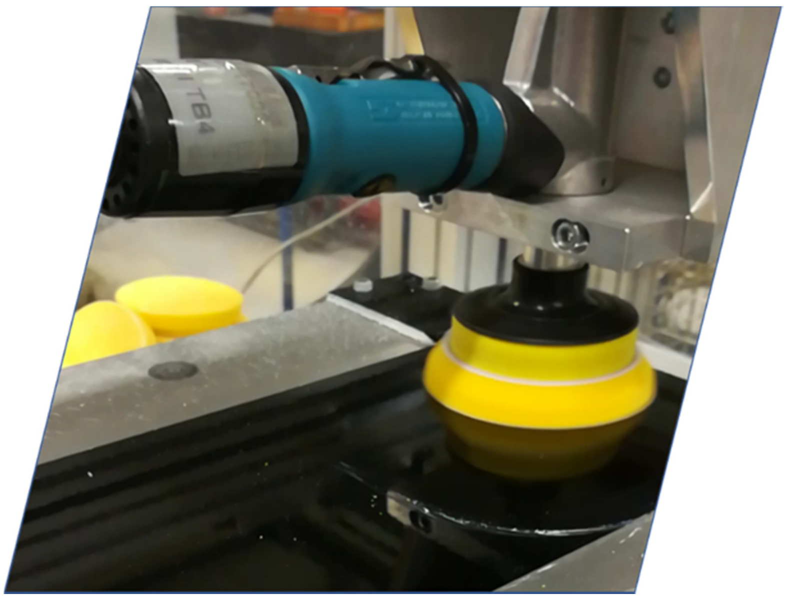
Robust Polishing

Public report



Project within FFI Hållbar produktion
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Date 191129

Content

1. Summary

A defect free painted exterior of a vehicle plays a major role in how the product is perceived by the customer. Some repairs on the ready painted vehicles are sometimes required and in order to eliminate defects, a polishing operation is usually required. These manual operations can in turn create other defects and the occurrence of these polishing defects are dependent on a number of factors, including the coating material, polishing equipment and polishing operation parameters. There is today not a standard way for verification of polishability of coatings, why it can be difficult to introduce new paint systems. Furthermore, the knowledge of how parameters of the manual polishing operation such as pressure, time and movement of the tool, affects the final results after polishing is not clarified. The goal of this project has been to fill some of these knowledge gaps.

In this project, an equipment and method for automated testing of polishability of coatings as well as testing different operation parameters have been developed. Based on results from analysis of manual polishing operations, a window for operation of the automatic polishing equipment has been defined. Trials have been made with the automated polishing equipment with the window in order to assess what polishing parameters gives the best results (least visible defect). Furthermore, different coating systems have been tested in order to assess if the polishability of the different paint systems can be verified with a given polishing system (tool, polishing pads, etc.). Apart from the difference observed between the different materials, it has been possible to show that the appearance of polishing defects may change over time after finished polishing operation.

In order to measure the defects in a repeatable way, an existing surface analysis equipment - Waviness measurement system (WMS) - has been used and adapted for analysis of polishing defects. Furthermore, interferometry has been used to analyze the surface defects. Results from both these techniques were correlated to visual assessments and with both systems, discrimination between bad and good polish operations could be done.

The project has been a collaboration between Halmstad University, Volvo cars, AB Volvo and Beckers. Future possibilities for collaboration between industry and academia has been enabled through this project and it has laid the groundwork for further development within this area. The next step would be to create a working industry standard for verification of polishability of coatings and different polishing equipment based on the findings in this project. In the long run, when findings regarding polishing parameters effect on the final result is communicated and implemented in production, the amount of defects is expected to be diminished and less paint rework should be required.

2. Sammanfattning på svenska

En defektfri målad exteriör av ett fordon spelar en stor roll i hur kunden upplever kvalitén på produkten. Vissa reparationer på färdigmålade karosser är ibland nödvändiga för att eliminera defekter och oftast används då polering som metod. Polering är vanligtvis en manuell operation, där tidigare slipning som gjorts på den lackade ytan för att ta bort en defekt, tas bort genom betydligt finare slipning av ytan. Detta eliminerar sliprepor, men riskerar skapa andra visuella artefakter. Bildandet av dessa polerdefekter är beroende av ett antal faktorer, inkluderande huvudsakligen färgmaterial, polerutrustning och olika parametrar för poleroperationen.
Det finns idag ingen standardiserad metod för att verifiera polerbarheten hos färgmaterial, vilket kan försvåra införandet av nya lacker i måleriprocesser, då poleringen måste verifieras med manuella operationer. Utöver detta, så är kunskapen om hur olika parametrar så som tryck, tid och rörelse hos polerverktyget påverkar polerresultatet begränsad. Målet i detta projekt har därför varit att öka kunskapen inom detta område.
I detta projekt har en utrustning och metod för automatiserad provning av polerbarheten hos lacker och provning för olika poleroperationsparametrar utvecklats. Utrustningen som har byggts kan repeterbart polera en lackerad yta och parametrarna för detta kan varieras. Baserat på resultat från analys av poleroperatörers manuella operationer, har ett processfönster för poleringen definierats. Detta har översats till den automatiserade polerutrustningen och försök har sedan gjorts för att bedöma för vilka parametrar det bästa polerresultatet kan uppnås. Fortsatt, har olika lacker provats för att bedöma om polerbarheten kan verifieras med ett givet polersystem (verktyg, polerkuddar, polermedel, etc). Skillnader mellan de olika lacker som provats har observerats och likaså har man kunnat påvisa att polerdefekter kan uppkomma en tid efter utförd polering.
För att repeterbart kunna mäta defekter har olika metoder använts. En existerande utrustning kallad ”Waviness measurement system” (WMS) har anpassats för analys av polerdefekter. Med denna har man kunnat kvantifiera hur stort område av den lackerad yta som har en defekt. Interferometri har också använts för att analysera polerade ytor, genom att mäta och kvantifiera repmönstret. Likaså har visuella bedömning av ytor polerade av manuella operatörer och den automatiska polerutrustningen gjorts i standardiserade ljusförhållanden. Dessa resultat har korrelerats till mätningar gjorda med interferometer och WMS. Resultaten visar att båda utrustningarna kan användas för att, i viss mån, diskriminera bra polerade ytor från dåliga.
Projektet har varit ett samarbete mellan Halmstad Högskola, Volvo Cars, AB Volvo och Beckers. Framtida möjligheter för samarbete har blivit möjliggjorda genom detta projekt och det har lagt grunden för fortsatt utveckling inom detta område. Nästa steg hade varit att skapa en industriell standard för verifiering av polerbarhet hos lacker och olika polerutrustningar och metoder, baserat på resultat framtagna här. Implementering av denna standard kan leda till kortare ledtider för att föra in nya färgmaterial i löpande produktion som till exempel lacker härdade vid lägre temperaturer. På längre sikt, när slutsatser från polerparametrars effekt på polerresultatet är kommunicerat i produktion, hade mängden defekter kunnat minskas och mindre ommålningar och manuella justeringar behövts.

3. Background

The surface finish of a vehicle plays a major role on the perceived product quality, and it is therefore of great importance to secure a homogeneous and defect free surface finish. Today, most car and truck bodies undergo end-of-line repairs, i.e. local abrasive polishing to eliminate spot defects, which can lead to other types of defects. The occurrence of the later depend on a combination of the coating system and polishing operation parameters – and the possibilities to detect the defects. In this project, a test method to evaluate the polishability of new coating systems before introducing them into the production line will be developed to facilitate more efficient implementation (and operation) of new coating systems and any post-treatment in production. A more efficient way to teach new polishers was also requested, as well as a robust and standardized way to polish.

The project was divided into 6 work packages (WP):
WP1 Sample preparation Decision on the choice of appropriate test items, i.e. dimensions and coating system (with focus on 'low bake' systems), and relevant surface phenomena (defects caused by the polishing process). Continuous supply of test samples from included companies during the project.
WP2 Process development Development, set-up and tuning-in of a test equipment to study polishability (called the Pol-rig), further development of a measurement devise (the WMS) to study surface phenomena, and a literature study to complement the pre-study focused on how perceived surface quality can be linked to measurable surface parameters.
WP3 Data collection and DoE Test procedure with the Pol-rig based on statistical design of experiments, data collection based on manual polishing, and compilation of test results.
WP4 Modelling Suggestion of a model of the polishing mechanisms involved in abrasive polishing of coated surfaces.
WP5 Adaption of test equipment for education/training purpose Development of suitable equipment to teach and train operators to optimize the polishing procedure including relevant and clear instructions to communicate both polishing strategies and surface assessment.
WP6 Project management Project management and reporting.

4. Purpose, research questions and method

The aim of the project was to gain a better understanding of the mechanisms controlling the polishability of different coating systems. The following research questions were announced:

- Could process data collected from professional polishers' give a hint on 'the best polishing technique', and how polishing roses arise?
- Could a test method for polishability be developed in purpose to structurally and objectively evaluate new coating systems?
- How could a model for material removal (abrasive finishing of coated surfaces) look like?
- How could findings regarding affecting polishing parameters be implemented in production?

The project covered studies of different strategies for end-of-line repairs of coated surfaces and its rise to surface imperfections. DoE trials in a one for the purpose developed CNC-machine were preformed to study the influence of various process parameters, and data was collected to study how professional polishers work, i.e. what process parameters they apply and what surface quality they achieve.

Electro coated cold rolled steel panels were painted at Volvo AB Umeå and Surface treatment center at Volvo cars. The panels had dimensions around 400x400x300mm in order to fit in the test equipment. Paint material was supplied by Beckers and the samples were painted by Volvo cars Torslanda and AB Volvo Umeå paint process. A primer was applied before painting the following four paint systems that were tested:

- Base coat + High bake clear coat Volvo Cars Torslanda
- Base coat + Low bake clear coat Beckers
- Base coat + Low bake clear coat AB Volvo Umeå
- Low bake Top coat AB Volvo Umeå

All coating systems tested were in black solid colour, since dark colours are more prone to show polishing defects. One high bake (cured at >100°C) and three low bake systems (cured at <100°C) were tested. Three paint systems were base- and clear coat systems, were the upper coating consists of a coloured base coat and a transparent high gloss clear coat. One system from AB Volvo was a "top coat system", where the functions of the clear coat and base coat are combined in one paint layer. The paint materials were selected based on the currently used paint systems in current production for the three different parties Volvo Cars, AB Volvo and Beckers.

All relevant samples were assessed in the WMS (see ch. 6.1) and by a visual estimation at Volvo Cars performed in one for the purpose designed set-up with defined lighting conditions simulating direct sunlight, the most critical light condition for perceiving polishing defects. The grading was based on three inter-linked criterions – intensity related to the strength of the defect, severity related to the size of the defect and angle related to the visual detectability. A combination of these three criterions gave the final grade in a scale from 1 to 10, where 1-3 – sanded and poorly polished (surface quality not ok), 4-6 – sanded and polished but surface quality not ok, 7-9 – sanded and polished with ok surface quality, and 10 – no defects observable.

5. Objective

The goal was to develop a method to test the polishability of coating which was expected to lead to a more efficient implementation (and operation) of new coating systems and any post-treatment in production.

6. Results and deliverables

The four deliverables set for the project will be discussed separately in ch. 6.1-4, the goal fulfillment in ch. 6.5. The Pol-rig, FMT system and WMS (a patented technology) are all based on previous versions developed by [1].

6.1 Objective method for surface characterisation of coatings

The WMS (Waviness Measurement System) was further developed and redesigned into a photometric stereo system with two sets of four RGB COB LED bars containing eight 30W COB LEDs each [2]. One set, i.e. the four LED bars in the corners (shown as blue rings with a cross inside in figure 1), is only used as background light, and therefore the angle to the sample is quite high. The other set is used for image acquisition, i.e. the four LED bars called Lamp 8-1 0/90/180/270 (shown as blue rings in figure 1). Each LED is controlled individually and one picture per LED and colour (R, G, B and RGB) is taken by the camera (Basler GigE acA2040-25gm [3]) with a resolution of 2048x2048 pixels which gives a maximum image size of 205x205 mm). After image acquisition, the region of interest is selected manually by cropping the image to only include the area that has been repaired. Gaussian Mixture Models [4-5] are used to extract relevant features, i.e. repaired areas, before the fraction of defective area are calculated for each lamp and angle combination.

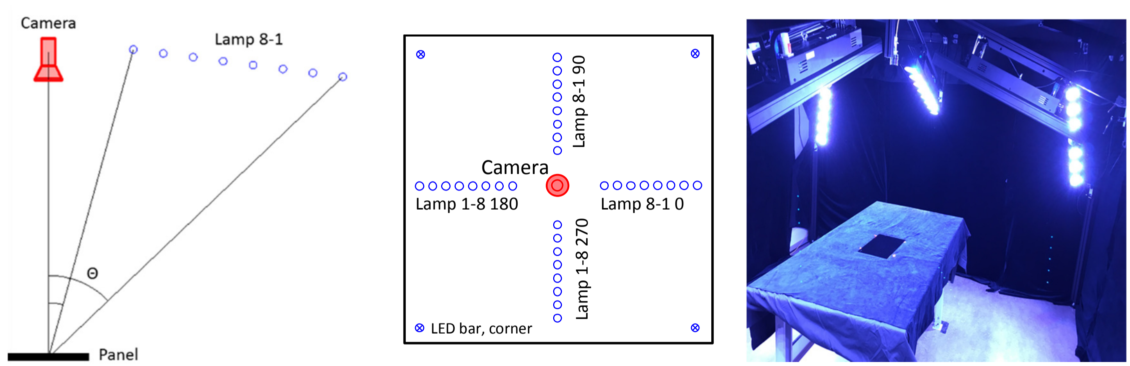


Figure 1. Left, schematic view of a part of the measurement set-up; Θ is the angle between the individual LEDs and the camera, which is in the range of approx. 5-35°. Mid, a schematic top view of the measurement set-up, which is placed in a dark room (size approx. 3x3x2.5 m) shown in the photo to the right.

A problem with the WMS is overexposed images, i.e. direct light reflections and wrong exposure times. An automatic function was made to adjust the exposure time for each lamp. For comparison, the optimal settings for actual samples were fixed through the project. Figure 2 shows an example of a typical polishing rose captured by one of the lamps; the grey circle are rubbed area, the more ‘white’ areas the polishing rose.

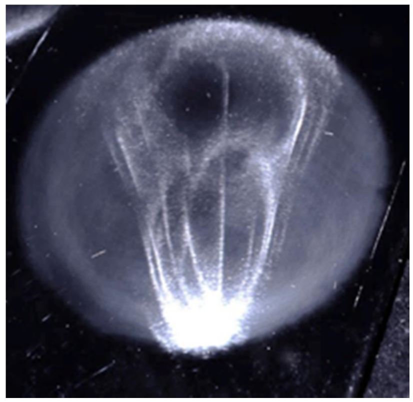


Figure 2: WMS images of a polishing rose on a rubbed sample.

A prototype of a smaller version of the WMS was built up in purpose to be mounted on the Pol-rig, see figure 3. The principle is the same, but instead of having several lamps, only one lamp is used, which is, together with the camera, moved over the sample.

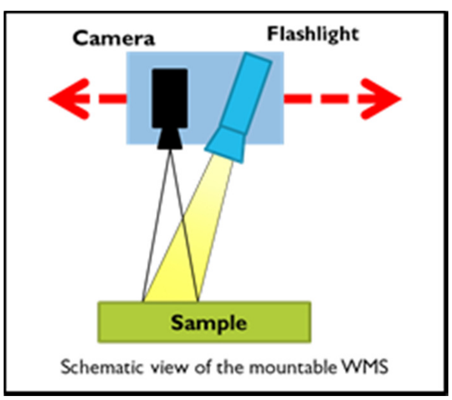


Figure 3: The mountable WMS; left a schematic view, right the prototype mounted on the Pol-rig.

Evaluation criteria

The WMS images were correlated to the visual estimation based on the calculated fraction of defective area. Figure 4 shows the result for Panel 4 with automatic and corrected exposure time; the measurements with corrected exposure time correlated better to the visual estimation (1-3 are red, 4-6 are orange, 7 is dark green, and 8-9 are green). Panel areas graded to be ok, i.e. marked green, were measured to have less defective areas, and the defects found were stronger with decreased illumination angle. This means that any polishing marks left on the repaired areas estimated to be ok were measured to be small in size and only visible when illuminated by small angles. The panels graded to be ok, but measured to have averages close to 100 % were over exposed. However, a line from a marker was detected as defective area on Panel 4 A2 which increased the defective area and therefore the results were not fully trustworthy. The effect of the marker is decreasing with decreasing illumination angle since the polishing rose become larger with smaller illumination angles.

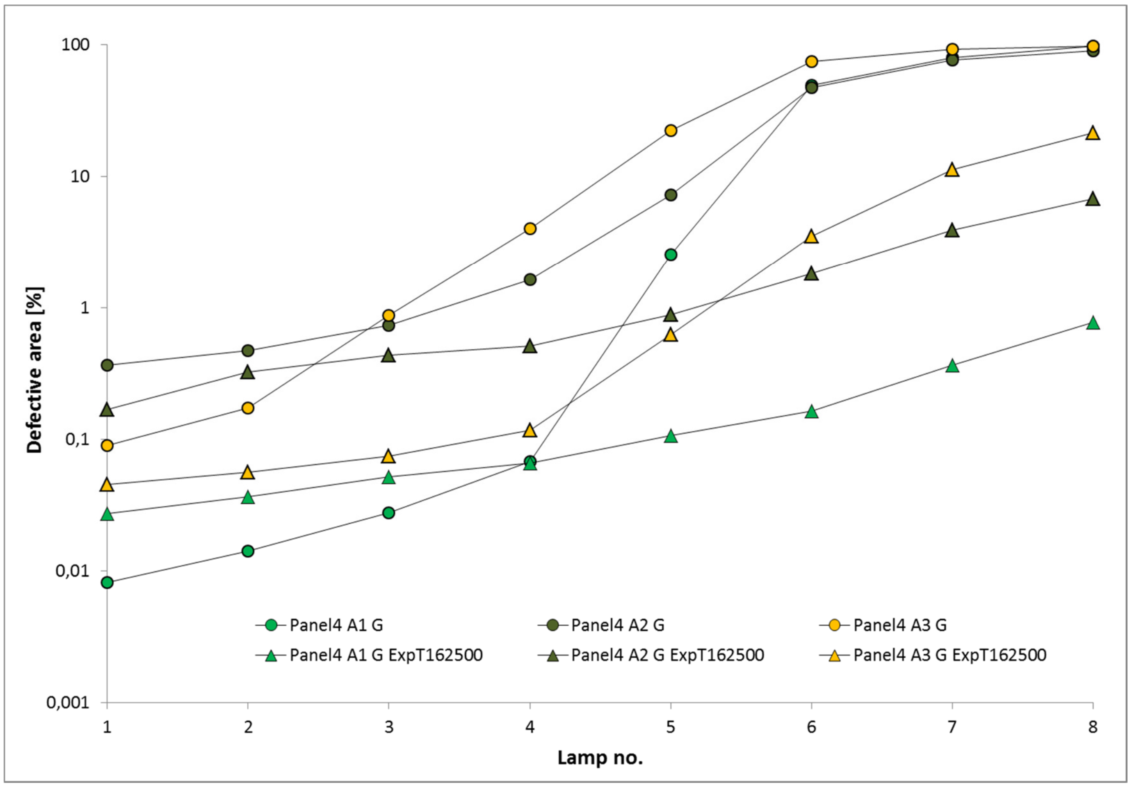


Figure 4: Percentage of defective area versus illumination angle, i.e. Lamp no., for Panel 4 with automatic exposure time (circle) and corrected one (triangle). Green samples had acceptable surface quality [6].

Surface measurements were performed with a 20x objective on an interferometer with a phase-shifting technique (quoted vertical resolution of 0.1 nm and a sampling interval of ~1 µm). Traceology, or in particular, a method for scratch analysis of cylinder liner surfaces [7] has been further improved and adapted to study the properties width, height, coverage, and no. of polishing scratches (see ch. 6.3). MountainsMap [8] was used to filter the surfaces. A polynomial of 3rd degree and a low-pass robust Gaussian filter (cutoff: 25 mm) were applied for parameter calculations. Additionally, a closing morphological filter with a 1.3 mm long line segment was applied before those surfaces were transferred to Matlab for scratch detection.

A 5x objective was used for surface parameter calculations in MountainsMap; the ‘isotropy’ value turned out to be a useful indicator to determine polishing roses (see fig. 5). Values above 60% means no visible defect, values below 40% that there is a defect, i.e. a reworked surface with defects has dominated scratch orientations, which also confirms that polishing roses are only visible at certain angles.

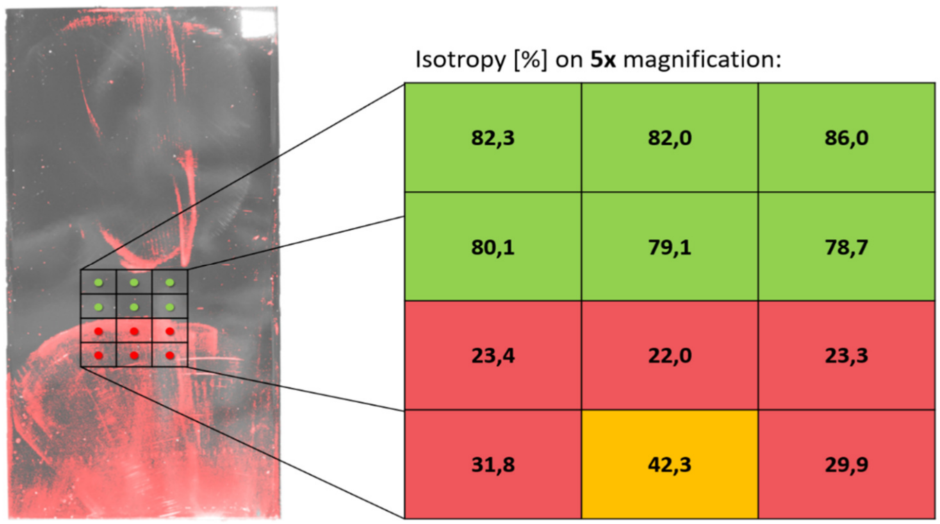
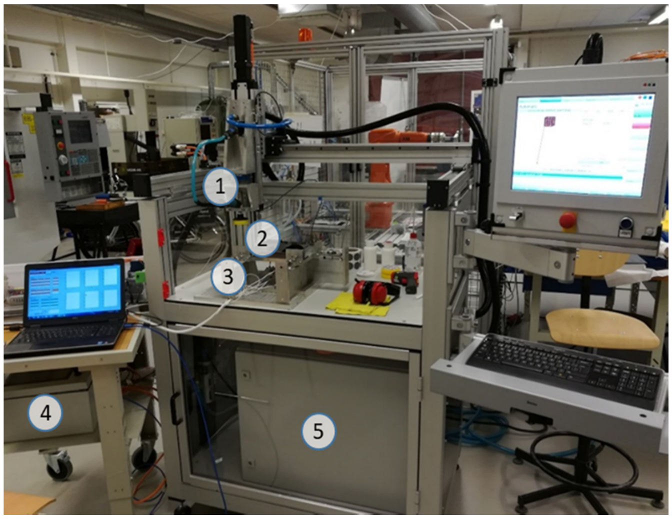


Figure 5: Left, WMS image of a panel where the red area corresponds to a polishing rose. The matrix shows where the WLI measurements were taken and, right, the isotropy values in the respective area.

6.2 Equipment to study and evaluate the polishability of coating systems

A 3-Axis Gantry Crane Type CNC machine, called the Pol-rig (see fig. 6), was built up to run and record data of grinding and polishing applications. It was designed to be portable, i.e. its base area has the same dimensions as a Euro Pallet (1200 x 800 mm), and its additional systems were built up as independent modules with their own power circuits. To keep the usage of the Pol-rig simple a software application was created to automatically generate the G-code for specific paths, which means that operators do not need to have a CNC background to run tests on it. A rotary buffer (Dynabrade 51400 3” dia. 7), fixed in a tool holder on the z-axis via a manual tool change system [9], was used for all tests in the project. The tool can relatively easy be replaced with other types of tools (or the developed prototype of the mountable WMS, see ch. 6.1).



1. Sanding/Polishing tool
2. Sample
3. FMT module
4. RPM sensor/module
5. Electrical cabinet (including controller, servo drives etc.)

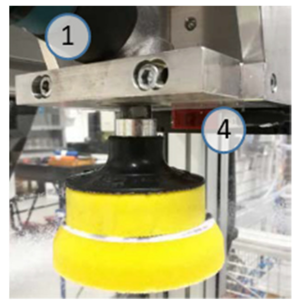


Figure 6: Pol-rig in the lab at HH.

The built up modules were:

RPM module – to measure the speed of the rotating sanding/polishing tool. A retro-reflective photoelectric sensor with a polarization filter was used to enable contactless measurements. A HMI based on MATLAB [10] was created to ease the usage; one part contains actual settings, start/stop and displays live data, the other provides analysis and saving of previously measured data.

FMT module – to detect and measure forces in x-y-z direction. At first, a new version was designed, a piezoelectric 3-component dynamometer [11] where a vacuum table should form the top plate. Unfortunately, this new design was abandoned due to too high costs. Instead, the old system (see fig. 7), a measurement platform utilizing strain gauge sensors in order to detect appearing forces in three directions, was updated and calibrated. Figure 8 shows the created HMI based on MATLAB [10]. Additional MATLAB applications were created to visualise and simplify analysis of recorded data (see fig. 9).

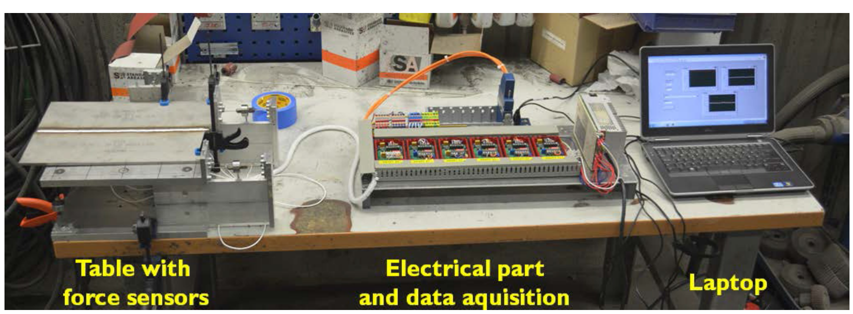


Figure 7: The updated FMT set-up.

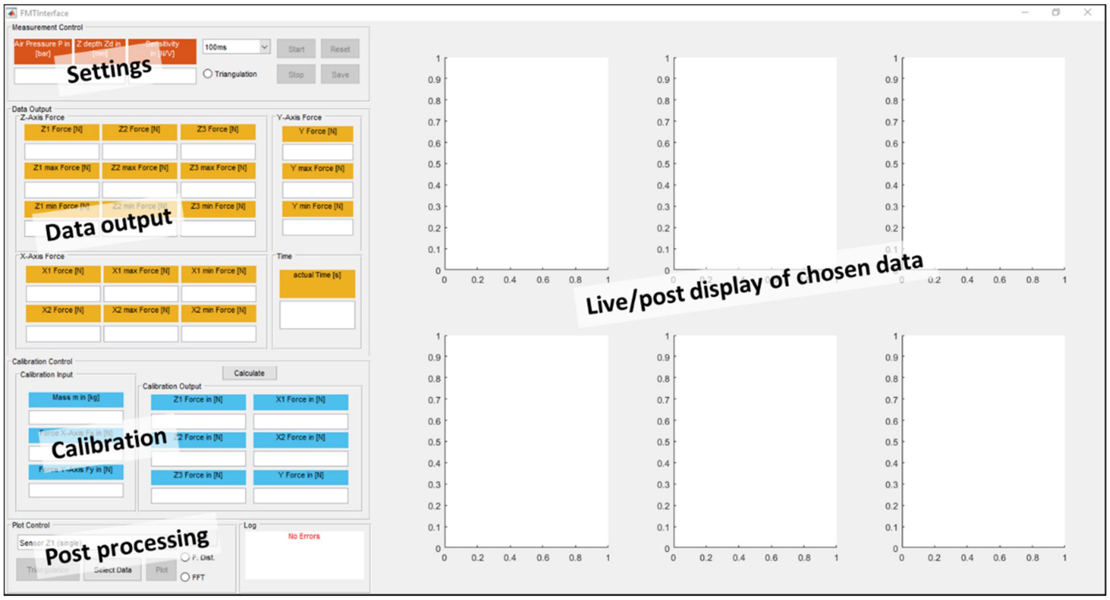


Figure 8: HMI for FMT control and data visualisation.

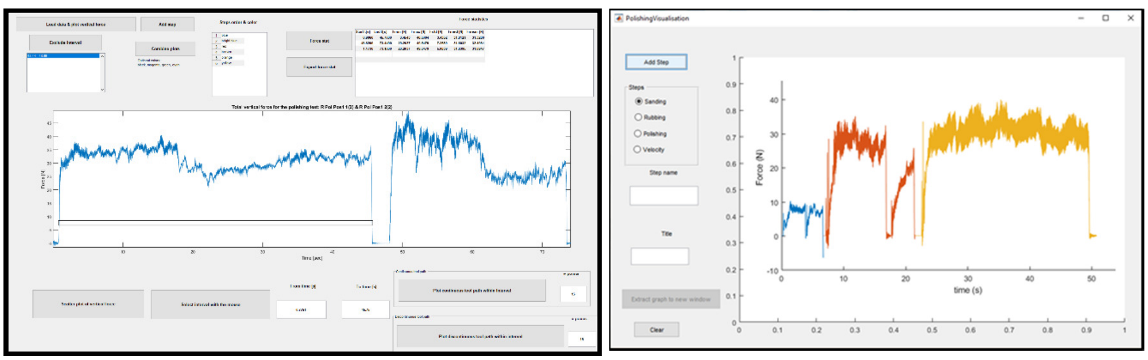


Figure 9: MATLAB applications for force analysis (left), and visualisation (right).

The FMT and Rpm module can, and were, also used to collect data based on manual polishers. The experimental set-up is shown in figure 10; 10 polishers, all working with end-of-line repairs in the production, made four 'repairs' distributed on 2 samples. They were told to do the 'repairs' as they used to do, i.e. sanding, rubbing and polishing. Applied forces, rpm and tool paths were measured continuously. Some polishers comment that the car body feels more flexible and elastic than the sample fixed on the force table, which might have an effect on the results (the substrate was not as 'forgivable' as a car body). Also, they did not have the same lightening conditions as in the production line. However, some polishers were using a handheld lamp (simulating daylight) to ease the visual estimation.

1. Polisher
2. Video recording – paste & tilt
3. Sample mounted on the FMT module - force & tool path recording
4. Rpm module
5. Infrared thermometer – temperature measurements before and after each step
6. Visual estimations made by polisher & in light box

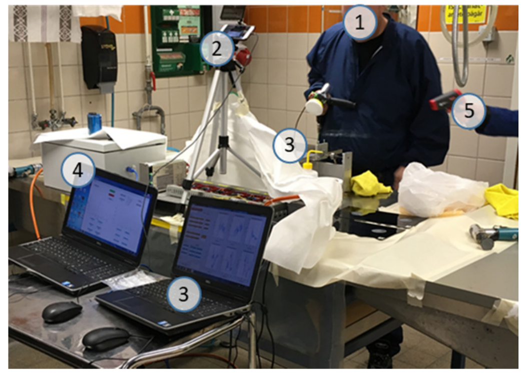


Figure 10: Test set-up at VCC.

Conclusion of results – manual polishing

As expected, the results based on the data collected from manual polishing showed strategy variations, both between different operators, and from operation to operation; table 1 summarizes the test data, figure 11 shows sum-up graphs, one for each step.

Table 1: Summary of the process data based on the manual polishers' strategies.

Step	**Force [N]**	**Time [s]**	**Runs**	**Path**
1 - Sanding (wet/dry)	1-30	2-12	1	Circular
2 – Rubbing	5-60	5-35	1-3	Random / structured
3 - Polishing	5-50	10-50	1-3	Random / structured

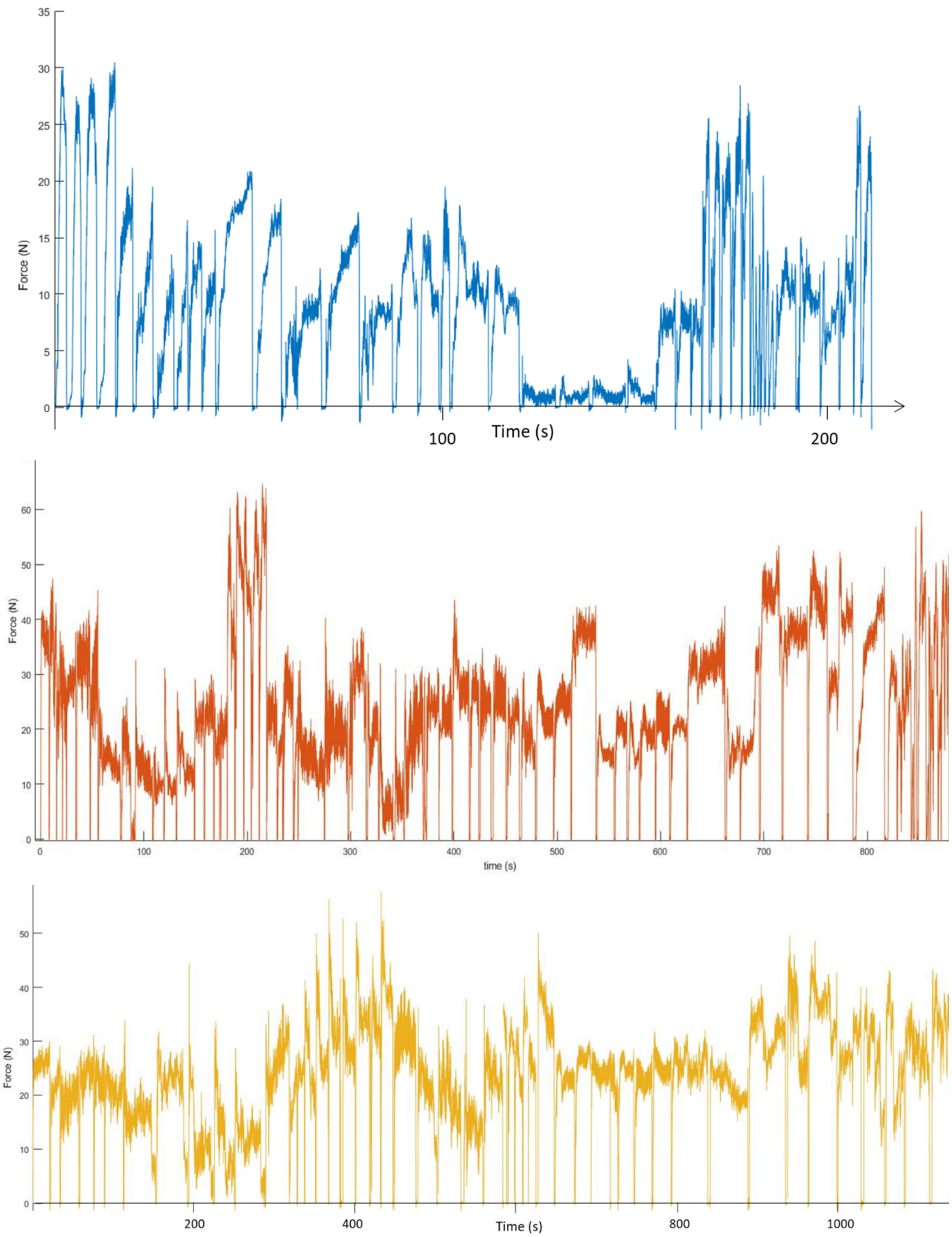


Figure 11: Detected force (N) in z-direction vs. the time (s). Top, Sanding (blue); middle, Rubbing (red); bottom, Polishing (yellow).

The following conclusions were taken into account when the Pol-rig should be tested:

Sanding: short time (5-10 s), low force (ca. 10N) and 'gentle' handling facilitated the avoidance of dents, sharp edges and overheating. As small area as possible should be sanded. The sandpaper shall only be used for 1-2 defects, then replaced with a new one (otherwise it looses its cutting effect due to stuck/gathered residuals).

Rubbing: longer time in combination with higher forces and structured paths (see fig. 12-13) tended to generate better surface finishes, i.e. no visible scratches and polishing roses. Rubbed area should be larger than the sanded area. However, no clear strategy was detected. Both new and old (already used) pads were used; it was claimed by some polishers that the used pads were softer than the new ones (the paste makes the pad wet and bulging, and so softer). Sometimes, the pads were squeezed before usage, also with the purpose to make the pads a bit softer. They also applied various amount of pastes and applied/spread it differently over the substrate and/or pad, but they all polished until the paste has 'converted' into an oily film on the surface. Even though a plane contact between surface and tool was said to be preferable, polishers quite often tilted their tools to easier get rid of sanding marks. Those areas also had a higher frequency of polishing roses.

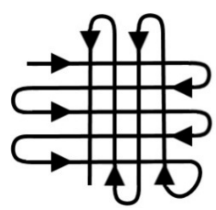


Figure 12: Left, structured path.

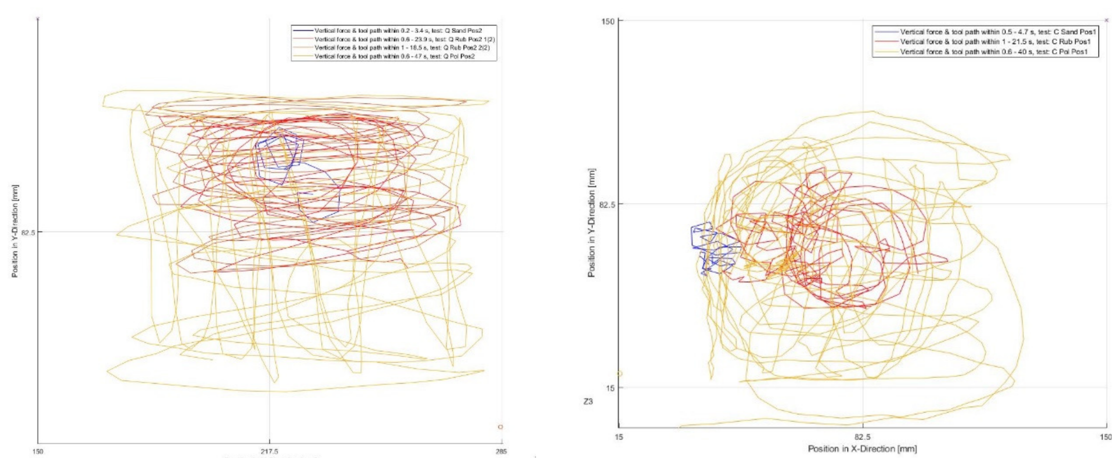


Figure 13: Left, visual estimation OK where the polisher has used a structured path; right, visual estimation NOK where the polisher has used mainly circular motions.

Polishing: longer time than rubbing (too short time lead to polishing roses) in combination with high forces in the beginning and lower ones in the end tend to generate the best surface finishes, i.e. no visible scratches and polishing roses, but no clear strategy was detected. Polished area should be larger than the rubbed area. Some also used non-centred pads.

Conclusion of results – Pol-rig polishing

Conclusions from the analysis of the data from the ten polishing operators were used for setting a process window for the Pol-rig. The area being repaired should be increase between steps, see figure 14. The pad should be kept in contact with the surface during rubbing or polishing to keep the heat, which was assumed to smoothen the coating more efficiently than if it allows to cool down.

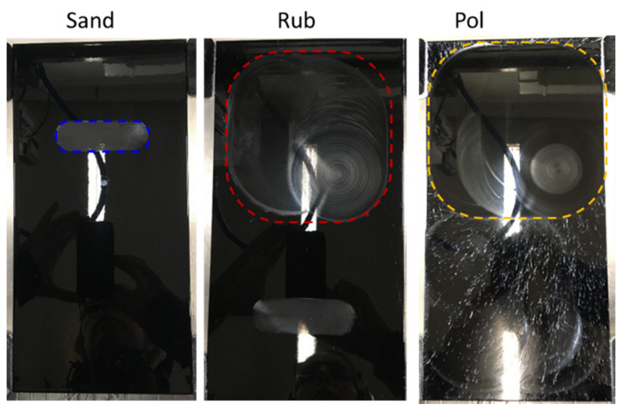


Figure 14: Sanded area < rubbed area < polished area.

Sanding:

A smoother foam than the 'black' one used at VCC shall be used for the sanding to make the process more forgivable to smaller height variations in samples/table. See performed foam tests in Appendix II. Both different line and spiral trajectories were tested, but no major impact could be detected and therefore a line track was used which smoothly get in contact with the surface to lessen sharp marks in the beginning of the track. A new sandpaper shall be used for each area. The pressure should be kept on 6 bars, tool speed 1000mm/min.

Rubbing:

The rubbing step shall remove all sanding marks; a tool speed of 4,000 mm/min speed (kept constant, which can be compared to a constantly variating tool speed applied by the polishers) and a force around 20-25N seemed to generate the best surface quality. Too low forces, below 20 N did not remove the sanding marks efficiently, and too high forces, above 25 N, increased the risk of scratches. A rubbing time of 10s was deemed to be enough (longer times were tested with no significant improvements even though it was recommended to continue the rubbing process for 15-20s to heat up the surface. The temperature measured at the samples after the rubbing tests at VCC showed that the samples rubbed 10s were measured to be as hot as the samples rubbed 20s.). The amount of paste turned only for 10s out to be a critical factor; less than 2ml did not remove the sanding marks, but from 2-6ml no major difference could be detected. Therefore, 2ml paste spread out evenly on a new pad before rubbing is suggested (i.e. 0.2L/m2). Tests of whether there is a difference in softness between new (dry)/old (wet) pads and pads that are squeezed or not were performed, but no significant results were found (see Appendix III).

Polishing:
The polishing step shall bring back the surface into its 'original' surface quality by removing all deeper scratches created in the rubbing step; a tool speed of 4,000 mm/min speed and a beginning force around 35-40N for 20s (for efficient removal of rubbing marks by high dynamic friction) followed by 10-15N for 40s (to further smoothen the surface) seemed to generate the best surface quality. Figure 15 clearly shows how the surface quality got worsen again when the force was increased. A slight shift of the path between every cycle further improved the results, since scratches became more evenly distributed over the surface. 2-3ml paste spread out evenly on a new pad before polishing is suggested; too much paste gave rise to vibrations and scratches, too little was insufficient to remove rubbing marks.

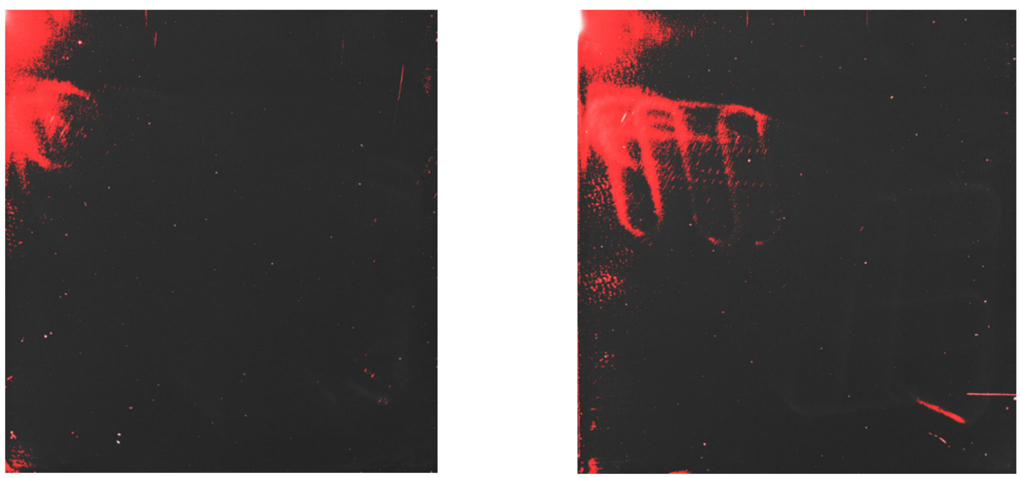


Figure 15: Left, the sample polished by one high force cycle followed by a low force cycle. Right, the same sample after an additional high force cycle was applied.

Since the force is set via the penetration depth, it was vital to know what force corresponded to what penetration depth. However, the measured force differed between a rotating (the foam seemed to be compressed by 1mm) and non-rotating tool, and between a wet (with paste, which made the pad softer) and a dry (no paste) pad, see figure 16. This was probably also the reason to why vibrations sometimes occurred during the polishing operation; the set penetration depth of 1.3mm became nearly zero in reality when the tool was rotating which made it 'jump' over the surface causing the vibrations.

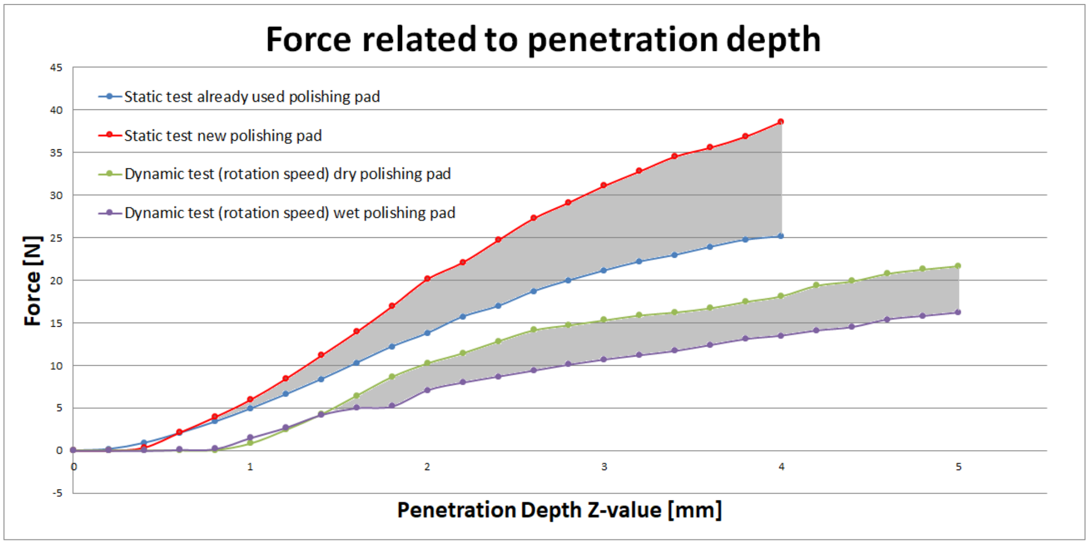


Figure 16: Measured force vs. penetration depth.

The surface quality seemed to worsen over time; panels estimated to be visually acceptable could some days later have a more prominent polishing defect. Tests showed that the cleaning procedure did not have a significant effect, neither had heat (polished samples were heated up in an oven to speed up any evaporation of residuals in the surface). However, the samples were visually estimated to be worse one day after they had been polished, a difference which was also detected by the WMS (see fig. 17). This might be due to a relaxation of the polymer coating after the stress of the polishing process and/or evaporated residues that were not possible to wash away. Wax included in many polishing agents tend to fill up any remaining scratches which lead to visually perceived 'perfect' surfaces [12].

Figure 17: Left, the sample directly after it has been polished. Mid, the same sample 1 day later. Right, the same sample 4 days later.

6.3 Model of the polishing mechanisms

The scratch analysis (see fig. 18-19) showed that the accepted area had fewer and smaller grooves than the unaccepted one. Additional samples confirmed that the no. of grooves correlated well to perceived surface quality, see figure 20. Higher enough forces were needed to get rid of scratches, but the most critical factor seemed to be applied tool pattern and the amount of paste – too much paste and only circular tool movements seemed to be devastating for the polishing result.

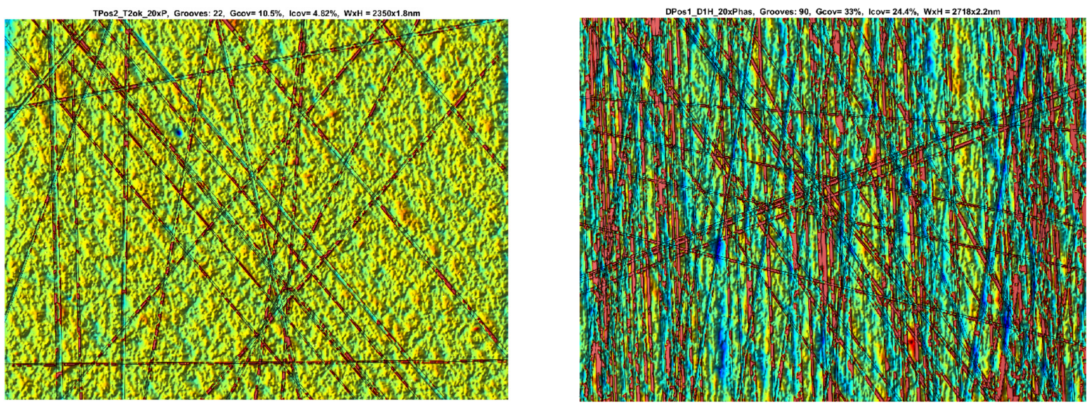


Figure 18: Scratch analysis of the accepted area (left) and unaccepted area (right); area: 0.3x0.4 mm.

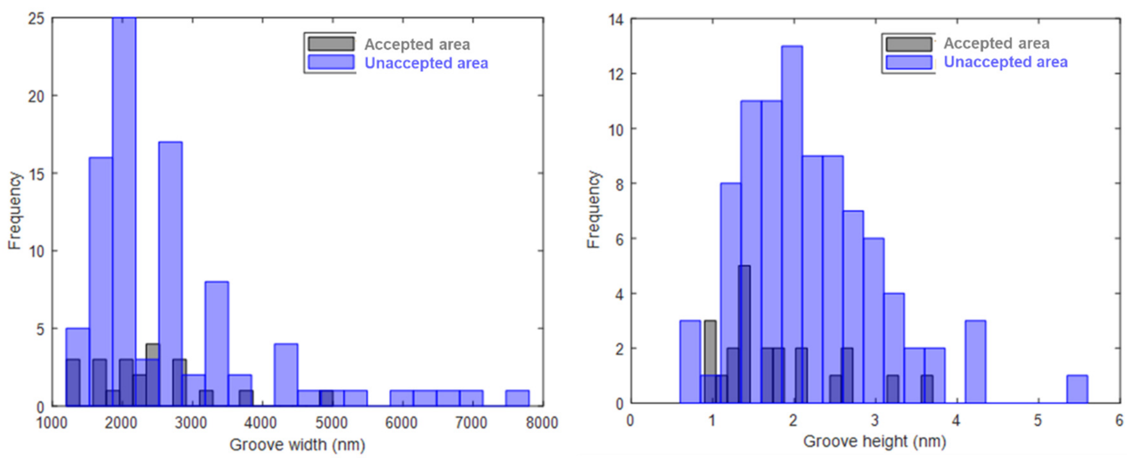


Figure 19: Accepted area (grey) showed a smaller number of grooves as well as smaller groove width and groove height than the unaccepted one (purple).

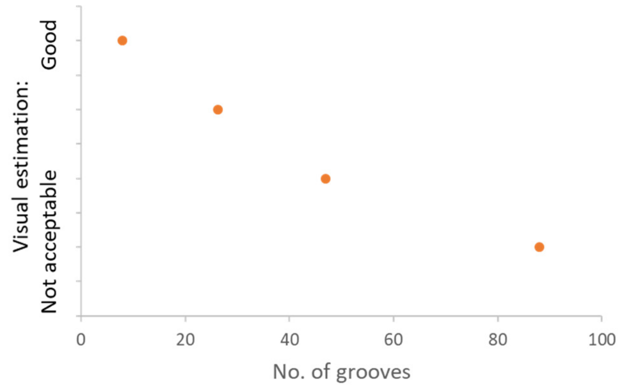


Figure 20: Visual estimation vs. calculated no. of grooves.

Tests in the Pol-rig confirmed these results; apply the right amount of paste on a fresh pad, keep the pad in contact with the surface, and do shift the structured tool path between each 'cycle' (see fig. 21). Also, to apply a higher force in the beginning of the polishing step followed by a longer time of low force polishing seemed to be preferable.

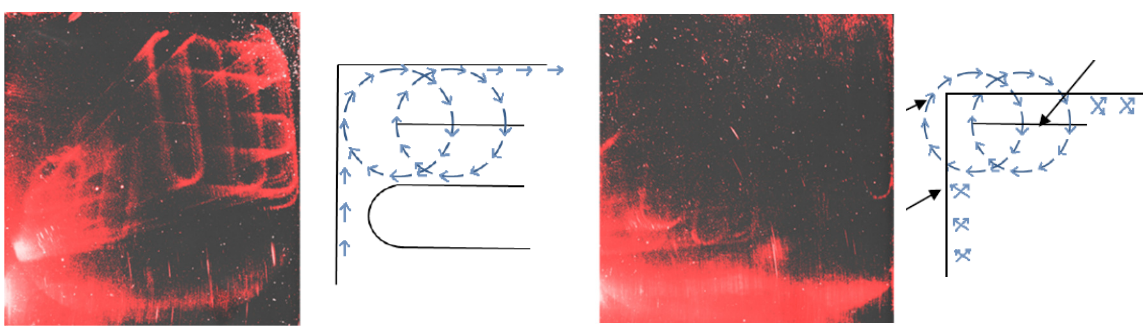


Figure 21: Left, sample with visible defects and its trajectory which is kept within the sample area. Right, sample without visible defects and its trajectory where the outer part of the pad passes outside the sample area.

The hardness of the coating affect the results; hardness tests (Pendulum hardness, König; 6° to 3°) showed that two of the tested coatings had small hardness variation over time (30min-10days). Soft coatings do need other pads and lower forces, which also might be applicable for coatings polished before 30 min after painting (i.e. if they behave softer). One way to achieve a more forgivable polishing is to use softer foams that absorb unintentionally high force application.

6.4 Academic merit

Sabina Rebeggiani is expected to build her docent application, within the field of functional surfaces with focus on polishing and surface finish of coatings, based on articles written within the project. Jonas Mazal quit the job at HH 2017.

6.5 Goal fulfillment

The project was mainly expected to contribute to one of the goals for the sub-program – Surface treatment and painting, which has been done by the development of equipment and test routines to evaluate the polishability of new paint systems. The work has formed the basis for further development within this area, i.e. to create a working industry standard for verification of polishability of coatings.
The cooperation between Halmstad University, Volvo cars, AB Volvo and Beckers, had strengthened the collaboration between academia, vehicle manufacturers and paint manufacturers, and opened up for future further collaborations. Also production personnel have participated in activities within the project and have contributed with their knowledge into the project.

7. Dissemination and publications

7.1 Dissemination

How are the project results planned to be used and disseminated?	Mark with X	Comment
Increase knowledge in the field	X	Seminars within the project and together with operators at VCC, and further testing based on the Pol-rig.
Be passed on to other advanced technological development projects	X	FMT used for metal polishing (within SYMPLEXITY); up-coming applications within the field of polishing will take advantage of the developed equipment.
Be passed on to product development projects	X	Development of internal way of working for verification of polishability of coatings.
Introduced on the market		
Used in investigations / regulatory / licensing / political decisions		

7.2 Publications

14 students (from France, Germany and Belgium) have done their internship period linked to this project, which all ended up in reports summarizing their works.

One abstract was presented by a poster (won Best poster award!) at the conference MetProps17 in Gothenburg in June 2017, and was later published in *Surface Topography: Metrology and Properties* (Rebeggiani et al 2018 *Surf. Topogr.: Metrol. Prop.* https://doi.org/10.1088/2051-672X/aabfb5).

Two abstracts were sent to MetProps19 in Lyon; one was presented as a poster, the other was cancelled due to sick leave. Both will be rewritten and sent in to upcoming conferences/journals.

8. Conclusions and future research

A method to test the polishability of coating systems was developed. The equipment, a built up CNC-machine with stand-alone modules for force and rpm measurements, enabled repeatable test procedures for structural and objective evaluations of coating systems. Collected data from professional polishers' formed the base for tested polishing strategies on the Pol-rig. The next step would be to create a working industry standard for verification of polishability of coatings and different polishing equipment based on the findings in this project combined with new tests. In the long run, when findings regarding polishing parameters effect on the final result is communicated and implemented in production, the amount of defects is expected to be diminished and less paint rework should be required.

The developed WMS system seemed to be a promising technique to detect and analyse polishing roses. The results correlated well to human visual estimations; the defects faded out with increasing angle which correspond to the visual estimation criterions clarity and angle. The size of the polishing roses, calculated as defective area, correlated to the severity of the defect. The system is also quite fast (almost real- time capability) and has a relatively large measurement area (205x205 mm). Further, the method for scratch analysis was successfully adapted to polished samples, and it could be concluded that accepted areas had fewer and smaller grooves than unaccepted ones and that higher forces in combination with a cross pattern tool movement and an appropriate amount of paste seemed to be preferable. It was also noticed that surface quality varied over time, a phenomenon that needs to be further investigated.

The cooperation between Halmstad University, Volvo cars, AB Volvo and Beckers, had strengthened the collaboration between academia, vehicle manufacturers and paint manufacturers, and opened up for future further collaborations.

9. Participating parties and contact persons

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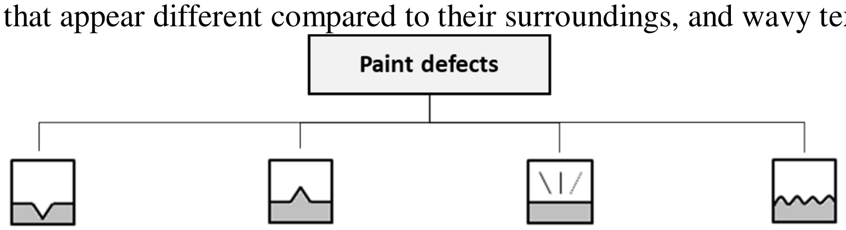
11. Appendix I-III

Appendix I - Literature study

The literature study was part of WP1 and will cover: terminology and definitions of relevant paint defects; a sum-up of found literature within metrology, and analysis and perceived surface quality of painted/coated OEM part surfaces (i.e. a complement to the pre-study).

Paint defects

Paint defects is a broad expression for all kinds of coating damages on vehicles, in factory as well as for the after-market. Figure I-1 is an attempt to divide the defects into different categories; vertically three groups based on when the damage has occurred (during the painting process, in-line repair or when the vehicles have left the factory, i.e. in service), and laterally four groups based on the type of damage (inwardly and outwardly directed defects, areas that appear different compared to their surroundings, and wavy textures).



Paint shop	- Defects occurred during the surface preparation/coating process; commonly blistering, mottling, dust contamination, orange peel, and loss of gloss			
In-line repair	- Hole - Dent - Polishing roses/ Hologram - Scratches	- Deposits	- Glossy area - Haze - Discoloration - Burn marks	
Environment / Service	- Defects occurred during usage, i.e. when the vehicle has left the factory; swirl marks, deep scratches, bird droppings, and colour fade			

Figure I-1: Proposed classification for polishing defects on painted exterior surfaces, adapted from [1].

This project only focused on the ‘in-line repair’ induced defects, which are sparsely discussed in research papers where focus more often seems to be ‘environmental’ induced defects, such as swirl marks or weather caused surface damage. However, [2] discuss the topic and the degree of surface damage is divided into three categories: sand scratches – ‘marks produced during the initial stage of defect removal from clearcoat’, swirl marks – ‘3D holographic circular marks typically produced…during the removal of sand scratches’, and haze – ‘milky appearance…produced by incomplete random orbital buffing’. No links between the degree of surface damage, visual appearance and surface topography are made, but they show how the surface topography typically change during a three step repair process, see figure I-2.

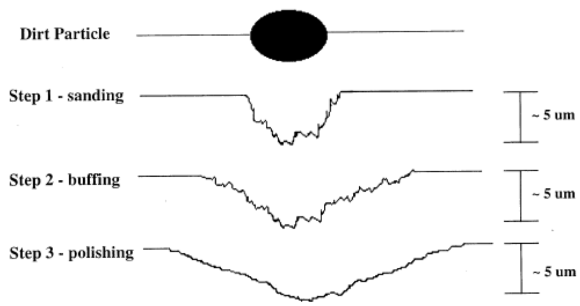


Figure I-2: Sketch of a 'Typical topography of the Finesse Process' [2].

Table I-1 lists the defects occurred during/after the in-line repair, presenting used terminology and a description of them.

Table I-1: List of relevant defects and their description.

Defect	Description
Hole	Small cavity (typically in the um-range) Commonly caused by torn out particles or layer penetration
Dent	Cavity (typically in the mm-range) Caused by too rough sanding, i.e. the tool hit the surface too hard (so called '*klossning*')
Polishing rose (Hologram)	Pattern/cluster of shallow micro scratches, which under certain lightening conditions create a three dimensional appearance (i.e. it moves when viewed from different angles similar to a hologram). Commonly caused by an improper final polishing step
Scratches	Random and isolated deeper grooves ('deep enough to see, but not deep enough to feel') Commonly caused by remaining abrasives or other unwanted particles
Deposits	Residue of polishing and/or cleaning solution
Glossy area	Local areas with higher gloss than the surrounding Commonly caused by topographical or thickness variations (40 ± 5 µm)
Haze	Local areas with lower gloss than the surrounding (matte appearance), sometimes visible only in certain lightening conditions but in most angles
Discoloration	I. Grey film (spec. on black solid) II. White spots (spec. blue & grey colours)
Burn marks	Physical/chemical destruction Commonly caused by too high temperatures

Commercial measurement devices

Commercial instruments for in-line control of surface appearance quality (mainly before any in-line repair) can be found on the market. E.g. [3-6], all based on the deflectometry principle, claiming to be able to detect low to high frequency defects (i.e. shape, waviness, roughness and local defects like pits and dust particles down to 10 um). Table I-2 summarises a selection of other types of measurement devices that could also be of interest in order to measure, estimate, and characterise repaired areas, for in-line inspection as well as for lab environment. For visual inspections a defined viewing distance and/or angle to the object, as well as a defined light source, e.g. D65* simulating daylight or fluorescent lighting, are commonly used. The PPS Colour Check Light from 3M is one example of a portable light source mimicking day light developed to identify polishing defects like holograms and swirl marks [7].

Table I-2: A selection of different types of measurement devises relevant for the topic.

Company: Instrument/s	Technique &/or output	Application	Reference
BYK Gardner: Appearance & color measurement devices	*Hazemeters* - GU: 20/60/85° and haze *Wave-scan* - Structure spectrum (<0.1 to 30 mm) *Mottlingmeter* - simulates visual evaluation under different observing angles *Spectrophotometer* - Colour values (45° illumination): -15°, 15°, 25°, 45°, 75°, 110°	Micro structures, like haze & glossiness; brilliance & smoothness; paint defect of lightness variations; lightness &/or colour	[8]
Konica Minolta: Colour and gloss measurement devices	*Spectrophotometer* (e.g. CM-512m^{3}A) – Colour values (25°, 45° & 75° illumination): 0° *Glossmeter* (e.g. Rhopoint iQ) - GU: 20/60/85° & haze, DOI etc.	Spec. for metallic/pearl coatings; microscopic textures or residue on a surface, like halos, polishing marks and poor cleanliness/surface residue	[9]
STIL: REFLET & DIAMOND	*Goniophotometers* - measures back- and forward scattered light	Surface quality, e.g. texture & roughness	[10]
QISAB: CWS – Coherent Wave Scatter System	Laser coherent scattering – e.g. Gaussian (dB) directly correlated to Sq, gloss (dB)	Surface quality, e.g. texture & roughness	[11]
Accurion: e.g. nanofilm_ep4	Ellipsometry (analysis of the polarization state of reflected light) - film thickness, refractive index and absorption.	Thin film characterization	[12]
ADE Phase Shift Technology: MicroXAM 100-HR	*Interferometer* - surface roughness parameters down to nm level	Lab-environment analysis of surface topography	[13]

*D65: ISO 10526:2007 (CIE S 014-2/E:2006). CIE standard illuminants for colorimetry

Other references to measurement solutions, mainly colour, gloss/haze and appearance:
Tricor systems Inc. www.tricor-systems.com/products/surface-analysis.htm [Accessed 27/11/13].
HunterLab Inc. www.hunterlab.com/coating-color-measurement.html [Accessed 27/11/13].
Murakami Color Research Laboratory. www.mcrl.co.jp/english/ [Accessed 27/11/13].

Methodology for quantitative surface assessment

In production the area being subjected to sanding/polishing are frequently inspected by the polishers; the actual area is cleaned and the effect of the polishing action is evaluated visually (no marks from previous steps should be visible in certain light conditions and viewing angles). In lab environments more stable conditions for surface assessments can be built up, sample shape and dimensions as well as lightening conditions and viewing angle can be defined. And, theoretically, any kind of suitable measurement instruments could be used to detect and quantify surface quality. However, commercial instruments seem to be sparsely used, instead in-house defined procedures are used, e.g. including set-up, lightening and viewing angles, and internally developed surface quality scales.

This means that the surface assessment in both production and R&D suffers from its subjectivity while it relies on human perception (and in production also the available lightening conditions). However, objective inspection systems, if they are quick enough, also have drawbacks, as discussed in [14]: 'An objective system provides one expert opinion that everyone can agree upon. …The methodology for quantifying defects should be the same for any type of defects, but the filtering scheme, thresholds, and characteristics used to quantify the severity of the defect may differ. …the problem lies in extracting useful numerical data that allows the severity of defects to be quantified and correlated to the visual defect.' This link between the visual perception and the measured surface data is further discussed below.

Visual perception and surface measurement data

Surface information can be captured in different ways, e.g. by focusing on the surface or the reflected surface image (see figure I-3), or by tactile techniques. The reflected image gives the so called image forming qualities (optical properties), i.e. the overall impression of the surface quality in terms of e.g. brilliance, gloss and blurriness. Tactile techniques and those focusing on the surface give more quantitative data, such as size, depth and shape of the surface structure [15].

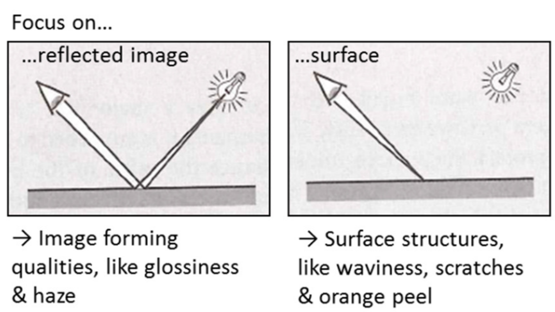


Figure I-3: Surface information captured with the surface in focus differs from data captured based on the reflected image, adapted from [15].

Several attempts have been made to overcome the subjectivity of visual estimations in order to establish a well-functional quantification system for surface inspections. See e.g.:

- [16-17] mainly based on the wave-scan DOI instrument (BYK-Gardner) developed to measure *waviness*, '*distinctness of image*' (DOI), and '*dullness*' (the ratio between 'the amount of light scattering within and outside the aperture in a defined range'), i.e. structure sizes between 0.1 to 30 mm, and light scattering caused by structure sizes < 0.1 mm. The relationship between visually perceived and instrumentally measured appearance of coated surfaces was investigated; both dark and light coloured samples were included. It was concluded that the measured parameters were strongly correlated to the human perception of the light coloured samples, but only a moderate correlation was found for the darker ones [17-18].
- [19] where they are using the Ra and Rz parameters (the arithmetic mean deviation and the maximum height of the roughness profile, respectively), based on interferometric measurements, to be able to compare the surface quality of samples polished by their own developed polishing machine mimicking manual polisher's strategies [20] to the manual

polisher's output. The criteria for surface quality after finishing are stated to be Ra 30 nm and Rz 60 nm, no discussions regarding any visual appearance are made.

- [21] discuss the problems to convert measured data to numerical parameters describing the degree of human perception of 'cosmetic defects', including
  - [22] where a method to quantify the visibility of a scratch on a polymer surface is presented.
  - [23] who developed a new approach to investigate any correlations between visually perceived estimations and instrumentally measured appearance of coated surfaces.
  - [24] where the relationship between scratch visibility and scratch deformation mechanisms are studied to develop a quantitative evaluation method for polymer surfaces.
- [2] used a goniophotometer to evaluate manually as well as machine polished samples (own developed polishing machine). Reflectance measurements (angle of 30 degrees) were taken into account to study the overall scratch level, and it was concluded that the surface quality varied more between the manually polished samples compared to the machined polished ones. Further, a 'Swirl Rating Scale' from 1 – the best, to 10 – the worst, based on visual estimations and ranking of test panels, was developed but not linked to the goniophotometer measurements.
- [25] suggests a model to predict the surface appearance of effect coatings by one gloss and three colorimetric values (also a summary of standards for measurements of pigmented paints is included in this article).

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Appendix II

The relatively stiff black foam used at VCC made it hard to control the sanding force on the Pol-rig due to small height differences of sample/table. Therefore, different foams were tested by increasing the penetration depth with 0.1 mm every minute; the resulting force was recorded before the tool was removed from the surface before the next measurement. The results can be seen in figure II-1; it is clear that the black foam gave a much smaller height range within the desirable force span of 10-12 N.

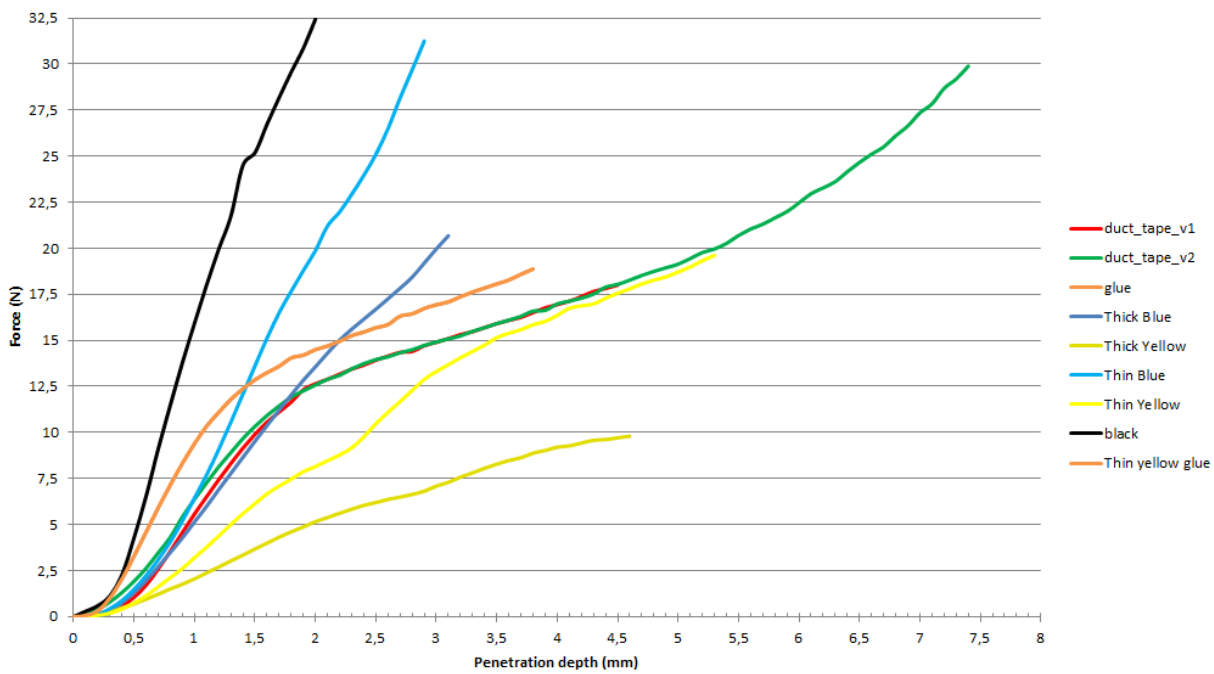

Figure II-1: Measured force (z-dir.) vs. penetration depth.

Appendix III

Tests performed to measure any change of the rub pad softness before/after paste application, and before/after it has been squeezed. As can be seen in figure III-1, no significant differences were detected.

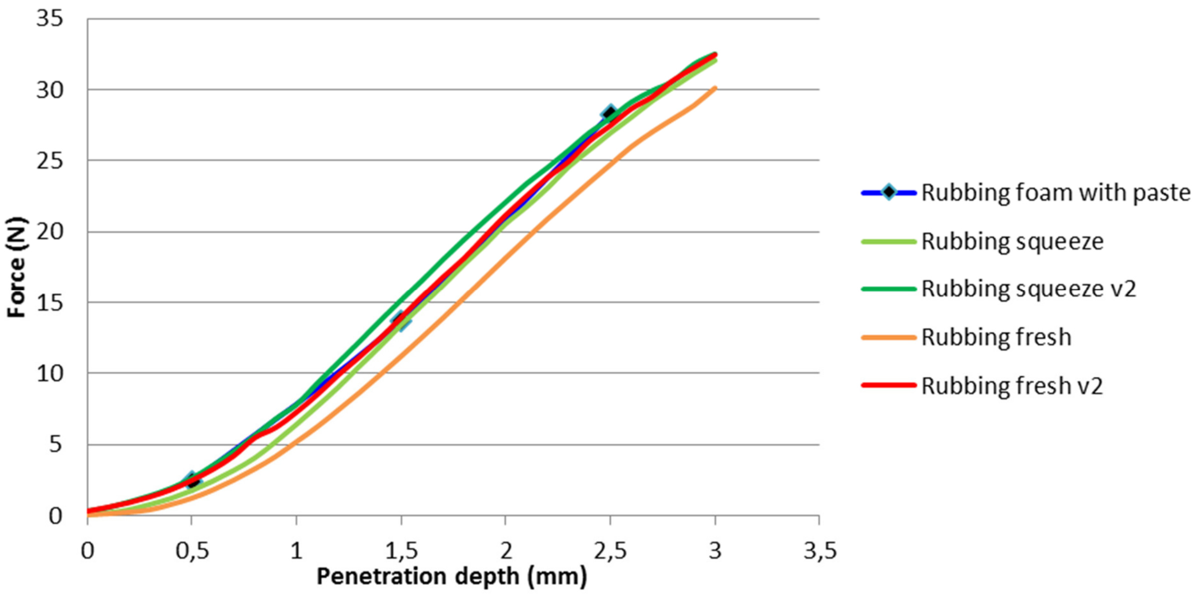

Figure III-1: Measured force (z-dir.) vs. penetration depth.