POST ON
DRIVE R-TYPE

R-PROFILE
EVA-L 4.0mm
λc 0.8mmX5

Rz 2.47μm

R-PROFILE
EVA-L 4.0mm
λc=0.8mmX5
×5K
×50

Ver. 2.0μm/cm
Hor. 200.0μm/cm

Bore: 2
Position: 0°
Sample: 101

Mitutoyo Surftest SJ-301

DATE	10-24-2001
TIME	17:33:41
STAND	ISO1997
PROFILE	DIN4776
FILTER	GAUSS
EVA-L	4.0mm
N	5
λc	0.8mm
λs	2.5μm
TILT-COMP.	ALL
M-SPEED	0.5mm/s
RANGE	AUTO
	ESC
PRE/POST	ON
DRIVE	R-TYPE

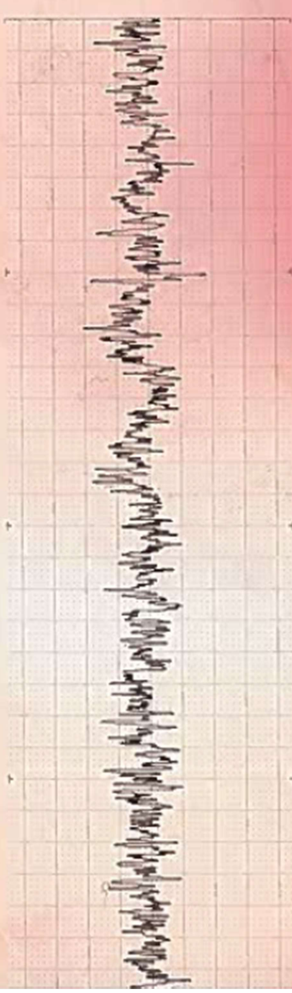
DIN4776

EVA-L	4.0mm
λc	0.8mmX5
RPk	0.53μm
Rvk	0.56μm
Rk	1.44μm
Mr2	92.0%

DIN4776

EVA-L 4.0mm
λc=0.8mmX5
×5K
×50

Ver. 2.0μm/cm
Hor. 200.0μm/cm



Sample 110
Bore: 2
Position: 180°

Mitutoyo Surftest SJ-301

DATE	11-16-2001
TIME	17:25:31
STAND	ISO1997
PROFILE	R
FILTER	GAUSS
EVA-L	4.0mm
N	5
λc	0.8mm
λs	2.5μm
TILT-COMP.	ALL
M-SPEED	0.5mm/s
RANGE	AUTO
	ESC
PRE/POST	ON
DRIVE	R-TYPE

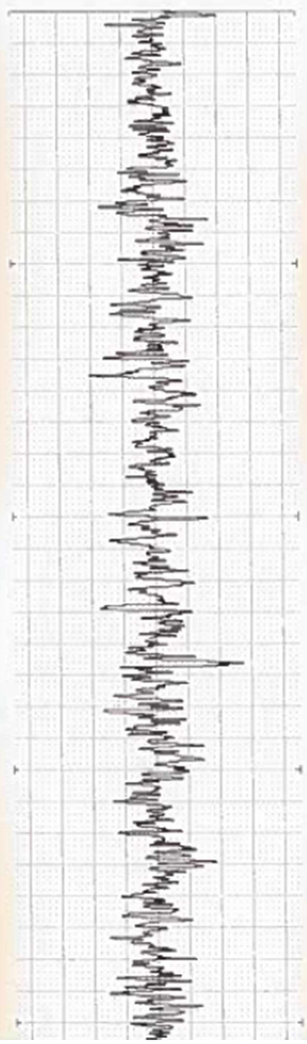
R-PROFILE

EVA-L	4.0mm
λc	0.8mmX5
Rz	3.74μm

R-PROFILE

EVA-L 4.0mm
λc=0.8mmX5
×5K
×50

Ver. 2.0μm/cm
Hor. 200.0μm/cm



Sample 120
Bore: 1
Position: 90°

Mitutoyo Surftest SJ-301

DATE	11-15-2001
TIME	17:58:40
STAND	ISO1997
PROFILE	R
FILTER	GAUSS
EVA-L	4.0mm
N	5
λc	0.8mm
λs	2.5μm
TILT-COMP.	ALL
M-SPEED	0.5mm/s
RANGE	AUTO
	ESC
PRE/POST	ON
DRIVE	R-TYPE

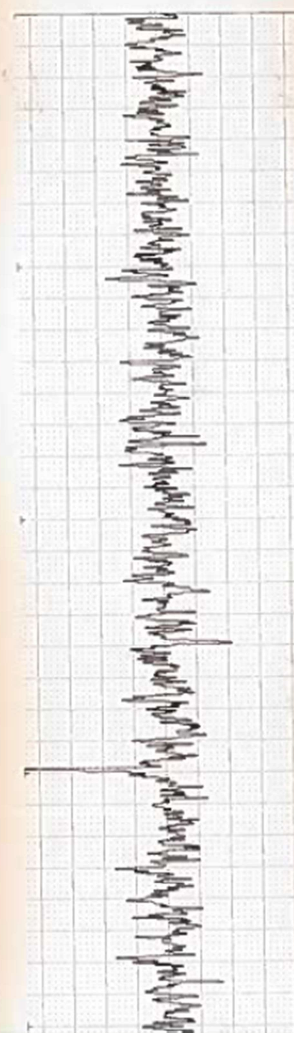
R-PROFILE

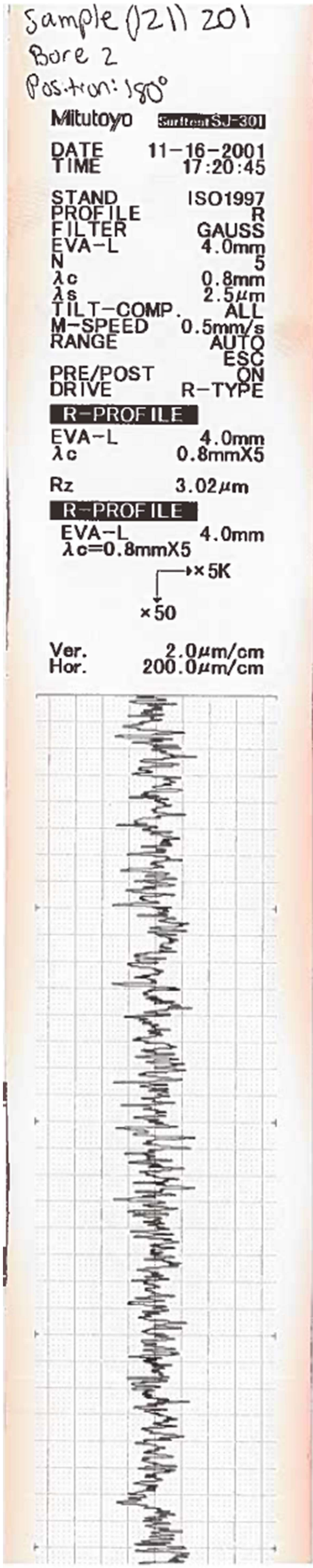
EVA-L	4.0mm
λc	0.8mmX5
Rz	4.51μm

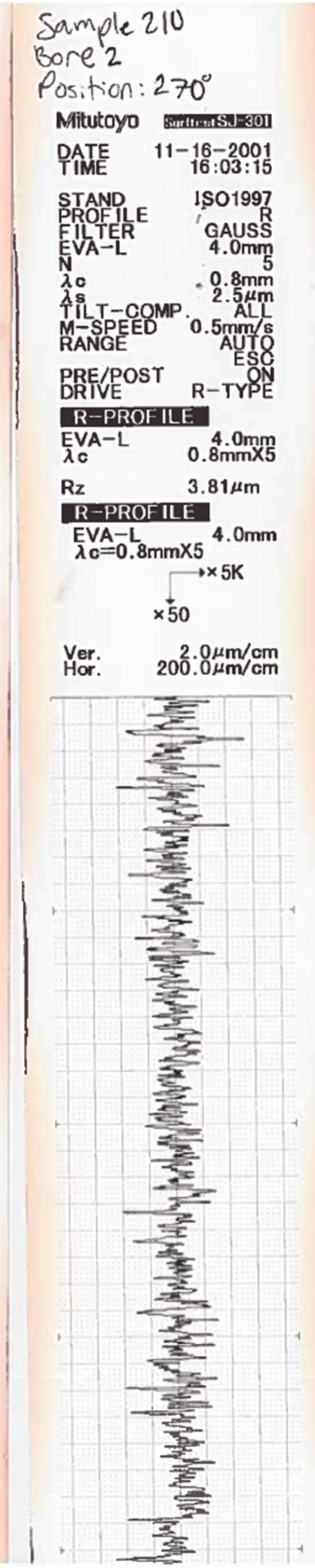
R-PROFILE

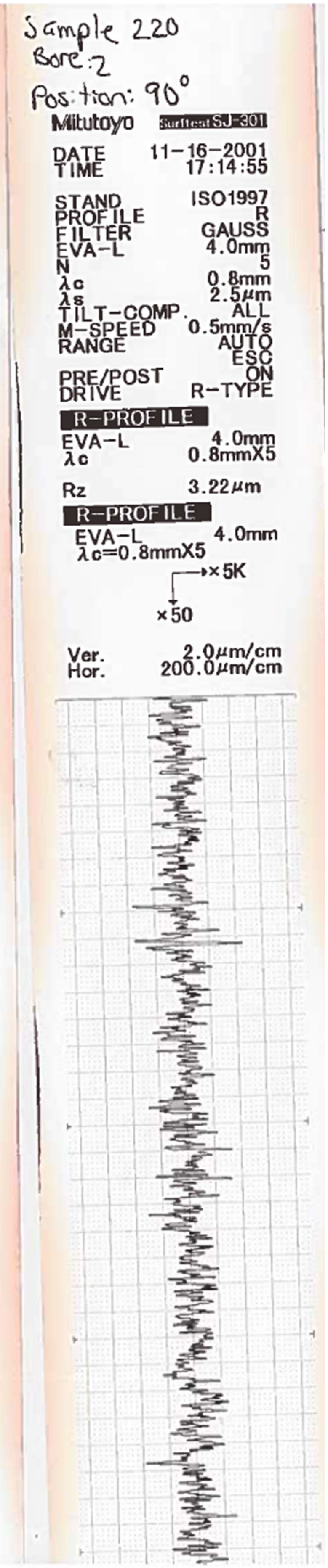
EVA-L 4.0mm
λc=0.8mmX5
×5K
×50

Ver. 2.0μm/cm
Hor. 200.0μm/cm




Sample (121) 201
Bore 2
Position: 180°
Mitutoyo Surftest SJ-301
DATE 11-16-2001
TIME 17:20:45
STAND ISO1997
PROFILE R
FILTER GAUSS
EVA-L 4.0mm
N 5
λc 0.8mm
λs 2.5μm
TILT-COMP. ALL
M-SPEED 0.5mm/s
RANGE AUTO ESC
PRE/POST ON
DRIVE R-TYPE
R-PROFILE
EVA-L 4.0mm
λc 0.8mmX5
Rz 3.02μm
R-PROFILE
EVA-L 4.0mm
λc=0.8mmX5
×5K
×50
Ver. 2.0μm/cm
Hor. 200.0μm/cm


Sample 210
Bore 2
Position: 270°
Mitutoyo Surftest SJ-301
DATE 11-16-2001
TIME 16:03:15
STAND ISO1997
PROFILE R
FILTER GAUSS
EVA-L 4.0mm
N 5
λc 0.8mm
λs 2.5μm
TILT-COMP. ALL
M-SPEED 0.5mm/s
RANGE AUTO ESC
PRE/POST ON
DRIVE R-TYPE
R-PROFILE
EVA-L 4.0mm
λc 0.8mmX5
Rz 3.81μm
R-PROFILE
EVA-L 4.0mm
λc=0.8mmX5
×5K
×50
Ver. 2.0μm/cm
Hor. 200.0μm/cm


Sample 220
Bore 2
Position: 90°
Mitutoyo Surftest SJ-301
DATE 11-16-2001
TIME 17:14:55
STAND ISO1997
PROFILE R
FILTER GAUSS
EVA-L 4.0mm
N 5
λc 0.8mm
λs 2.5μm
TILT-COMP. ALL
M-SPEED 0.5mm/s
RANGE AUTO ESC
PRE/POST ON
DRIVE R-TYPE
R-PROFILE
EVA-L 4.0mm
λc 0.8mmX5
Rz 3.22μm
R-PROFILE
EVA-L 4.0mm
λc=0.8mmX5
×5K
×50
Ver. 2.0μm/cm
Hor. 200.0μm/cm

Sample 301
Bore 3
Position: 0°

Mitutoyo Surftest SJ-301

DATE 11-16-2001
TIME 15:21:58

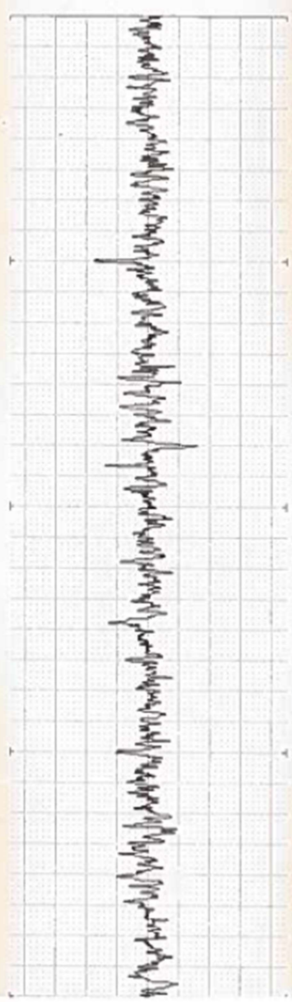
STAND ISO1997
PROFILE R
FILTER GAUSS
EVA-L 4.0mm
N 5
λc 0.8mm
λs 2.5µm
TILT-COMP. ALL
M-SPEED 0.5mm/s
RANGE AUTO
ESC
PRE/POST ON
DRIVE R-TYPE

R-PROFILE
EVA-L 4.0mm
λc 0.8mmX5

Rz 3.11µm

R-PROFILE
EVA-L 4.0mm
λc=0.8mmX5
×5K
×50

Ver. 2.0µm/cm
Hor. 200.0µm/cm



Sample 310
Bore: 2
Position: 270°

Mitutoyo Surftest SJ-301

DATE 11-16-2001
TIME 11:40:20

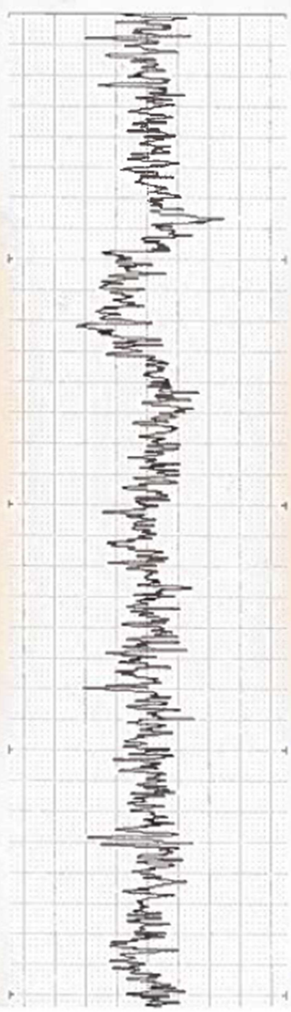
STAND ISO1997
PROFILE R
FILTER GAUSS
EVA-L 4.0mm
N 5
λc 0.8mm
λs 2.5µm
TILT-COMP. ALL
M-SPEED 0.5mm/s
RANGE AUTO
ESC
PRE/POST ON
DRIVE R-TYPE

R-PROFILE
EVA-L 4.0mm
λc 0.8mmX5

Rz 3.71µm

R-PROFILE
EVA-L 4.0mm
λc=0.8mmX5
×5K
×50

Ver. 2.0µm/cm
Hor. 200.0µm/cm



Sample 320
Bore: 2
Position: 270°

Mitutoyo Surftest SJ-301

DATE 11-16-2001
TIME 14:03:56

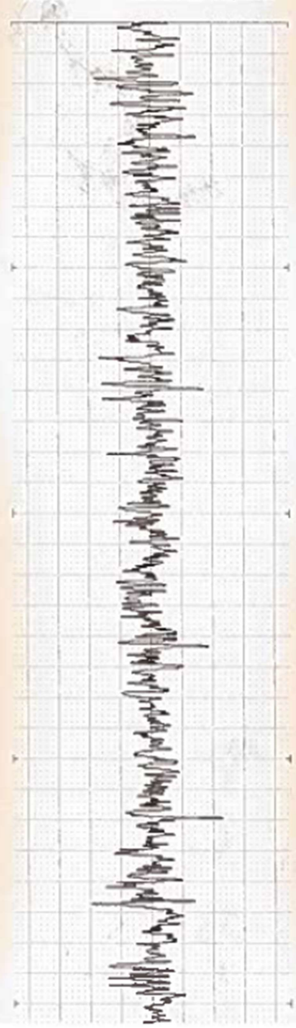
STAND ISO1997
PROFILE R
FILTER GAUSS
EVA-L 4.0mm
N 5
λc 0.8mm
λs 2.5µm
TILT-COMP. ALL
M-SPEED 0.5mm/s
RANGE AUTO
ESC
PRE/POST ON
DRIVE R-TYPE

R-PROFILE
EVA-L 4.0mm
λc 0.8mmX5

Rz 3.49µm

R-PROFILE
EVA-L 4.0mm
λc=0.8mmX5
×5K
×50

Ver. 2.0µm/cm
Hor. 200.0µm/cm



xi. Works Cited

[1] Accretech – Tokyo Seimitsu; "Explanation of Surface Characteristics – Standards;" page 234

[2] Hoen, Thomas; Schmid, Josef; Stumpf, Walter; "Less Wear and Oil Consumption through Helical Slide Honing of Engines by Deutz;" MTZ 0412009 Volume 70; 2009; page 49

[3] https://www.google.com/url?sa=i&rct=j&q=&esrc=s&source=images&cd=&ved=0ahUKEwiHusO19sjNAhUn6oMKHQz8A6wQjRwIBQ&url=http%3A%2F%2Fwww.ijens.org%2FVol_15_I_01%2F156901-3737-IJMME-IJENS.pdf&psig=AFQjCNHdHNT_R4R3vlC1Dv5MpdwRPyUaAg&ust=1467132527549925