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Material removal simulation for steel mould polishing

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ABSTRACT
The surface finish of an injection mould influences the quality of the moulded polymer optic parts. In order to improve and control the surface finish of the mould it is important to be able to predict the material removal during the polishing process of this mould. The aim of this work is to predict the material removal during the polishing process, comparing the results obtained from polishing attempts on steel samples and the results obtained from a simulation model. A simulation model is developed with the abrasive wear Holm-Archard equation in ANSYS. This simulation model will help to eliminate the iterative trial and error polishing, therefore facilitating the steel mould production.

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KEYWORDS
Steel mould polishing; material removal; FEM simulation

1. Introduction

Plastic injection moulding is a manufacturing process, where melted plastic is injected into a mould and parts can be produced. The geometry of the produced parts is given by the used mould. Most of the produced parts use, for their production, a steel mould tool. The steel material of the mould needs to have unique and specific demands (Uddeholm, 2014). Easily machined and polished, stable during heat treatments and free of defects are just some of them. The surface quality and shape deviation of the steel mould influence the quality of the moulded parts as stated by (Speich & Börret, 2011). The polishing process is still responsible for 30% of the total mould price as mentioned by (Uddeholm, 2014). This is due to the fact that steel moulds are still polished by hand as stated by (Börret, Klingenmaier, Berger, & Frick, 2008). To reduce the costs of the polishing process on moulds production, robot polishing is now starting to be more used as it brings more stability and reproduction to the moulds (Speich, Börret, Harrison, & DeSilva, 2013).

However, robot polishing is still a new field that requires further investigation in order to totally replace hand polishing. There are still some unknown factors as the current robot polishing process consists of eight to fourteen different polishing parameters as mentioned

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by (Speich, Rimkus, Börret, & Harrison, 2012). The variation of these polishing parameters affect the final quality of the surface as it produces different surface roughness and material removal rates. The investigation of the material removal is continued from the previous work conducted on plastic samples (Almeida, Börret, Rimkus, Harrison, & DeSilva, 2015), but now on steel samples. The simulation of the robot polishing process can help correcting the geometrical shape of steel moulds using robot polishing. This will reduce mould production costs and will guarantee the right surface roughness, and shape deviations of the mould.

2. Identification of the problem

The mould making process is a very demanding process, for the produced parts to achieve the required client's tolerances and specifications. To reduce the manufacturing time of a produced a part, it is therefore necessary to optimize the moulds used in the plastic injection moulding. This will make an after work or correction of the produced parts much shorter or even unnecessary. Figure 1 shows on the left a convex steel mould after being milled with a 200 nm surface roughness and a shape deviation of 20 μm. Figure 1 on the right shows the spherical mould after the robot polishing process done in the Centre for Optical Technologies. This polishing process could improve the surface roughness to 3 nm and the shape deviation to approximately 4 μm.

However the shape deviation of 4 μm for some applications is not good enough due to problems of focus of light sources. Nowadays there are precise HSC milling machines able to mill a workpiece, where the surface parameters are extremely good to start the polishing process. Figure 2 shows a tactile measurement of two convex steel samples milled using a HSC machine. Depending on the tool path and on the milling parameters used, different shape deviation were achieved. The left illustration shows the measurement of the steel sample, where a spiral tool path was used and a shape deviation of 11.8 μm was obtained. The right illustration the measurement of another steel sample, where a linear tool path was used and a shape deviation of 8.3 μm was achieved.

This being said, it is nowadays possible to obtain a much better geometrical form, even before the polishing process, by using an HSC machine, which makes this research even more interesting. The goal is to be able to go even further and with these good starting

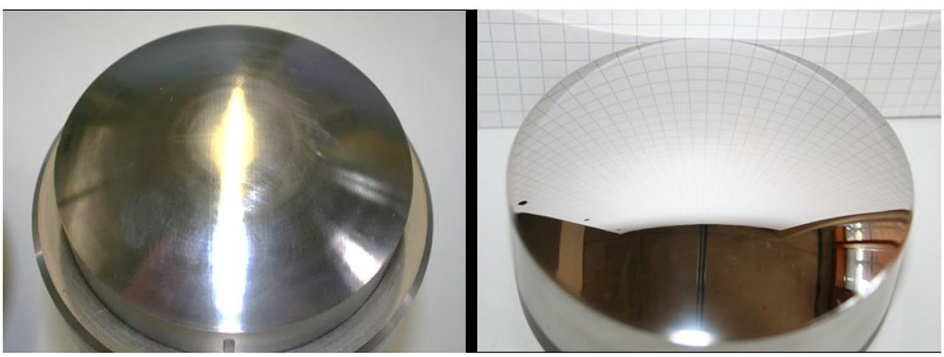

Figure 1. Convex steel mould.
Notes: The left illustration shows a convex steel sample after being milled with 200 nm surface roughness and a shape deviation of 20 μm; the right illustration shows the same convex steel sample after the robot polishing process with an improved surface of 3 nm surface roughness and a shape deviation of 4 μm

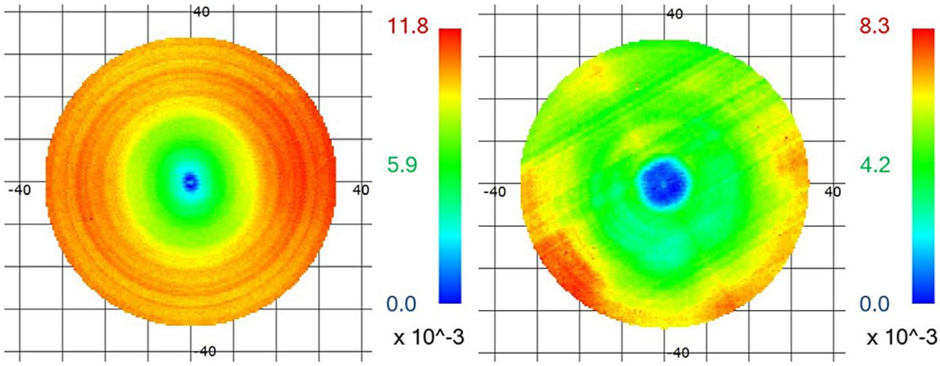

Figure 2. Geometrical shape deviations using different tool paths.
Notes: The left illustration shows a convex steel sample after being milled with a shape deviation of 11.8 μm; the right illustration shows the another convex steel sample after being milled with a shape deviation of 8.3μm.

parameters, to control and manipulate the material removal, therefore controlling the shape deviation and improving it.

The objective of this work is to predict the material removal during robot polishing on steel samples. For this reason a simulation model was developed using the Finite Element Method software ANSYS. This simulation model should be able to predict the material removal during robot polishing upon variation of the polishing parameters. The abrasive wear Holm-Archard equation was implemented with the help of ANSYS's APDL code to simulate the material removal. In the pad polishing process the material removal occurs due to the contact of the hard abrasive grains from the polishing suspension with the surface. This contact results in the wear of the sample's surface. The simulation of the robot polishing process is not evolved as the simulation of other manufacturing process. A few simulation models were developed to simulate the polishing process but none was found which was able to accurately in a nanometer range predict the material removal. This work will help to get a better understanding about the polishing process, simulating the material removal that happens during this manufacturing process.

3. Theory of abrasive wear

The polishing process is a manufacturing process that exists for a long time (Hwa & Miller, 1999). It is used to enhance the brightness, colour, reflectivity and elegance of certain objects, reducing the surface roughness so that present scratches are no longer visible to the human eye. This manufacturing process allows surfaces to achieve a surface roughness of less than one nanometre and shape accuracies in the nanometre range, which is why this process is still used nowadays as a finishing technique.

Regarding the attainable surface roughness in dependence of the material removal the abrasive polishing process is one of the most effective ones. The abrasive polishing is also one of the most effective polishing processes available to obtain smoother surfaces (Brinksmeier, Riemer, & Gessenharter, 2006). During the abrasive polishing process it is assumed, that the material removal occurs predominantly due to the abrasive wear. The abrasive wear occurs when two bodies with substantially different hardness are in contact or the intermediate layer contains hard particles, in our case the polishing suspension.

The Holm-Archard Equation (1) is a mathematical approach that describes the generated wear between two bodies touching each other. The equation describes that the removed volume V is proportional to the distance travelled S and to the normal force F_n. The hardness H of the material is inversely proportional to the removed volume. The wear coefficient K represents all tribological properties of the contact pair present. The Preston Equation (2) is another mathematical approach used to predict the material removal during the polishing process of glass samples. This equation says that the material removal rate is proportional to the contact pressure p, the relative velocity V_r and the Preston coefficient K_p. In the Preston coefficient are all the tribological properties of the contact whereas K_p inherits all tribological properties of the two bodies in contact.

$$V = \frac{K}{H} \times F_n \times S \tag{1}$$

$$\frac{dz}{dt} = K_p \times p \times V_r \tag{2}$$

After the statements above it can be seen that both equations have some similarities. This research investigates the polishing process of steel surfaces using an abrasive grain suspension together with its abrasive wear mechanism. In the developed simulation model, the Holm-Archard equation is implemented, simulating the same mechanism as in the polishing attempts.

4. Polishing attempts using robot polishing

4.1. Experimental method

The investigation of the material removal continued, from the previous work on plastic samples (Almeida et al., 2015), on steel samples. The stainless steel A506 was used to conduct polishing attempts and investigate the material removal during the polishing process. The samples were milled with a standard configuration used in the centre for optical technologies, in order to be able to fix them during the polishing attempts and measurements. This increased the accuracy of the results because the samples were always on the same adapter during the polishing attempts and during the measurements.

To be able to measure the different polishing attempts, the workpieces needed to be able to reflect the light beam from the optical measuring machine. The optical measuring method was chosen because measurements in between the polishing attempts could be done faster than using the tactile measuring method. This is why after the grinding process the work pieces needed to be prepared, using the lapping process to produce a smooth surface. The optical measuring machine used to measure the material removal obtained in the steel samples was the interferometer Schneider ALI 201. For the lapping process, a lever arm polishing machine was used. In order to have the same initial conditions in the beginning of each polishing attempt, the out-coming surface roughness of lapping process was controlled. The goal was to obtain, through the lapping process, approximately the same surface roughness on every single steel sample. For this purpose three points were measured arbitrarily proving the homogenous distribution of the surface roughness over the steel sample. For the surface roughness control a white light micro interferometer was used. The measuring field size used in the white light micro interferometer was 4.94 × 3.70 mm. Figure 3 shows the measurements conducted before and after the lapping/preparation step.

The following Table 1 shows the different surface roughness in the initial stage of the ground samples and in the final stage after the lapping process. This preparation step assured that the surface initial conditions during the polishing attempts were as constant as possible.

The polishing attempts were conducted on the steel samples using an industrial robot 'ABB IRB 2400'. For the polishing attempts of the material removal on steel samples a single path was continuously polished forward and backwards using a flat polishing tool. The flat polishing tool guaranteed the full contact between tool and workpiece. The purpose of the single polishing path procedure was to obtain material removal on the steel sample in order to predict the removal rate. The polishing attempts were done using a polishing pad made of GR-35 polyurethane material and a foam layer made of Sylodyn ND material. Figure 4 shows the polishing tool and the workpiece during the experiments.

To begin the material removal polishing attempts the force applied to the polishing tool was varied. The expectation of the material removal's depth is that it increases proportionally with the force applied to the polishing tool, as already stated by Preston and from the Holm-Archard equation. This means that with double the applied force, the depth of the material removal is increased by a factor of two. The polishing parameters used during the polishing attempts are shown in Table 2.

4.2. Determination of material properties for the FEM model

In order to obtain a realistic simulation model developed in the FEM program ANSYS, some material properties need to be known and some experiments needed to be done. Some of these material properties could simply be obtained from datasheets, while others required

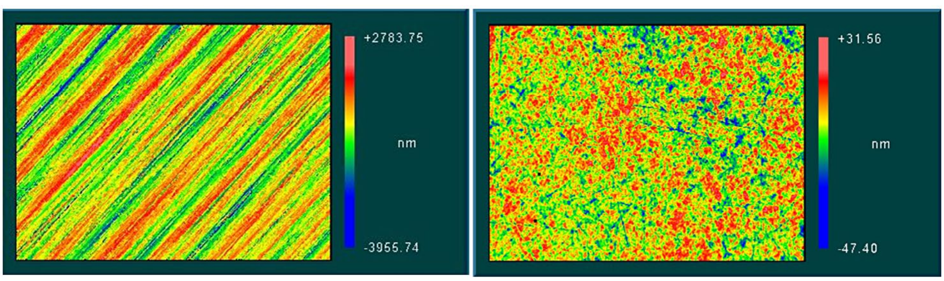

Figure 3. The left illustration shows the steel surface after the grinding process.
Note: The right illustration shows the steel surface after the lapping process and ready for the polishing attempts.

Table 1. Surface roughness control of the lapped steel samples.

Surface roughness	Sample 1 (Ground)			Sample 2 (Lapped)			Sample 3 (Lapped)		
Measurement	1	2	3	1	2	3	1	2	3
PV-Value (nm)	6738	9507	10,170	121	378	104	141	96	75
RMS-Value (nm)	795	749	1055	9	7	8	9	9	8
Ra-Value (nm)	630	598	876	7	5	6	7	7	6

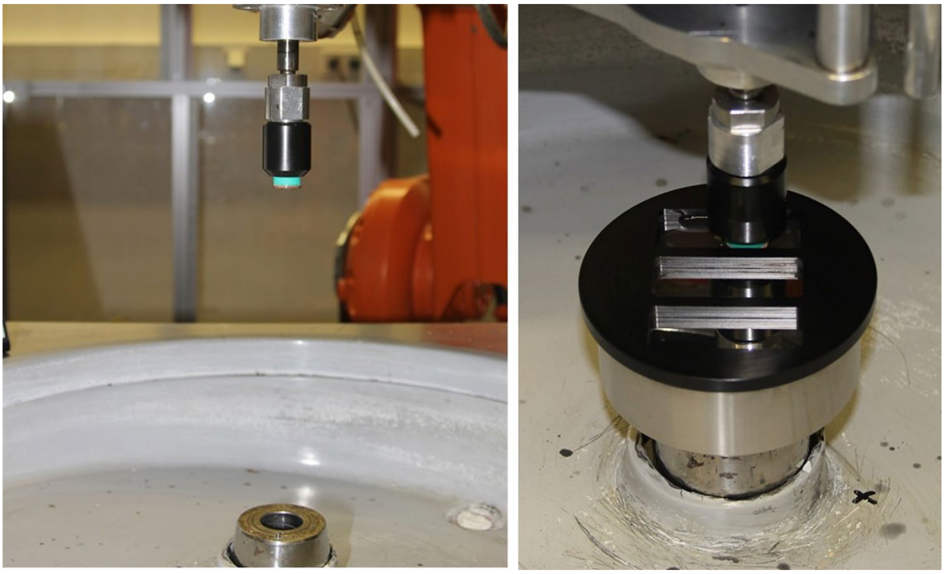

Figure 4. Material removal polishing attempts showing the polishing tool and the workpiece.

Table 2. Polishing parameters used during the polishing attempts on steel samples.

Force of the polishing tool	5 N, 10 N, 15 N
Rotation speed of the polishing tool	300 rpm
Feed of the polishing tool	15 mm/s
Polishing tool diameter	16 mm
Number of polishing paths	600 times
Polishing suspension	6–12 µm
Optical measurements	Every 100 paths

some experimental tests. For this purpose, the material properties for the polishing pad GR-35 and for the steel samples A506 needed to be known. The two more relevant material properties that needed to be obtained through experiments were the hardness of the steel material and the wear coefficient.

The hardness of the steel work pieces was necessary for the implementation of the Holm-Archard equation in the simulation model. In the laboratories of the Aalen University the Vickers hardness of the two A506 steel samples (Ø 90 × 35 mm) was measured. On each sample, three measurements were conducted inwards from the outside. With the six measurements, it was concluded that the hardness values on the outside were higher than the values in the centre. It was concluded that the hardness value on the outside was around 240 HV 10 and on the inside around 190 HV 10. The average value of the six measurements of the two A506 samples was 211 HV 10.

The determination of the wear coefficient was the most important experiment in order to obtain a realistic wear FEM simulation model. The purpose of this experiment was to evaluate a certain wear volume, which could be used to determine the wear coefficient via the Holm Archard equation. To produce this wear volume a stipulated number of polishing paths was done. The difference between the wear coefficient experiment and the polishing attempts was, that for the determination of the wear coefficient the polishing tool had no rotation speed. Due to the non-rotating polishing tool, the workpiece surface was more scratched compared to the surface where the polishing tool was rotating. Figure 5 shows two polishing paths, which were done using a rotating polishing tool, and one polishing path with a non-rotating polishing tool.

Figure 6 shows different types of material removal mechanisms during the polishing process. It was assumed that during the wear coefficient experiment the abrasive grains have been embedded into the polishing pad. The abrasive grains move repeatedly over the surface causing grooves, which in the end of the experiment lead to an extremely deep groove formation in the workpiece surface. This did not occur with a rotating polishing tool during the polishing attempts. It was assumed that the grains rolled between the polishing pad and the work piece, generating smoother surfaces.

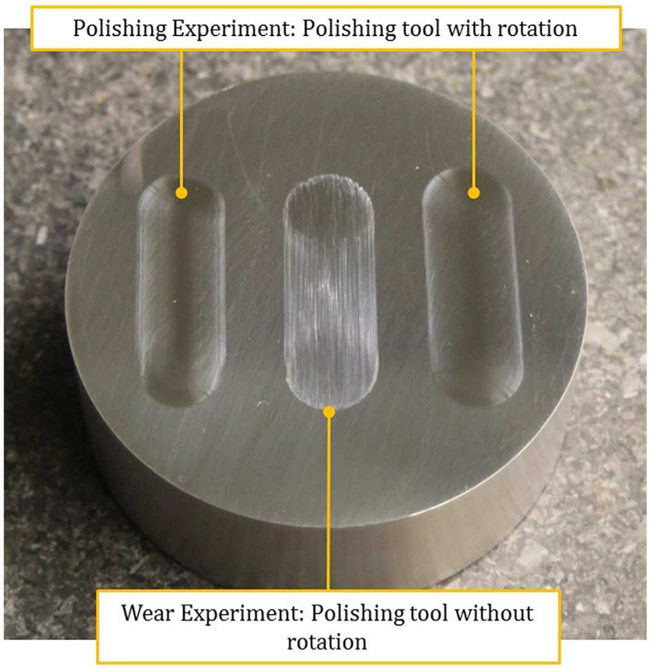

Figure 5. The illustration shows the polishing path with and without rotation speed of the polishing tool on an A506 steel sample.

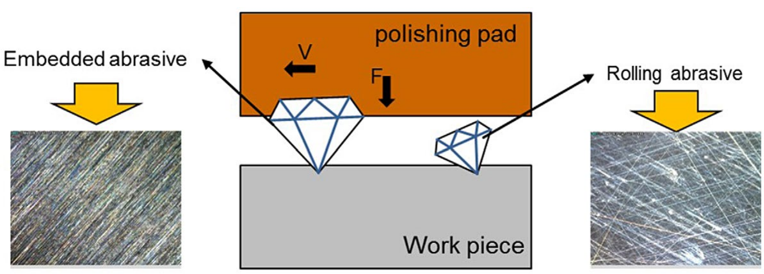

Figure 6. Material removal mechanisms during the polishing process (similar to Brinksmeier et al., [2006]).

4.3. Optical measurements of the polishing attempts

The interferometer Schneider ALI 201 was used to measure the material removal polishing attempts on the steel samples. This measuring device does not only provide a better resolution than the tactile measuring machine, but measurements can also be done faster. For the material removal polishing attempts in steel samples, the material removal's depth (Peak-to-Valley PV) was measured, which is the distance between the highest and the lowest point of the removed material. The second parameter used for the evaluation of the results was the removed volume. These two parameters were later compared with the developed simulation model.

For the measurement of the material removal's depth and the removed volume the same measuring machine, the same software MetroPro and the same application CTV5 were used. With the help of Figure 7 it is possible to understand how the evaluation of the removed volume was obtained. The evaluation of the removed volume was not as easy and as accurate, as the evaluation of the material removal's depth. For the removed volume two fields needed to be defined: an experiment field and a reference field. The precision of the definition of these two fields would later influence the evaluation of the removed volume. After the definition of these two fields was successfully done, the offset represented in the Figure 7 could be corrected and the removed volume below the reference axis could be determined as shown in Figure 8.

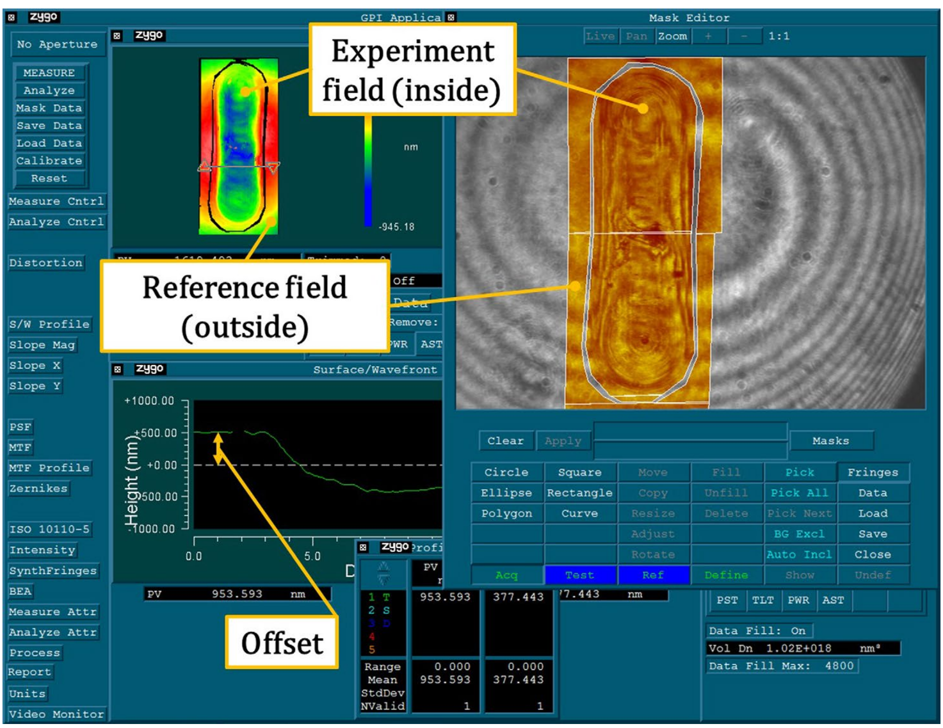

Figure 7. Definition of the experiment and reference field for the evaluation of the removed volume during the polishing attempts on steel samples.

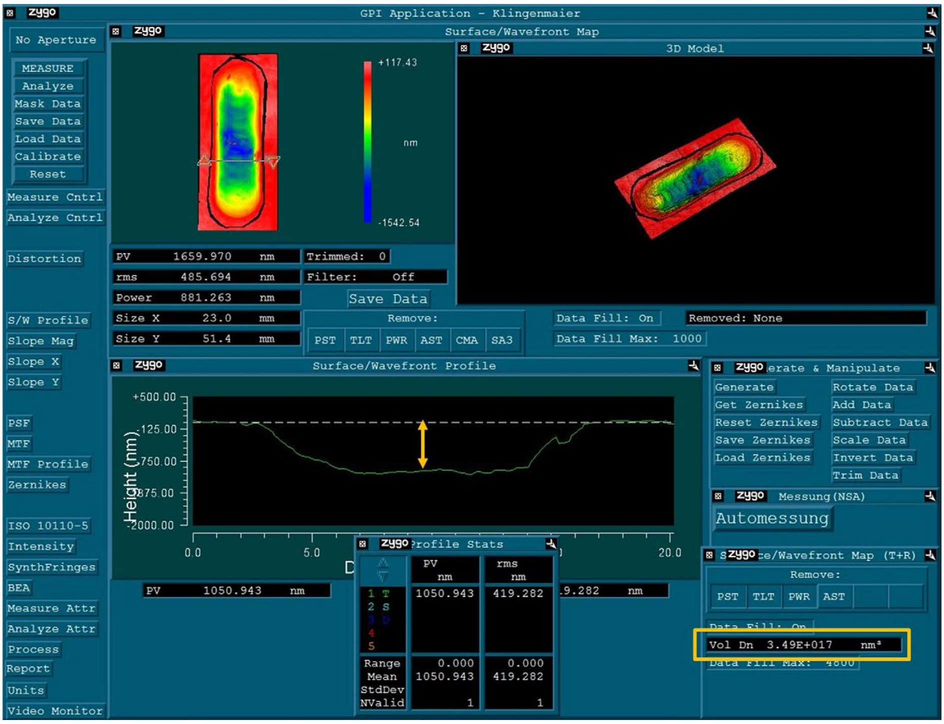

Figure 8. Removed volume measured below the reference axis during the polishing attempts on steel samples.

5. Wear FEM simulation model

In order to simulate the material removal conducted during the polishing attempts on steel samples, a two part simulation model was constructed. The first part was a block (50 × 20 × 5 mm), which represented the work piece and the second part was a cylinder (Ø16 × 2 mm), which represented the polishing pad. The polishing pad did a linear forward and backwards movement over the workpiece, simulating the movement conducted during the polishing attempts on steel samples. Figure 9 shows the simulation model developed in ANSYS.

In this simulation model the Archard wear model was used to define the contact between the polishing tool and the work-piece. During the simulation process of both

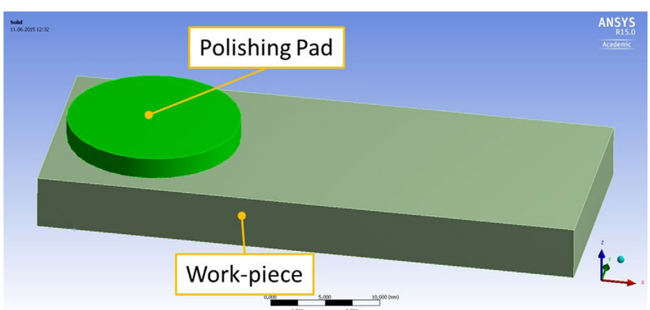

Figure 9. Simulation model parts: polishing pad and work piece.

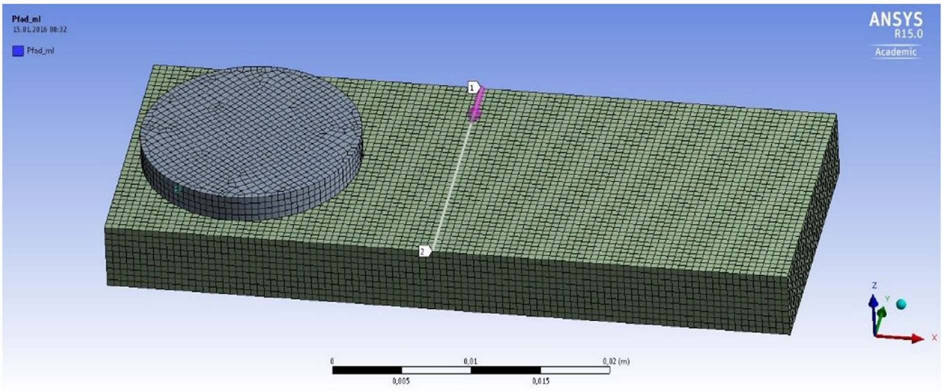

Figure 10. Cross sectional line path used for the evaluation of the simulated material removal's depth.

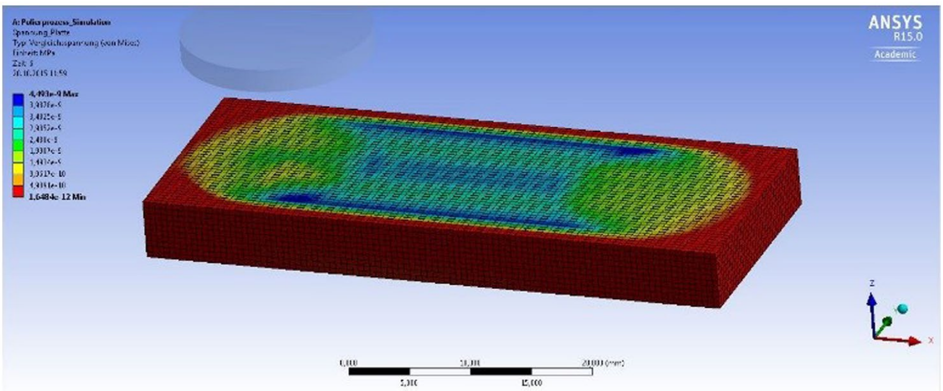

Figure 11. Simulated total material removal obtained on the surface of the work piece.

parts, the tool moves on top of the workpieces creating a closed contact between them. This requires that the material of the workpiece is defined as a material whose characteristics possess wear properties upon contact. (ANSYS Theory Reference, 2013) shows how a random material is defined to acquire wear properties in ANSYS 15.0. The wear of a material is calculated by repositioning the contact nodes of the workpiece. These new coordinates of the nodes are calculated using one of the available models in ANSYS 15.0. Due to the new position of the contact nodes, the contact variables change. This means that equilibrium may be lost and the program ANSYS needs to continue to iterate until equilibrium was reached (ANSYS Theory Reference, 2013). In this case ANSYS provides two wear models: the Archard wear model or the user defined wear model. Equation (3) describes the Archard wear model implemented by ANSYS as referred by (ANSYS Theory Reference, 2013). This well-known wear model is often used for wear simulations, providing good results (Figure 10).

$$\dot{w} = \frac{dw}{dt} = \frac{K}{H} \cdot p^{i} \cdot V_R^{j} \tag{3}$$

Different studies were done as: time-step control, time-step size, stiffness of the polishing pad, meshing size, and *x*-direction movement control. These were conducted in order to study their influence on the calculation time and on the simulation results of the material removal's depth and removed volume (Figure 11).

In order to analyse the material removal's depth in specific areas of the work piece, a geometrical path was created. Along this predefined path, the result of the local displacement in the *z*-direction could be calculated. Due to the linear escalating behaviour of the material removal's depth and removed volume upon variation of the contact pressure, only one final model was necessary. This means that for the comparison of the material removal's depth and the removed volume results from the polishing attempts, the simulation results were simply scaled from the 5 N model to 10 and 15 N.

6. Results & conclusions

Figures 12–14 show the results for material removal's depth from the polishing attempts, where the force applied to the polishing tool was varied. The simulation results from the material removal's depth were compared with the polishing attempt's results. The results show that for each individual force variation attempt, the material removal's depth was constant through the repetition of the number of polishing paths. The results also show that the material removal's depth results followed the Holm-Archard and Preston equations. This means, by increasing the applied force on the polishing tool from 5 to 10 N, the results increased with a factor of two. The same happened when the applied force to the polishing pad changed from 5 to 15 N, the results also increased with a factor of three. The same material removal's depth could be achieved during the polishing attempts, when the same set of polishing parameters was used. The reproducibility of the same material removal's

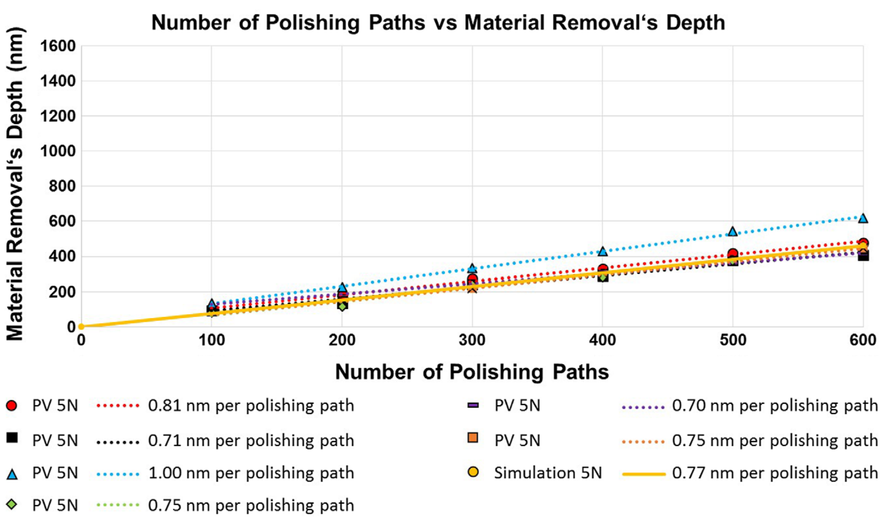

Figure 12. Comparison of the material removal's depth between simulation and the polishing attempts for a polishing force of 5 N.

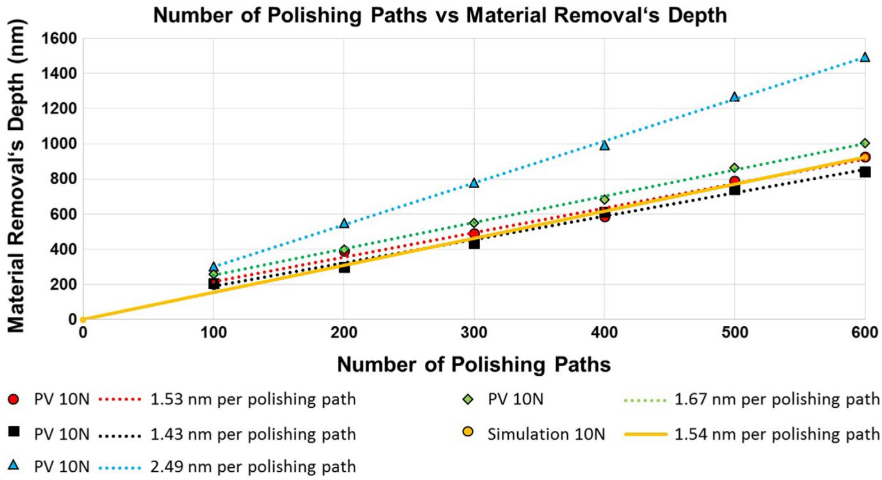

Figure 13. Comparison of the material removal's depth between simulation and the polishing attempts for a polishing force of 10 N.

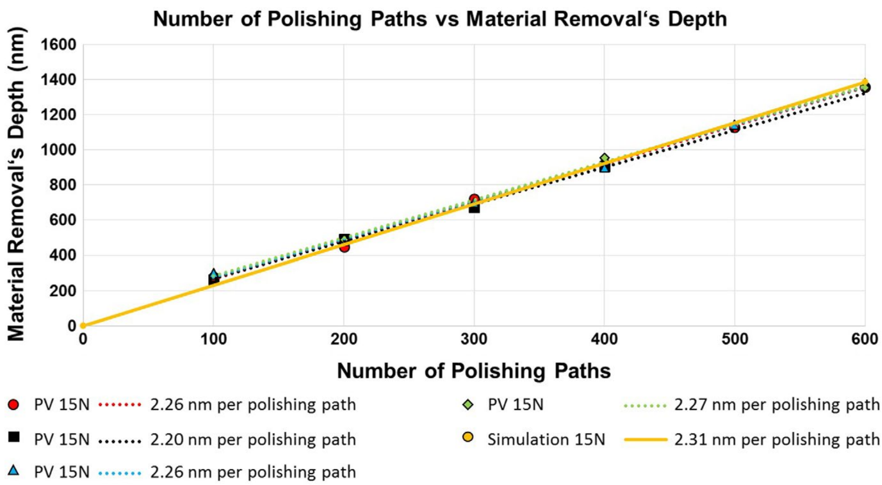

Figure 14. Comparison of the material removal's depth between simulation and the polishing attempts for a polishing force of 15 N.

depth is important in order to control the material removal for the correction of geometric forms and proves that the experimental procedure is stable.

The Figures 15–17 show the results of the volume removal from the same polishing attempts. The removed volume corresponding to the number of polishing paths is represented. The results show that for each individual attempt, the removed volume was constant through the repetition of the number of polishing paths. The same behavior happened during the evaluation of the material removal's depth. The removed volume was used together with the material removal's depth to test the accuracy of the new developed simulation model in the ANSYS program.

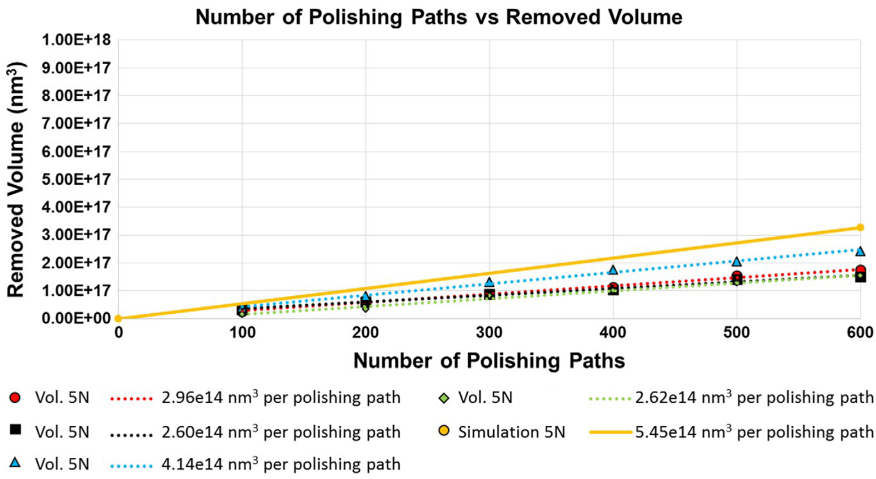

Figure 15. Comparison of the removed volume between simulation and the polishing attempts for a polishing force of 5 N.

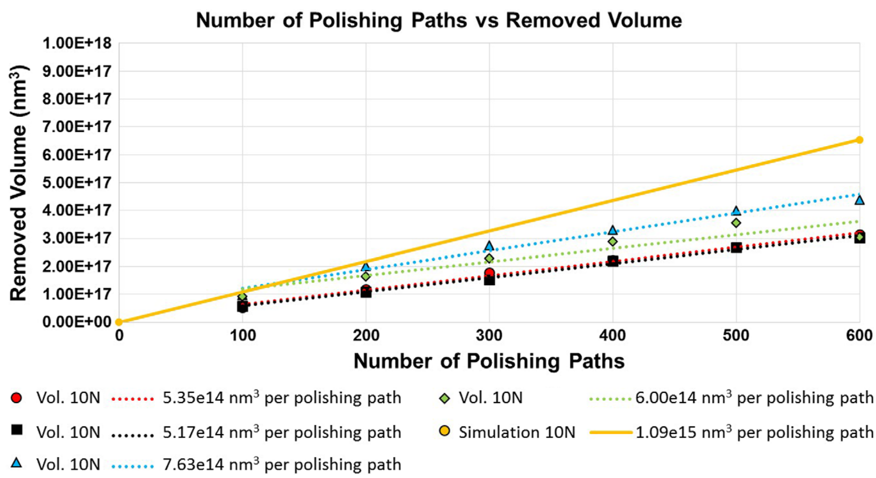

Figure 16. Comparison of the removed volume between simulation and the polishing attempts for a polishing force of 10 N.

The FEM simulation model results showed a good prediction of the material removal's depth compared to the results obtained by the polishing attempts conducted on steel samples. These results can now be used in order to predict the material removal's depth when the force applied to the polishing tool is varied. The simulation model showed a slightly bigger deviation for the predicted removed volume when compared to the same conducted polishing attempts. This difference was caused by the trigonometrical movement function definition of the polishing pad in the final model, which made the polishing pad to produce more wear. By defining a linear movement function, the difference between the results of the simulation and the experiment decreased. Despite this there is still space for improvements. Reducing the mesh size allowed a better convergence of results, but the calculation time increased drastically. Another reason for this difference was the measurement technique.

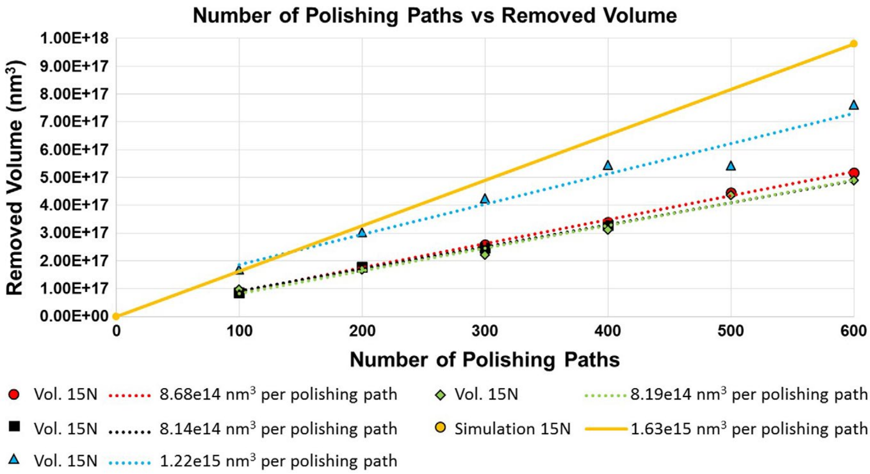

Figure 17. Comparison of the removed volume between simulation and the polishing attempts for a polishing force of 15 N.

Small adjustments on the definition of the above mentioned areas would result on an immediate oscillation of the removed volume.

Further polishing attempts will be conducted on hardened steel samples with a material hardness of approx. 56 HRC. The goal is to be able to control and predict the material removal on hardened steel in order to be able to correct the geometrical shape of steel moulds.

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Disclosure statement

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