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Geometrical shape improvement of steel moulds by robot polishing process for polymer optic replication

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ABSTRACT

The quality of injection-moulded polymer optic parts depends on the surface finish of the respective mould. In order to improve the surface finish of the mould, it is important to use a tactical material removal, which allows a controlled correction of the mould's surface geometry. The aim of this work is to use a polishing correction technique to improve and correct the flatness of hardened steel samples in order to reduce the need for manual polishing. A polishing tool function is simulated from the contact between the tool and the hardened steel sample and used to determine the material removal rate per time. A feed profile is calculated, which allows the industrial robot to tactically control the material removal. It is observed that a correction improves the surface's flatness by up to 70%.

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material removal control;
material removal simulation;
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1. Introduction

Plastic injection moulding is known as a manufacturing process. In this process, material is injected into a mould and parts are produced. These produced parts' geometry acquire the form of the respective mould. This manufacturing process is, unconsciously, present on everyone's lives. Kitchen products, plastic buckets, drafting tools and plastic toys are just some examples of the products manufactured by means of plastic injection. Mostly plastic injection moulding parts are produced using a steel mould tool. A moulder knows that the material of the steel mould has unique and specific demands. The material needs to be easily machined and polished, stable during heat treatments and free of defects. A particular type of plastic injection moulding is the production of plastic optics. The quality of the moulded products depends on the surface quality and shape deviations of the respective mould (Speich & Boerret, 2011). The produced moulds do not always have a spherical shape; some moulds are also cylindrical shaped (Speich & et al., 2011). Nowadays, moulds for plastic injection moulding are still polished by hand (Boerret & et al., 2008), which is why moulds production is very expensive. Workers require extensive experience to achieve good polishing results concerning shape deviation. Automatic robot polishing processes are used for the polishing step of the production of steel moulds. This process provides

higher stability to the mould production than the manual polishing (Speich & et al., 2013). Achieving a good shape deviation by hand polishing is quite difficult compared to achieving a good surface roughness. As stated by Speich & et al. (2013), a surface roughness of 3 nm Root Mean Square using the automatic robot polishing can already be achieved. Further, it is necessary to obtain also good results concerning shape deviation while using the robot polishing method.

The goal of this work is to apply a polishing correction technique on flat hardened steel samples in order to improve their flatness. This work brings the possibility to use an industrial robot for the polishing process of steel moulds instead of doing manual polishing. This assures reproducible results and more accuracy on achieving restrict tolerances. This technique was developed in the Centre for Optical Technologies and implemented in our proprietary software Zaphod. Zaphod is a software that is constantly being updated and adjusted to the needs of the employees of the Centre for Optical Technologies. With Zaphod it is possible to create different tool paths for the robot movement, and for the polishing correction. It is also possible to analyse and edit measuring data, which can be further used for tool path generation or just for evaluation of results. Within this polishing correction technique, the material removal will be manipulated to remove the shape error of the samples. Different measuring techniques are used in order to investigate how to manipulate the material removal rate. It is observed that using an optical measurement technique allows the process to be faster and to obtain better results. Based on the previous works done on PMMA (PolyMethylMethAcrylate) (Almeida & et al., 2016a), on soft steel (Almeida & et al., 2016b) and on hardened steel the research of material removal during the polishing process continues.

2. Aims of the research

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 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 RMS surface roughness and a shape deviation of 20 μm . Figure 1 shows 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 RMS 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 high-speed cutting (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 deviations were achieved. The left illustration shows the measurement of the steel sample, where a spiral tool path is used and a shape deviation of 11.8 μm is obtained. The right illustration shows the measurement of another steel sample, where a linear tool path is used and a shape deviation of 8.3 μm is achieved.

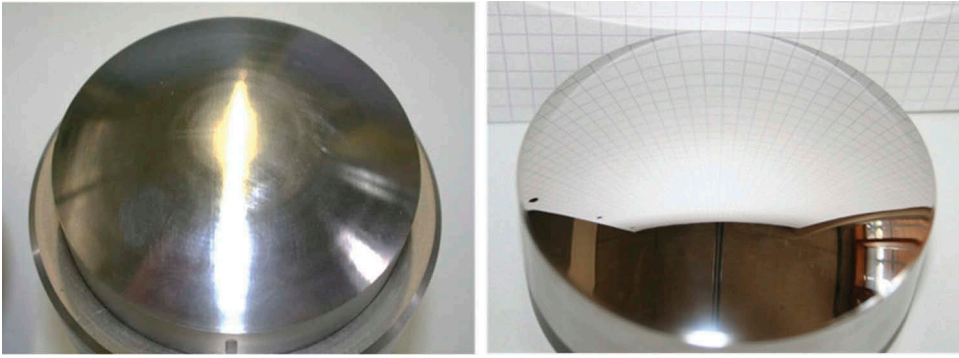


Figure 1. Convex steel mould. The left illustration shows a convex steel sample after being milled with 200 nm RMS surface roughness and a shape deviation of 20 μm ; the right illustration shows the same convex steel sample after the robot polishing process with an improved surface of 3 nm RMS surface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

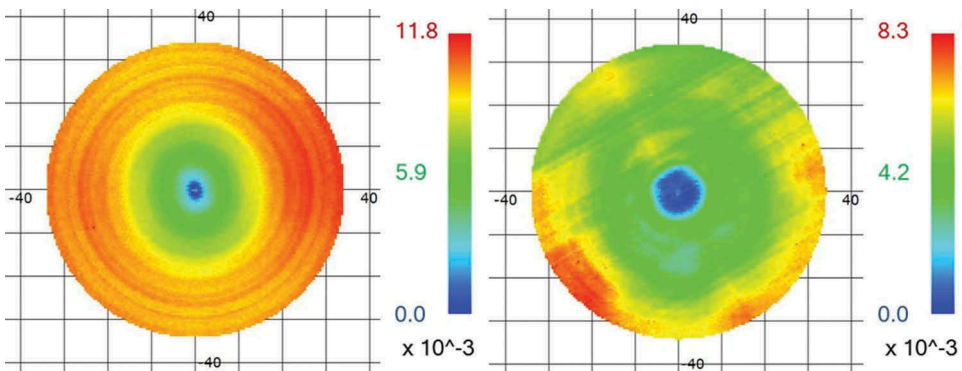


Figure 2. Geometrical shape deviations using different tool paths. The left illustration shows a convex steel sample after being milled with a shape deviation of 11.8 μm ; the right illustration shows another convex steel sample after being milled with a shape deviation of 8.3 μm .

This being said, it is possible to obtain a much better geometrical form, even before the polishing process, by using a HSC machine, which makes this work even more interesting. The goal is to be able to go even further and with these good starting parameters, to control and manipulate the material removal, therefore controlling the shape deviation and improving it. Klocke & et al. (2011) performed a corrective zonal polishing process on ceramic geometries using a polishing tool function obtained from previous investigations. However, there was no literature found regarding the corrective polishing on steel samples, especially with a simulated polishing tool and the respective prediction. The goal in this work is to use the knowledge obtained from previous works and improve the flatness of hardened steel samples using a polishing correction technique developed in our Centre for Optical Technologies. This polishing correction technique manipulates the material removal in order to remove the shape error of the samples. The manipulation of the material removal can be realized by using one of three different parameters in order to create a correction profile. These parameters are

either the applied force, the rotation speed or the feed rate of the polishing tool. As the feed of the industrial robot is more responsive to adjustment than the force or the rotation speed applied by the polishing tool, a feed calculation is preferred for the correction profile. When the feed rate is varied, it is lowered on hikes of the uneven surface in order to increase the material removal on this particular point. On the other hand, on wells of the uneven surface, the feed rate is increased to achieve less material removal. With this procedure, the material removal is tactically used to reduce the shape error of flat samples.

For this material removal manipulation, a complex algorithm is developed in the Centre for Optical Technologies, which is responsible for the calculation of the correction profile using either the applied force, the rotation speed or the feed rate of the polishing tool. The algorithm requires various input data to perform the calculation of the correction profile. These data are typically acquired from measuring systems or CAD programs. The user needs to input the following data into the algorithm: the surface's actual shape, the surface's desired shape, the polishing tool function and a tool path used for the correction. With this data the algorithm calculates appropriate force, rotation speed or feed-based correction profiles. Figure 3 shows a schematic representation of this polishing correction technique. The upper graphic of Figure 3 shows the flat polishing tool with the working direction. The actual shape is shown and also the desired shape, which is a complete flat surface. The lower graphic of Figure 3 shows the necessary feed profile for the robot to drive the flat polishing tool in order to correct the actual shape to obtain the desired shape. This illustrates the idea that on hikes the feed rate needs to be lowered in order to produce a higher removal of material.

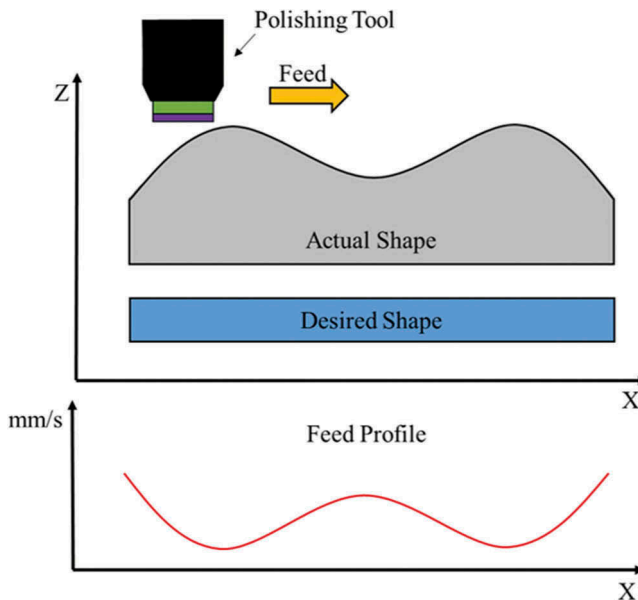


Figure 3. Depiction of a polishing correction technique. The top illustration shows the schematic representation of an actual shape of a surface, the desired shape and the flat polishing tool; the bottom illustration shows the necessary feed profile for the correction of the uneven shape.

From the previous works it is concluded that the same material removal's depth is achieved and reproduced on plastic samples, soft steel and hardened steel (Almeida & et al., 2017a). To apply such a polishing correction technique, it is of great importance to always achieve the same material removal while using the same set of polishing parameters and experimental procedure. Hardened steel is used for the production of moulds, which are used for plastic injection moulding. For this reason, the polishing correction technique is applied on hardened steel with the goal to improve the flatness.

3. Material removal theory

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 as mentioned by Brinksmeier & et al. (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 (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 (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.

$$V = \frac{K}{H} \times F_n \times S \quad (1)$$

$$\frac{dz}{dt} = K_p \times p \times V_r \quad (2)$$

After considering the statements above, it is assumed that both equations have some similarities. The Holm-Archard equation was implemented during the development of a simulation model able to predict the material removal's depth (Almeida & et al., 2017b). The same equation is used for the simulation of the polishing tool function, which represents the material removal through time during the polishing correction technique.

4. Experimental procedure

As a continuation of the material removal's research conducted on hardened steel samples, the material removal is tactically used for the correction of the shape error of the same flat samples. Prior experiments showed that the reducibility of the material removal is achieved reliably. The steel samples are made of the high performance plastic mould

steel M340. The samples are hardened and the distribution of the hardness is homogenous. The average value of the measured hardness of the M340 samples is 615 Vickers. The samples are produced and ground with the goal to make them flat and to reduce the surface roughness. Subsequently, the samples are lapped using a polishing lever machine, in order to reduce the surface roughness allowing for an optical measurement. Before the lapping process, the samples have an RMS value of 803 nanometres and afterwards the RMS value is around 7 nm. The surface roughness of each sample is inspected after lapping, using a white light micro interferometer. This assures that the initial surface conditions during the polishing attempts are always as constant as possible.

For the surface's flatness correction, the industrial robot ABB IRB 2400 (ABB IRB 2400, 2016) with an attached polishing head is used. In order to maintain the polishing suspension during the working process on top of the surface of the sample, an additional adapter is produced. This adapter is made of POM (Polyoxymethylene) and is depicted in Figure 4 during one of the polishing correction technique's attempt. An overview of the polishing parameters used during the polishing correction technique attempts is listed in Table 1.

5. Algorithm's input data

The following section explains the algorithm principle, which is used to calculate the feed correction profile that is used to improve the geometrical shape of steel samples using the robot polishing method. Figure 5 shows schematically the algorithm principle, where the yellow fields are the input data to the algorithm, respectively the polishing tool function, actual shape, desired shape and the tool path. The polishing tool function is obtained from



Figure 4. Experimental set-up during the polishing correction technique showing the flat polishing tool, the additional adapter and the polishing suspension.

Table 1. Overview of the polishing parameters used during the polishing correction technique.

Force of the polishing tool	15 N
Rotation speed of the polishing tool	300 rpm
Polishing tool diameter	16 mm
Polishing suspension	6–12 μm

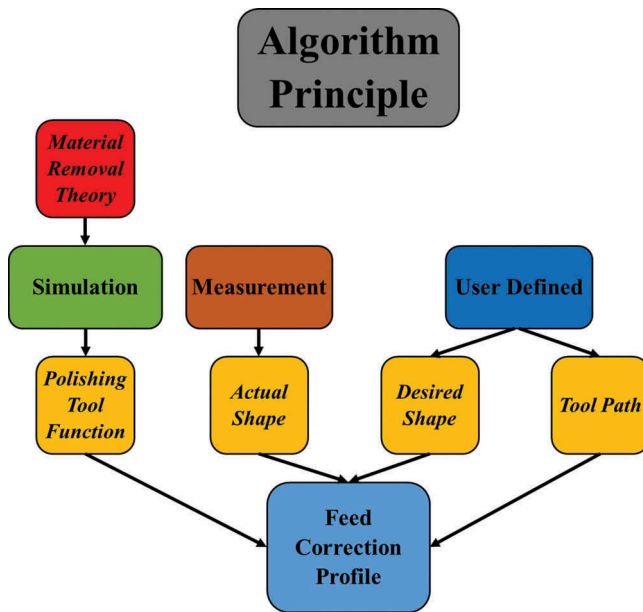


Figure 5. Algorithm principle showing with on yellow the needed input data in order for the feed correction profile to be calculated.

the simulation model, where the Equation (1) is implemented to simulate the material removal. The desired shape is obtained from a measurement conducted either from an optical or from a tactile measuring machine. The tool path and the desired shape are both defined by the user. The algorithm uses the tool path, which has a defined number of points and it places the actual shape and the desired shape on top of each other and the difference between these shapes is calculated for each point of the tool path. With the polishing tool function, the material removal is defined by time; for this reason, it is placed on each of these points and the feed profile is calculated according on how much time is needed to correct the difference between actual shape and desired shape. Furthermore, each individual input data is going to be explained into detail.

5.1. Actual shape

The actual shape of the steel samples is passed to the algorithm in a form of a point cloud. This point cloud is obtained with a measuring machine, which either uses a tactile or an optical method, or directly from CAD data. The algorithm is very flexible regarding the workpiece's geometry, so that even freeform surfaces can be used. [Figure 6](#) shows the measurement of the steel samples surface, conducted with the interferometer Schneider ALI 201 (Schneider Optical Machines, 2015). This measurement represents the actual shape of one of the steel samples. Due to the high resolution of the optical interferometer it is possible to acquire a high density of points. The density of points is relevant as it influences the algorithm's calculation accuracy. A more precise measurement of the actual shape enables a more accurate determination of the correction profile, allowing the material removal to be accurately applied at the desired location.

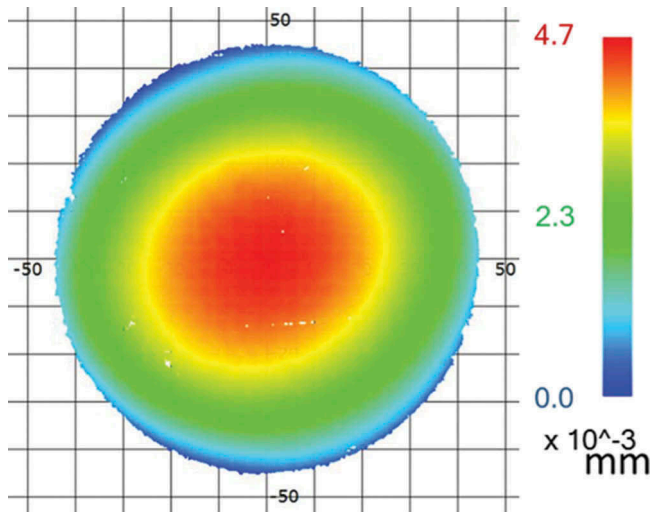


Figure 6. Optical measurement as input data for the algorithm used for the correction profile, showing the measurement of the entire sample's surface.

Accurate polishing correction of the entire surface is possible, but due to the experimental set-up only a part of the sample is corrected. Consequently, only the needed part of the sample's surface is passed as input data to the algorithm. Inputting only a part to the algorithm accelerates the calculation of the correction profile. The POM adapter, depicted in Figure 4, keeps the polishing suspension on top of the surface during the entire process and this stabilizes the suspensions concentration. Figure 6 shows the optical measurement conducted with the interferometer. Figure 7 shows the edited measurement data for the input into the algorithm.

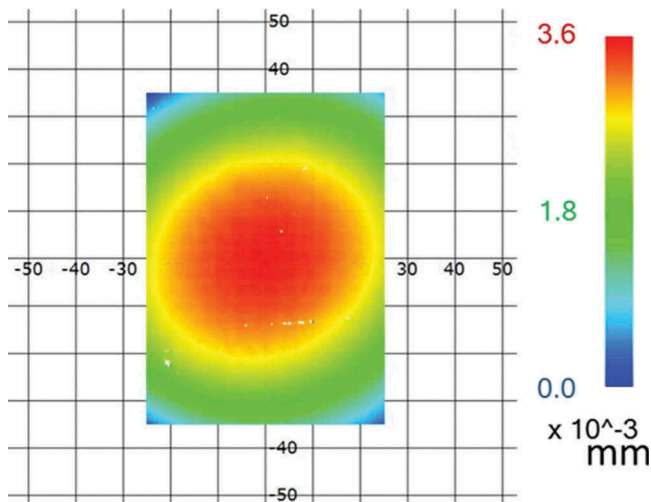


Figure 7. Edited optical measurement as input data for the algorithm, used for the correction profile.

5.2. Desired shape

In this case, the desired shape of the steel samples is a flat surface with a zero peak-to-valley (PV) value. Since the desired shape is a zero PV value, the algorithm will calculate a solution that will bring the actual shape of the surface as close as possible to this value. For this purpose, the desired shape's input data is generated with Zaphod, the Centre for Optical Technologies proprietary software. The desired shape's input data has to be at least the same size as the actual shape's input data or larger to enable the algorithm to calculate the necessary material removal. The material removal is calculated according to the distance in Z-direction between the desired shape and the actual shape. The higher the distance is, the higher is the necessary material removal. At the same time, a higher distance results in a higher polishing time. However, higher processing times are helpful, as the algorithm has more leeway to bring the actual shape into the desired shape. This means, the more material is removed, the better is the result in the end. [Figure 8](#) shows the desired shape created with Zaphod with a PV value of zero. [Figure 9](#) shows the correct positioning between the actual shape and the desired shape in Z-direction. Due to the continuous contact between the polishing tool and the sample's surface during the polishing correction, there is always a certain degree of material removed. If the desired material removal is zero, the polishing tool needs to move with infinite feed speed, which is impossible to obtain. To bypass this problem, an overall material removal is done on the entire surface, placing the entire desired shape underneath the actual shape in Z-direction.

5.3. Polishing tool function

The polishing tool function is a very important parameter of the polishing correction technique. If this parameter is not adjusted properly, the entire polishing correction is performed incorrectly and the geometrical shape of the sample will get even worse. The tool function defines the material removal on each point of contact between the polishing tool and the surface of the sample, while using a defined set of polishing parameters. As mentioned before, the polishing parameters and therefore the material

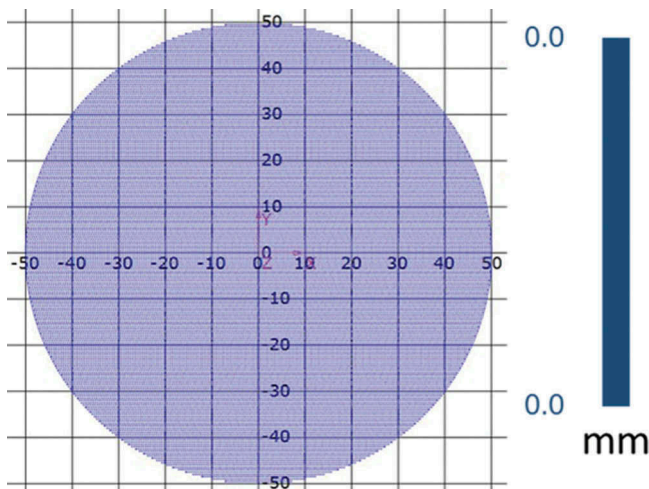


Figure 8. Desired shape's input data with a PV (Peak-to-Valley) value of 0, generated in Zaphod.

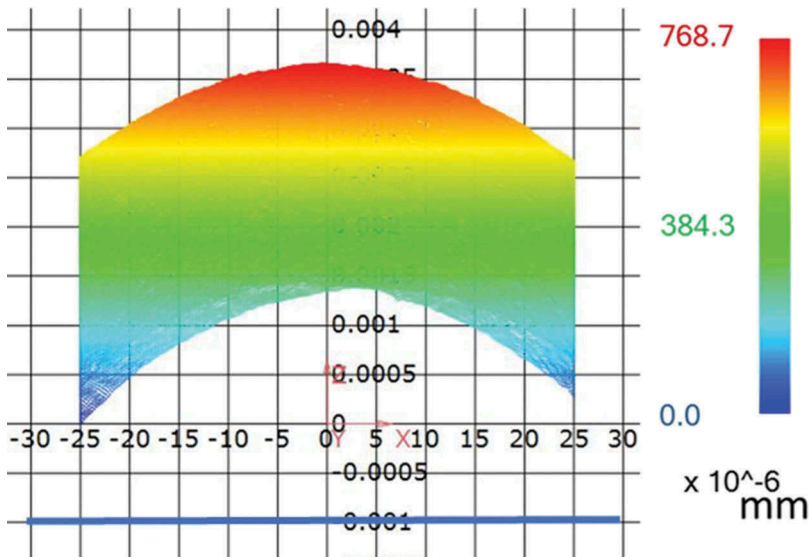


Figure 9. Edited desired shape's input data showing the XZ view of the positioning between the actual shape (top) and the desired shape (bottom) in Z-direction.

removal have to be constant during the polishing process, so that the tool function stays constant as well. Otherwise, a constantly changing tool function, producing alternating removal rates, will prevent the success of the polishing correction technique.

The polishing tool function is defined in a point cloud form, just like the desired and the actual surface's shape before. Typically, either a simulated or a measured polishing tool function is used. For this experiment, a simulated tool function is preferred. The veracity of the simulated polishing tool is tested using Zaphod's material removal calculation. It shows how well the simulated tool function can theoretically perform in terms of achieving a flat surface. The X and Y coordinates of each point of the polishing tool function describe the spatial position relative to the centre of the tool function. The corresponding Z coordinate indicates the material removal of the tool function at the corresponding location. When a measured tool function is used, it is necessary to record the removal rate of a stationary rotation tool. From the removed volume and the processing time, the removal rate per time unit is calculated. If the centre point of the tool function does not match the origin of the coordinate system or there is a displacement in the X or Y direction, the algorithm will assume these displacements are intentional. Therefore, any unwanted displacements have to be removed beforehand. [Figure 10](#) shows the simulation of the polishing tool function and the respective cross sectional line of the same polishing tool.

5.4. Polishing path

A polishing path can theoretically be defined with an infinite number of points. Therefore, the polishing tool traveling along this path will also have an infinite number

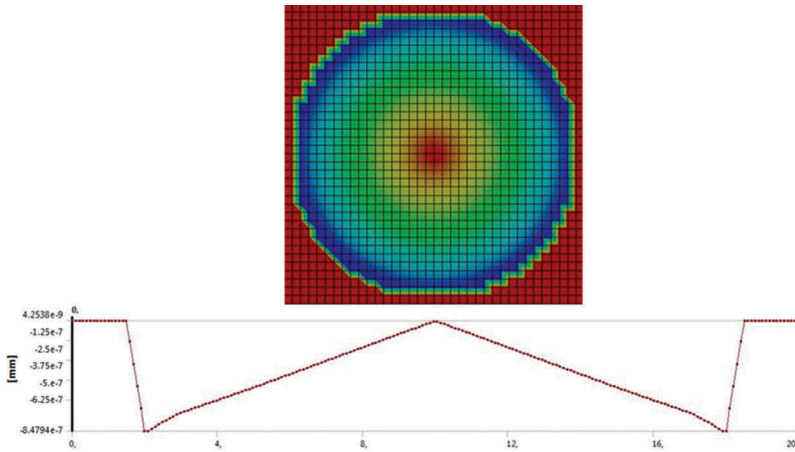


Figure 10. Simulated polishing tool function. The upper illustration shows the simulated material removal on the work-piece; the lower illustration shows the cross section of the same polishing tool.

of possible positions. In practice, the influence of the polishing tool function cannot be calculated for an infinite number of positions. Consequently, there are discrete points defined, for which the influence of the tool function on the surface is determined. These discrete points are represented by the points of the tool path. Thus, the dot pitch of the tool path defines the interval to calculate a correction profile. **Figure 11** shows the meander tool path for the calculation of the correction profile. The outer points on the boundary of the polishing path are worked one time. Therefore, the polishing tool will have one possibility to manipulate the material removal in these points. The number of possibilities, to manipulate the material removal, will increase towards the middle of the

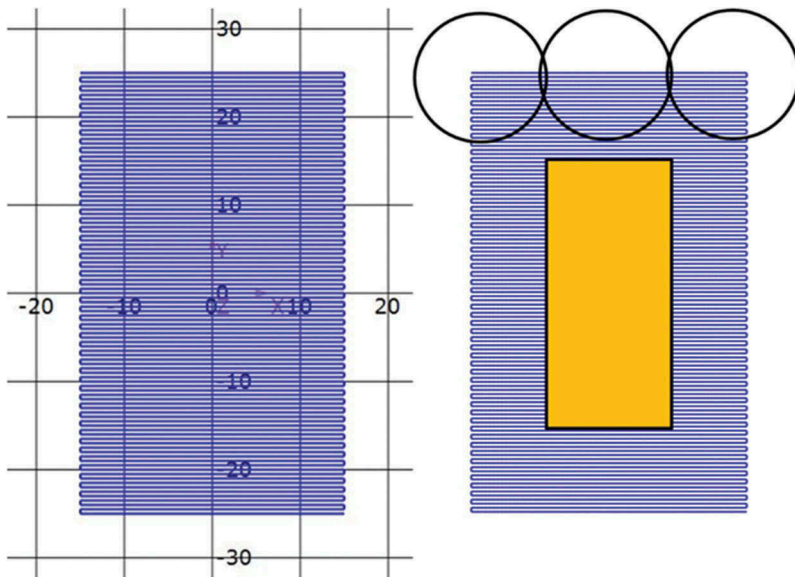


Figure 11. Polishing path with a dot pitch of 0.5 mm created in Zaphod.

polishing path. In a certain area, the total number of possibilities is the same. The higher the number of polishing tool functions affecting a single point is, the more leeway has the algorithm for the correction technique. For example, if a certain point on the surface can be machined from twenty positions of the polishing tool function, there are exactly twenty ways to provide the required material removal at this point. Accordingly, a lesser point distance along the polishing path leads to a more accurate correction profile. With an increase of the point density of the polishing path, on one hand, the accuracy of the calculation and also the required computational time increases.

In the right illustration of [Figure 11](#), the size of three polishing tool functions next to each other is depicted. The yellow rectangle represents the area used for the evaluation of the results. Its size is 34 mm × 14 mm. This area is selected because the polishing tool has the maximum and the same leeway to achieve the required material removal. From [Figure 11](#) it is possible to compare the size of the polishing tool with the evaluated area. This shows that on the entire width of the polishing path there is not enough space for more than two polishing tools next to each other. This condition leads to a complicated correction profile and makes this surface correction even more challenging and interesting.

6. Calculated correction feed profile

To obtain a uniform correction profile, all positions on the surface of the work-piece have to be machined with the same number of tool path points. At the edge of the polishing path there is only one correction possibility for the tool function. For this reason, the material removal on the edges is different than on the rest of the surface. To assure a constant material removal, the tool path needs to be larger than the sample's surface. For the right correction of an entire surface, an extra adapter needs to be created with the same contour as the samples surface. This will assure not only that the polishing tool stays constant the entire time but the number of possibilities for the material removal to be manipulated is the same. Extreme pressure, rotation speed or feed values are generated near the borders of the tool path, which makes it necessary to edit the feed profile subsequently. As the feed of the industrial robot is more responsive to adjustment than the force or the rotation speed applied by the polishing tool, a feed calculation is preferred for the correction profile. The calculated feed profile with the respective feed scale in mm/s is shown in [Figure 12](#) in the XY-view. The feed profile is calculated for a chosen number of 20 repetitions of the tool path. This means that after 20 repetitions the predicted material removal shall be achieved. The number of repetition can be changed according to the user's needs regarding the process time or the application.

7. Results and discussion

During the attempt of the polishing correction technique, the correction feed profile is calculated for a total of 20 repetitions. [Figure 13](#) shows the sample's surface before and after polishing correction, with their corresponding colour scale. The left picture shows the surface measurement of the evaluated area before the polishing correction. The right picture shows the surface's measurement of the evaluated area after the 20th repetition of the polishing correction. It is shown that the surface's flatness at the 20th repetition improved from 668.8 nm to 214.2 nm, which is an improvement of 68%.

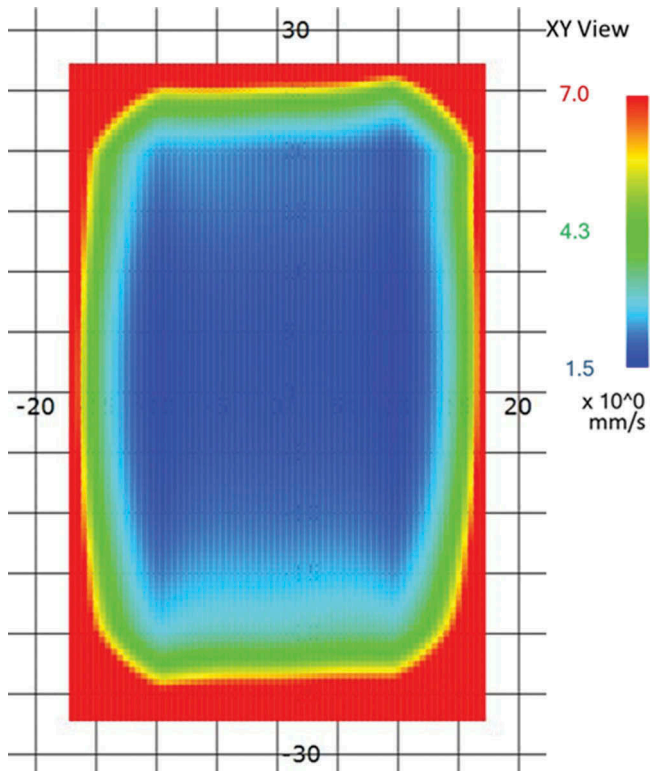


Figure 12. Correction feed profile for the polishing correction technique in the XY-view with the respective feed scale in mm/s.

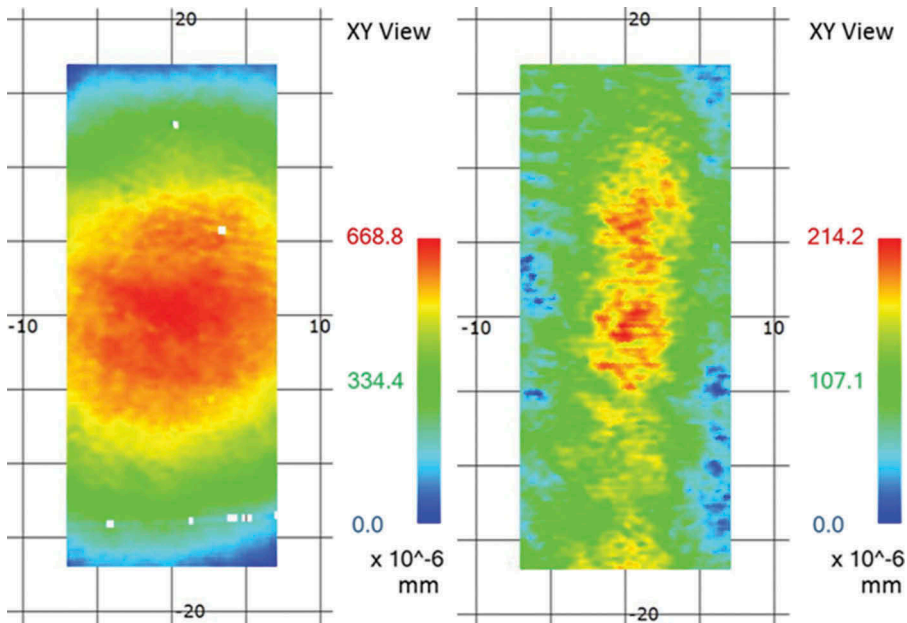


Figure 13. Geometrical shape correction attempt: actual shape of the evaluated area before (left) and after (right) the polishing correction technique, showing an improvement of the surface's flatness from 668.8 nm to 214.2 nm.

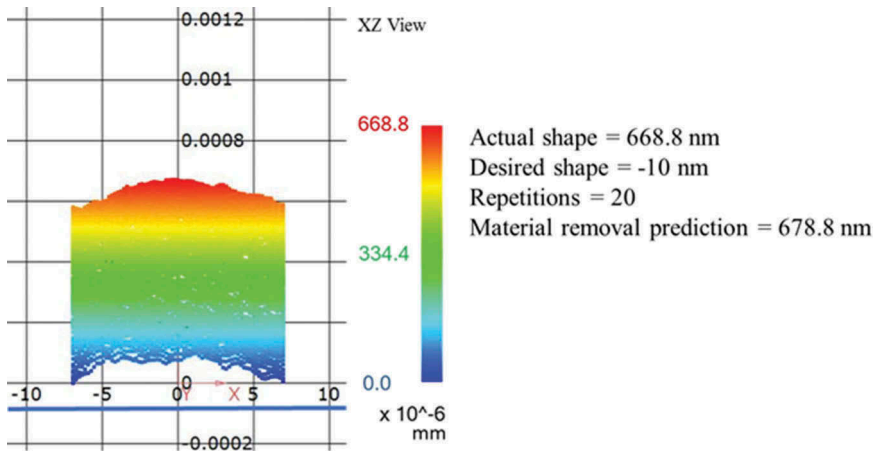


Figure 14. Geometrical shape correction attempt: material removal prediction of 678.8 nm before the polishing correction technique, showing the position in the Z-direction of the actual shape and the desired shape.

During this attempt, the total material removed in the Z-direction was controlled. [Figure 14](#) shows the position in Z-direction of the actual shape compared to the desired shape. The goal of the polishing correction technique is to bring all the points of the actual shape to the desired shape. As shown in [Figure 14](#), a total material removal of 678.8 nm is expected in Z-direction. This prediction appears plausible, since similar material removal was achieved during earlier research with single path attempts. Therefore, it is expected that the actual material removal will meet the material removal prediction.

[Figure 15](#) shows the material removal from the real polishing correction process after 20 repetitions. It is obtained by subtracting a reference measurement before the processing from the measurement afterwards. After the 20th repetition, a total of 673.9 nm is removed. This meets very closely with the Zaphod's prediction of 678.8 nm for 20 repetitions. This makes an error of 4.9 nm, respectively 0.72%.

Zaphod is a powerful tool, capable to predict the correct material removal, if the right input data is given. Nonetheless, it puts out a good prediction on which surface flatness to expect. [Figure 16](#) shows improvement of surface according to Zaphod's prediction: on the left side is the surface's measurement of the evaluated area and on the right side is the Zaphod's prediction on the evaluated area. The surface's PV value improved by 71.4% from 668.8 nm to 191.1 nm.

[Figure 17](#) compares the surface's measurement of the evaluated area after the polishing correction with Zaphod's prediction. The left picture shows that after the polishing correction technique, the surface has a PV value of 214.2 nm. This PV value represents an improvement of 68% of the surface's flatness. The right picture shows that Zaphod predicted a surface's flatness of 191.1 nm, which represents an improvement of the surface's flatness by 71.4%. Comparing the improvement of the reality with Zaphod's prediction, there is an error of 4.9%. However, this corresponds to an error between prediction and reality of just 23.1 nm. The comparison also demonstrates the high stability of the entire experimental procedure. Taking into consideration the size of the evaluated area, the size of the polishing tool, the material removal's depth prediction and the obtained result, it is concluded that the polishing correction technique is a success.

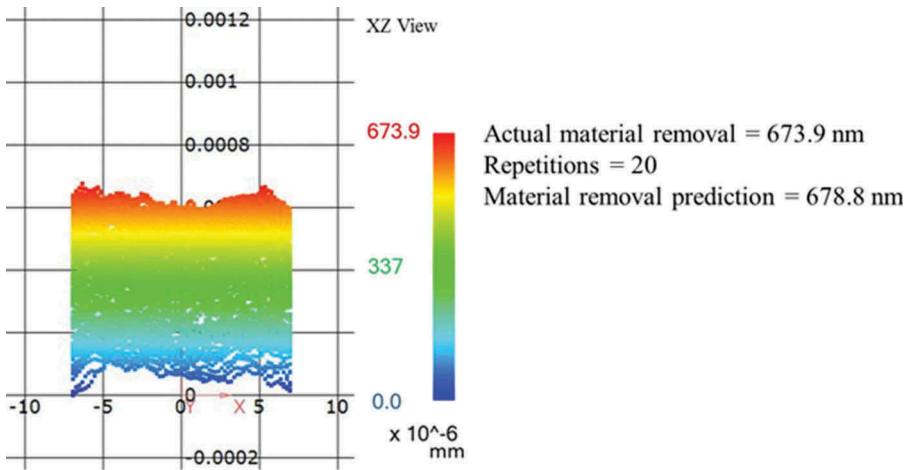


Figure 15. Geometrical shape correction attempt: material removal after the polishing correction technique at the 20th repetition, showing the total material removal of 673.9 nm compared with a material removal prediction of 678.8 nm.

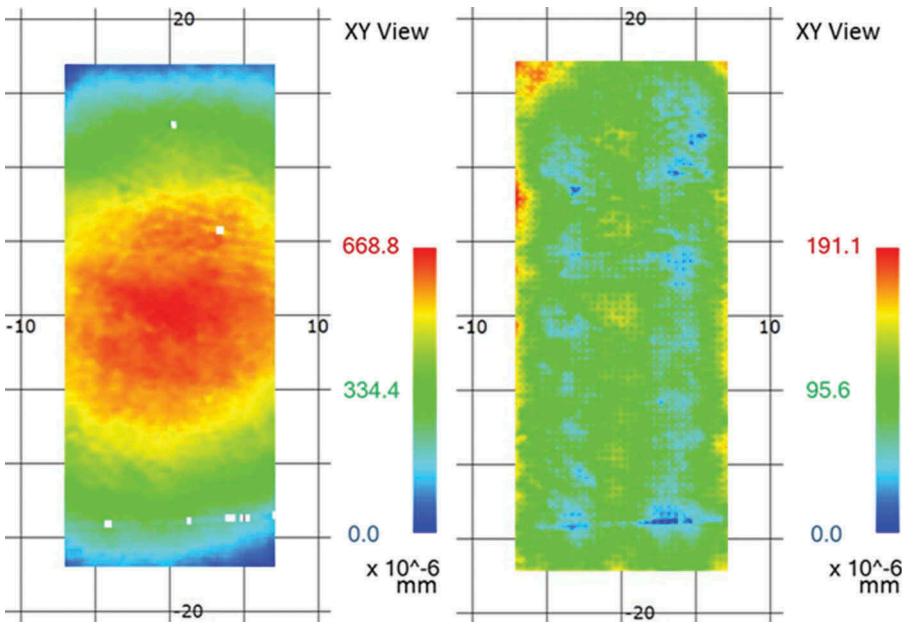


Figure 16. Geometrical shape correction attempt: actual shape of the evaluated area before the polishing correction technique (left) and the Zaphod's prediction after the polishing correction technique (right), showing an improvement of the surface's flatness from 668.8 nm to 191.1 nm.

8. Conclusions

This research successfully leads to the development of a polishing correction technique. This technique enables a correction of the flatness of hardened steel samples. This success leads to a development of a new process that can be used and tested for the polishing process of steel

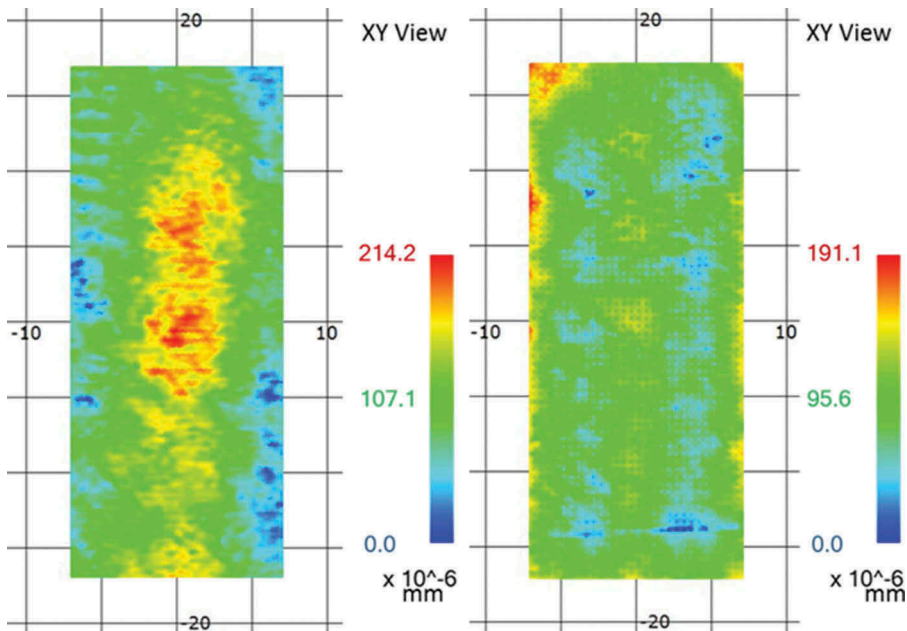


Figure 17. Geometrical shape correction attempt: actual shape of the evaluated area after the polishing correction technique (left) and the Zaphod's prediction after the polishing correction technique (right), showing a good prediction from 214.2 nm to 191.1 nm.

moulds used for plastic injection mould. Due to the size of the polishing tool and the experimental set-up, a smaller area is chosen for the evaluation of the results. This evaluated area is chosen in a way that the polishing tool has the same amount of possibilities to manipulate the material removal. Because of the experimental set-up outside this area, the polishing tool had less possibilities as the tool moves close to the boundaries of the surface. The evaluated area has a size of 34 mm \times 14 mm.

During the attempt, the polishing correction technique is calculated for 20 repetitions and a single measurement is conducted at the 20th repetition. Before the polishing correction technique, the evaluated area has a PV value of 668.8 nm. At the 20th repetition, the surface's flatness improves from 668.8 nm to 214.2 nm. This corresponds to an improvement of the surface's flatness of 68%.

The material removal's depth is observed during this attempt. A total material removal in the Z-direction of 678.8 nm is expected. At the 20th repetition, a total of 673.9 nm is removed in the Z-direction. An error of 0.72% between prediction and experiment is obtained, which corresponds to just 4.9 nm. This demonstrates very good control of the material removal and high stability of the entire experimental procedure. At the end, Zaphod's material removal calculation tool is used to predict the final PV value of the evaluated area after the polishing correction technique. Zaphod predicts an improvement of the surface's flatness from 668.8 nm to 191.1 nm, which corresponds to an enhancement of 71.4%.

Using the knowledge from this and previous research, future experiments will be conducted on convex hardened steel samples. Due to the new geometrical form, the contact between polishing tool and work-piece is different, which requires a new polishing tool function. Further, increasing the pressure of the polishing tool also increases the contact

area between tool and work-piece. For this reason, a simulation model will be developed in order to obtain a new polishing tool function.

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