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Influence of different polishing materials in the material removal of steel samples

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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 and control the surface finish of the mould it is important to be able to keep the material removal constant during the polishing process of these moulds. This will provide a tactical material removal therefore allowing a controlled correction of the mould's surface geometry. The aim of this work is to study the influence of different polishing materials in the material removal rate and its reproducibility during the polishing process of hardened steel. Different polyurethane polishing materials with different fillers were tested. It was observed that the filler material of the polyurethane is crucial in order to obtain constant and reproducible results. Experiments were carried out with an industrial robot and the material removal's depth value was compared.

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KEYWORDS
Polishing; material removal; polyurethane; filler

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 part's geometry acquires the form of the respective mould. This manufacturing process is, unconsciously, present in everyone's lives. Kitchen products, plastic buckets, draughting tools and plastic toys are just some examples of the products produced by means of plastic injection. Most of plastic injection moulding parts are produced using a steel mould tool. A moulder knows that the material of the steel mould needs to fulfil unique and specific demands. This 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 have always a spherical shape, some moulds are also cylindrical shaped (Speich, Börret, & Harrison, 2011). Nowadays moulds for plastic injection moulding are still polished by hand (Börret,

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Klingenmaier, Berger, & Frick, 2008), which is why mould production is very expensive. Workers require extreme experience to achieve good polishing results especially concerning shape deviation. A robot polishing process can now be used for the polishing step of the production of steel moulds. This process brings more stability to the moulds production as the manual polishing as stated by (Speich, Börret, Harrison, & DeSilva, 2013) and (Boerret, Raab, & Speich, 2014). However, this new process brought new complexity to the polishing process with eight to fourteen parameters that can be varied. (Speich, Rimkus, Boerret, & Harrison, 2012) created a FEM model with the LS-DYNA software to study the tool load, in order to understand material removal mechanism.

Despite the stability that this new process brought to the production of moulds there are still some unknown factors. One relevant factor, in order to improve and control the surface finish of the mould, is the constant material removal and its reproducibility. This can provide a tactical material removal and therefore allowing a controlled correction of the mould's surface geometry. The goal of this work is to study the influence of different polishing materials in the material removal rate and the reproducibility of results during the polishing process of hardened steel. Different polyurethane polishing materials with different fillers were tested. It was observed that different fillers result in different material removal rates and in the reproducibility of results. The material removal research during the polishing continues, based on the previous works on PMMA (Almeida et al., 2016a) and on soft steel (Almeida & et al., 2016b).

2. Aims of the research

Robot polishing requires always a polishing tool that is composed by different parts. In the Centre for Optical Technologies, the polishing tool is normally composed by three different parts: the tool, the foam layer and the polishing material layer. The polishing tool's composition influences the surface roughness and the material removal rate during the polishing process of either plastic or steel samples. This is why the polishing tool is of great importance. The polishing material layer of the polishing tool can be made of different materials from different cloths or polyurethanes. Even though cloths are softer than polyurethanes, during this project work only the polyurethanes were used as the material removal was more important than the surface roughness. In the Centre for Optical technologies there are three different polyurethanes that can be used for the polishing tool's assembly. Figure 1 shows the three different polyurethanes that were used during this work.

As it can be seen in Figure 1, these polyurethanes can be recognised by their colour and they have different fillers, different densities and different hardness's. The goal of this work is to understand the influence of these different fillers on the material removal during the polishing process as there are three different fillers with different hardness's: cerium oxide, zirconium oxide and silica. To test these fillers, an industrial robot with an attached polishing head was used. The Table 1 shows the hardness of the different fillers of the polyurethanes and the hardness of the different samples, which were tested.

The reproducibility of results is of extreme importance when it comes to the geometry correction of a surface because it is necessary to know how much material will be removed during the time in order to acquire the necessary and desired shape. From previous experiments, it was possible to conclude that on plastic samples (Almeida & et al., 2016) and on soft steel (Almeida & et al., 2016), the reproducibility of results was achieved but still not on

LP-66	
Filler	Cerium Oxide
Density g/cm^3	0,42
Durometer (Shore A)	78

GR-35	
Filler	Zirconium Oxide
Density g/cm^3	0,59
Durometer (Shore A)	90

LP-99	
Filler	Silica
Density g/cm^3	0,43
Durometer (Shore A)	80

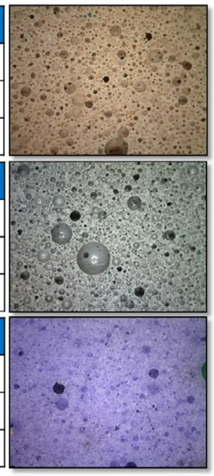

Figure 1. Different polyurethane polishing materials with different types of fillers [similar to (Universal Photonics, 2015)].

Table 1. Overview of the experimental procedure.

Material	Hardness (Vickers HV10)
Filler cerium oxide (LP-66)	102
Filler zirconium oxide (GR-35)	535
Filler silica (LP-99)	982
PMMA samples	–
Soft steel samples	211
Hardened steel samples	615

new hardened steel samples. Hardened steel is used for the production of moulds that are used in the manufacturing process of plastic injection moulding. This makes it important to know which polyurethanes provide this reproducibility on hardened steel samples, and why some don't.

3. Series of polishing experiments

3.1. Experimental procedure

As a continuation of the material removal research conducted on plastic and soft steel samples, this time the removal of material was studied on hardened steel workpieces. In order to be as successful as the polishing attempts on soft steel (Almeida & et al., 2016), during the polishing attempts on hardened steel samples, the same experimental procedure was applied. The high performance plastic mould steel M340 was used to start the polishing attempts on hardened steel samples. The workpieces had a homogenous distribution of the hardness. The average value of the measured hardness of the M340 samples was 615 Vickers.

The new workpieces were produced and ground with the purpose to make them flat and to reduce the surface roughness. Subsequently the workpieces were lapped, using a polishing lever machine, reducing the surface roughness in order to be able to conduct an optical measurement. Before the lapping process, the workpieces had an RMS value of 803 nanometres, and afterwards the RMS value was around 7 nanometres. The surface roughness of each workpiece was controlled, after they were lapped, using a white light micro interferometer in order to assure that the surface initial conditions during the polishing attempts were as constant as possible.

For the different polishing attempts, the same industrial robot ABB IRB 2400 (ABB IRB 2400, 2016), with an attached polishing head, was used. A single polishing path was polished forward and backwards in a total of 600 times with the help of an abrasive grain suspension, whose grain size was 6–12 µm. The reason behind this method was, to know the material removal's depth that happens while polishing a single polishing path using the industrial robot. An optical measurement was conducted every 100 polishing paths in order to determinate the material removal's depth and to prove if it increases linearly and if it was reproducible. An additional adapter, made of POM (Polyoxymethylene), was also produced in order to maintain the polishing slurry on top of the surface as shown in Figure 2. The reproducibility and the material removal's depth were studied during the polishing attempts. All the polishing parameters were left constant and the force applied to the pneumatic cylinder in the polishing head was varied. An overview of the polishing parameters used during the polishing attempts are in Table 2.

3.2. Measurement devices

The interferometer Schneider ALI 201 (Schneider Optical Machines, 2015) was a crucial measurement machine to measure the material removal's depth during the polishing attempts. This device provided a better resolution than a tactile measuring machine. In

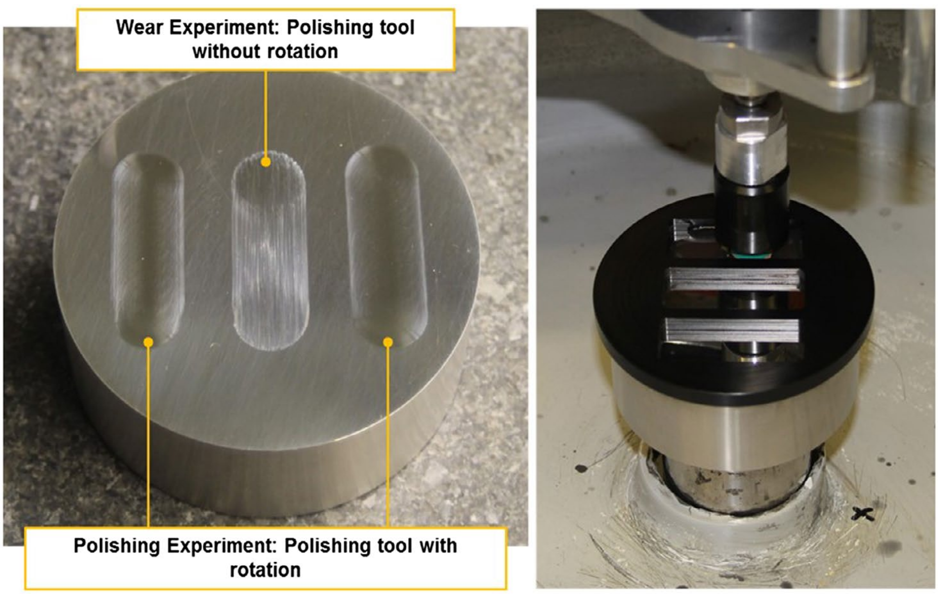

Figure 2. Left: Polishing path with and without rotation on an A506 steel sample; Right: polishing process during the series of experiments.

Table 2. Overview of the parameters used during the series of polishing experiments of 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 (grain size)	6–12 μm
Optical measurements	Every 100 paths

addition, measurements could be performed very quickly and easily. In order to properly evaluate the removal of material on steel samples, the material removal's depth (PV) value was considered. The material removal's depth (PV) value is the distance between the highest and the lowest point of the surface profile. To measure this parameter with a good accuracy, the software MetroPro from the company Zygo was used, allowing the determination of the removal of material at different stages of the process. Before the start of each polishing attempt and every hundredth polishing path, the surface of the steel workpiece was measured. With the help of the application CTV5 from the software MetroPro, it was possible to perform a correct analysis of the polishing attempts. As shown in Figure 3, different cross-section lines of the polishing path were used to analyse the material removal's depth.

After the creation of these cross-section lines, it was possible to see on another window a XY diagram. Figure 4 shows this new window, where the material removal's depth could be read. The interferometer measurements were filtered with the piston, tilt and power terms. The removal of material was calculated for each measurement until the workpiece was polished 600 times. With a table calculation tool, it was possible to obtain the variation of the material removal with the iterations of the line on steel samples.

4. Theory of the hardness of the polyurethane's filler

As already mentioned before each of the above mentioned polyurethane materials have a different filler. Each of one these fillers have also a different hardness value. For this reason

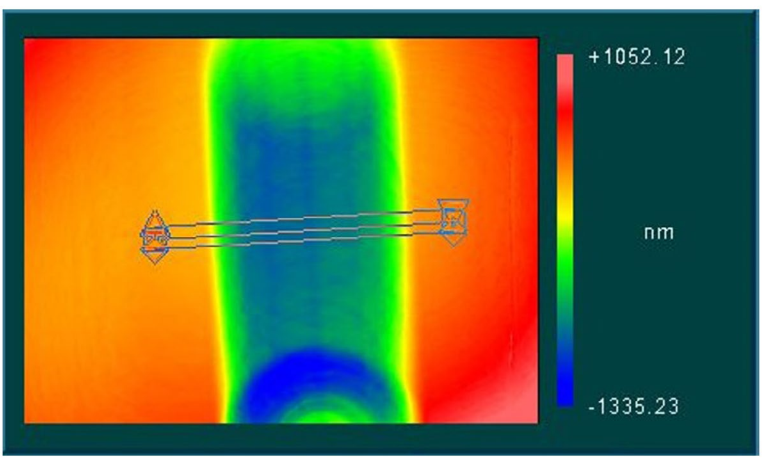

Figure 3. Cross-sectional lines of the polished path used for the evaluation of the material removal during the polishing experiments (field of view 45 × 32 mm).

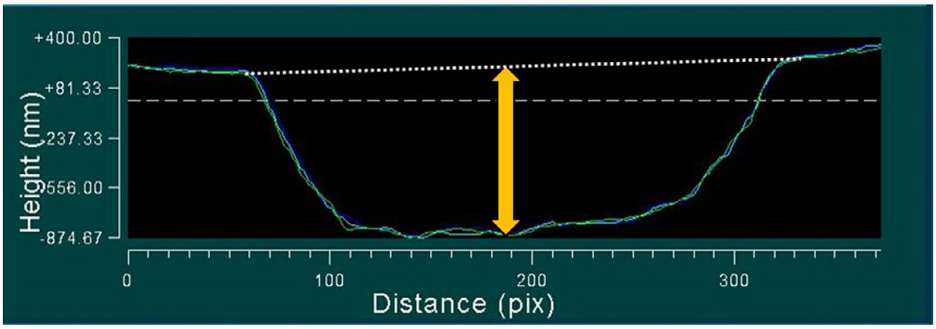

Figure 4. Cross-sectional view XY diagram of the polished path showing the material removal's depth.

it is to believe that the hardness of the polyurethane's filler has an influence in polishing process of a surface, especially in the material removal. This being said Figure 5 illustrates a polyurethane pad, a polishing grain and a workpiece, where the following theory was assumed.

It is to believe that during the polishing process the polishing grain creates a force 1 onto the work piece in order to remove material. As newton's third law says, for the force 1 there is also a reaction, which in this case is the force 2. This force 2 is then transferred and applied from the polishing grain to the polyurethane pad. Therefore, the polyurethane pad creates a reaction force 3. If the force 1 is higher than the force 3, then the polishing grains will penetrate the polyurethane pad reducing the material removal. If the filler of the polyurethane is harder, compared to the work piece that will be polished, there will be a resistance from the polyurethane to the force 1. This will prevent the polishing grains to penetrate the polishing pad, therefore holding the grains in a position, which will actively contribute to the material removal.

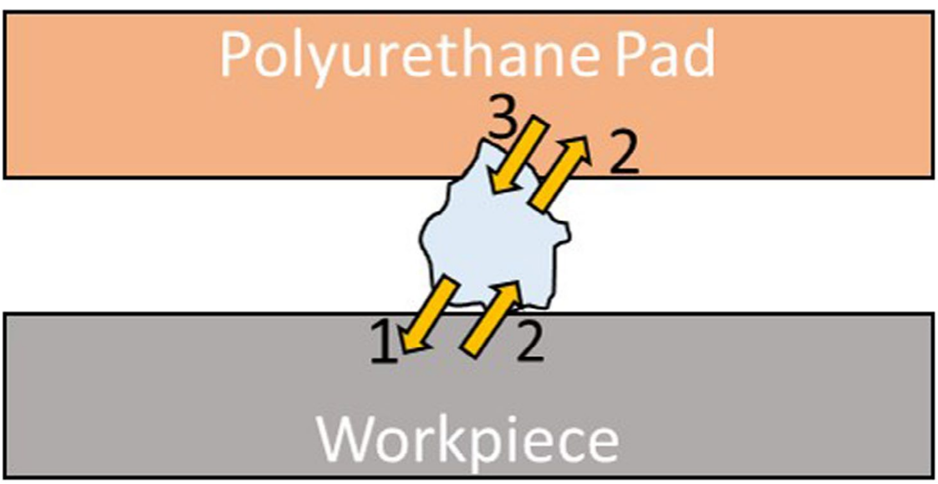

Figure 5. Schematic of polishing interaction between polishing pad and workpiece.

5. Results and discussion

5.1. PMMA polished with LP-66

To be able to reproduce always the same material removal during the polishing process is a very important aspect in order to be able to perform a correction of geometric forms. There are some factors that could influence this reproducibility such as: appropriate polishing tool, concentration of the polishing suspension or the accuracy of the industrial robot. It is important to know if the same material removal's depth can be obtained using the same set of polishing parameters, while executing exactly the same procedure. This will make it easier to understand the different polishing parameters, which can be varied and applied according to the required material removal's depth. In the previous work (Almeida & et al., 2016), it was possible to see that the reproducibility of the same material removal's depth could be achieved.

In this work, the polyurethane LP-66 was used as a polishing material of the tool together with a cerium oxide polishing slurry. As already mentioned, the same material removal's depth could be reproduced using the same set of polishing parameters and having the same initial conditions. Figure 6 shows that the same material removal's depth was achieved, while using the polyurethane LP-66 and using the same set of polishing parameters, during the polishing attempts on plastic samples. The polyurethane LP-66 has a cerium oxide filler that has a 102 Vickers hardness, which is higher than the plastic samples. This shows that the reproducibility was achieved when the hardness of the filler was higher than the workpiece's hardness, confirming the above mentioned theory.

5.2. Soft steel polished with LP-66

Further on, the same polishing attempts were conducted on soft steel samples A506 with a 211 Vickers hardness (Almeida & et al., 2016). The goal was to conduct the same experimental procedure used during the polishing attempts on plastic samples (Almeida & et

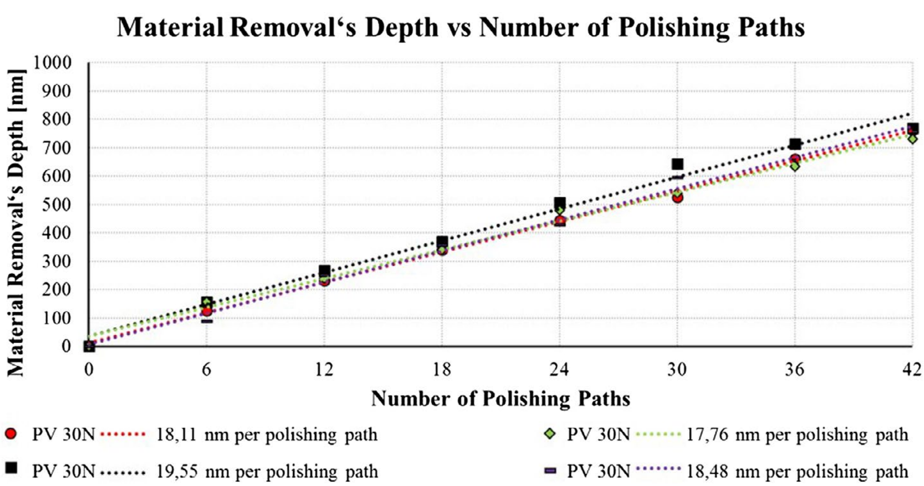

Figure 6. Different polishing attempts conducted on plastic samples using the polyurethane LP-66 and the same set of polishing parameters, showing that the same material removal's depth was achieved.

al., 2016), and see if steel also followed the Preston equation. This equation states that the material removal is linearly proportional to the applied force, which means, if the applied force increases with a factor of two, then the material removal should also increase with a factor of two. In the first polishing attempts, a single polishing path was polished and the applied force was varied from 5 N to 10 N and afterwards to 20 N. The material removal's depth of the polishing path was measured and evaluated while using the polyurethane LP-66. The polyurethane LP-66 uses a cerium oxide filler which has a lower hardness (102 Vickers) compared to the hardness of the used steel (211 Vickers). Figure 7 shows that the same material removal's depth was not achieved, while using the polyurethane LP-66 and using the same set of polishing parameters, during the polishing attempts on soft steel samples. When the same force was applied, different material removal's depths were obtained. The same happened when the applied force increased with a factor of two, where the material removal's depth did not increase as well with a factor of two. This shows that the reproducibility was not achieved when the hardness of the filler was lower than the workpiece's hardness, confirming once again the above mentioned theory.

5.3. Soft steel polished with GR-35

Afterwards a second row of polishing attempts was conducted using the polyurethane GR-35, with the goal to see if the same would happen with the material removal's depth or not. The polyurethane GR-35, as shown on Figure 1, has a different filler than the polyurethane LP-66. The polyurethane LP-66 has a cerium oxide filler while the polyurethane GR-35 has a zirconium oxide filler. The zirconium oxide filler had a hardness of 535 Vickers and the workpieces, as already mentioned, a hardness of 211 Vickers, meaning that in this situation the hardness of the filler was higher than the hardness of the samples. Figure 8 shows that the same material removal's depth was achieved while using the polyurethane GR-35 and

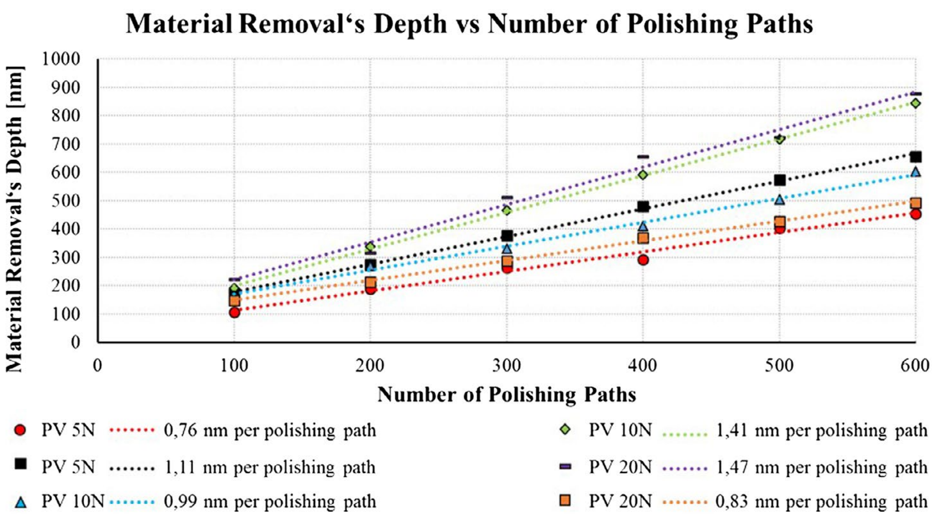

Figure 7. Different polishing attempts conducted on soft steel (24HRC) using the polyurethane LP-66, showing that the same material removal's depth was not achieved while using the same set of polishing parameters.

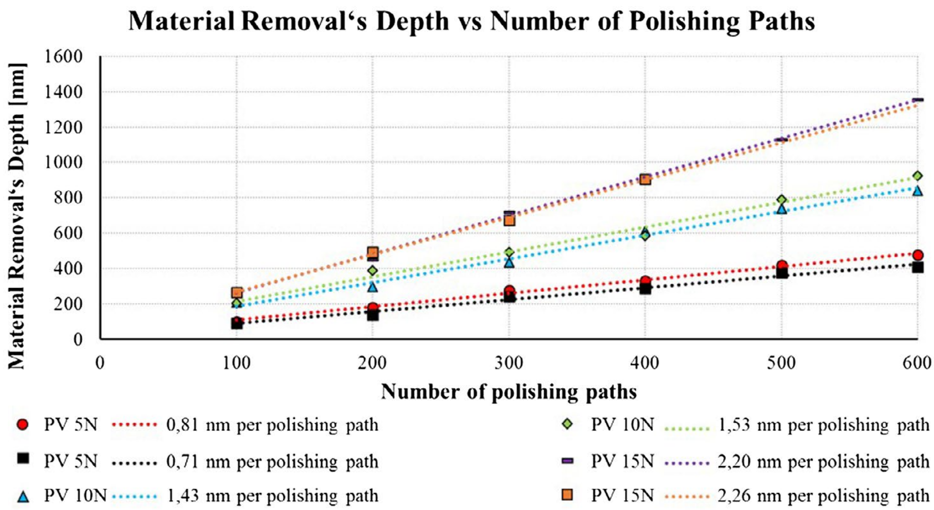

Figure 8. Different polishing attempts conducted on soft steel (24HRC) using the polyurethane GR-35, showing that the same material removal's depth was achieved while using the same set of polishing parameters.

using the same set of polishing parameters. The material removal's depth also increased with a factor of two, when the applied force to the polishing tool was increased with a factor of two. This being said, it is to believe that the above mentioned theory is true: the hardness of the filler has an important function when it comes to material removal reproducibility. If we compare the hardness of the filler with the hardness of the material in the last two materials, the reproducibility of the same material removal's depth was only achieved when the hardness of the filler was higher than the hardness of the material that was polished.

5.4. Hardened steel polished with GR-35

The production of steel moulds for plastic injection moulding uses hardened steel as a material. In order to achieve the goal of this research project and correct the geometrical shape of hardened steel samples, the material removal during the polishing process of these samples, needs to be controlled. For this reason, the same experimental procedure was once again conducted on hardened steel samples. The hardness of the new hardened steel samples was around 615 Vickers. Comparing the hardness of the GR-35's filler with the hardness of the steel samples, it was expected that the material removal's depth would not be the same, while using the same set of polishing parameters. Once again, according to the above mentioned theory for this to happen, it would be necessary for the hardness of the used polyurethane's filler to be harder than the workpiece itself.

Figure 9 shows that the material removal's depth was not the same, while using the polyurethane GR-35 and using the same set of polishing parameters. As it was mentioned above, this was expected to happen according to the theory. In this diagram, the same material removal's depth was achieved two times but with two different depths. From previous experience it was expected for the material removal's depth to be the same on every single attempt, when using the same set of polishing parameters.

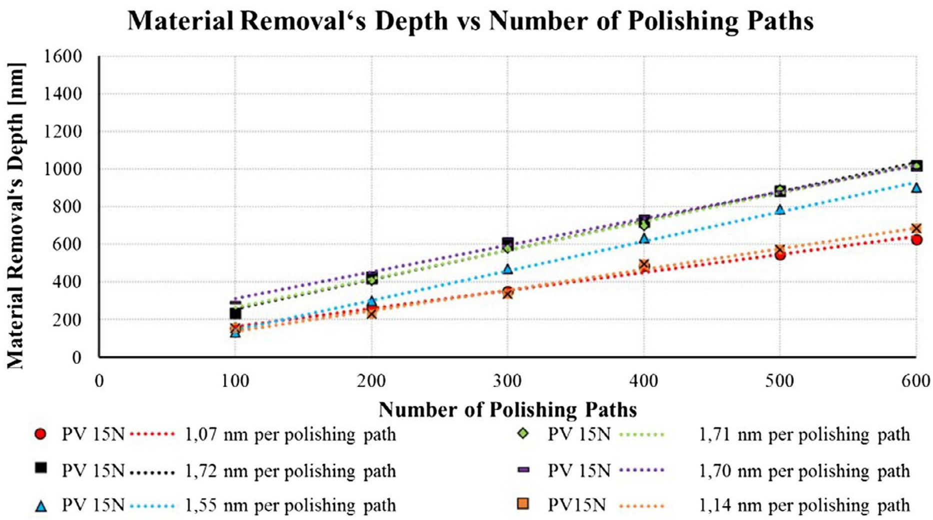

Figure 9. Different polishing attempts conducted on hardened steel (615 Vickers) using the polyurethane GR-35, showing that the same material removal's depth was not achieved while using the same set of polishing parameters.

5.5. Hardened steel polished with LP-99

After the previous statements, the same experimental procedure was used while using the new polyurethane LP-99. Once again the goal was see of the same material removal's depth could be obtained while using the same set of polishing parameters. As shown in Table 1, this polyurethane has a silica filler, which has a higher hardness than the hardened steel itself. Comparing the hardness values of each other, the silica filler has a hardness of 982 Vickers and the hardened steel 615 Vickers. Figure 10 shows that while using the same

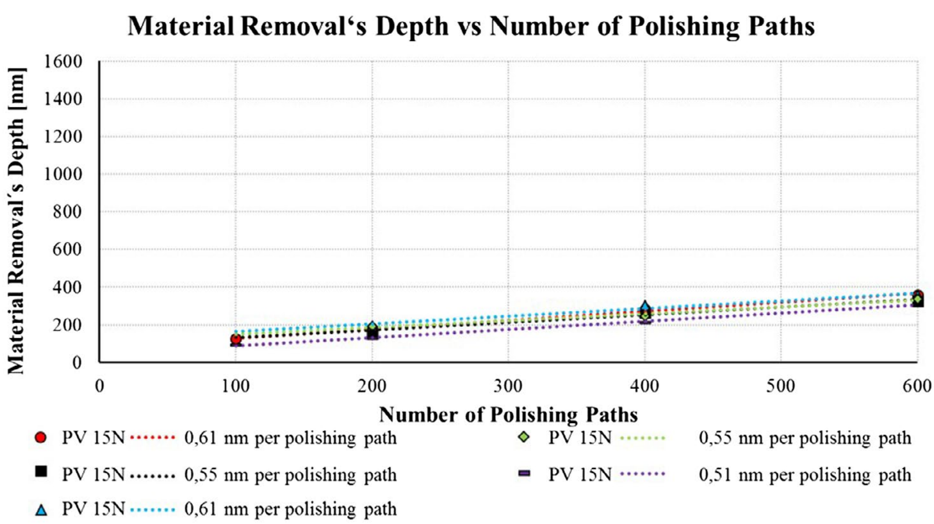

Figure 10. Different experiments on hardened steel (615 Vickers) using the polyurethane LP-99, showing that the same material removal's depth was achieved while using the same set of polishing parameters.

set of polishing parameters, the same material removal's depth was achieved on hardened steel. Taken into to conclusions all of the conducted polishing attempts on plastic samples, soft steel samples and on hardened steel samples, the same material removal's depth was only achieved when the hardness of the polyurethane's filler was higher than the hardness of the polished samples.

6. Conclusions

This research led to a stable process where the material removal's depth on hardened steel was constant and could be reproducible while using the same set of polishing parameters. The theory, that the hardness of the polyurethane's filler needs to be higher than the polished samples, in order to achieve a constant and reproducible material removal, was presumed. Different polyurethane polishing materials with different fillers were tested to prove the veracity of this theory. The reproducibility of the material removal during the polishing process was tested on three different materials: plastic samples, soft steel and hardened steel.

During the polishing attempts on plastic samples (PMMA) the polyurethane LP-66 was used. This polyurethane has a cerium oxide filler, which has a higher hardness compared to the plastic samples. In these attempts, the same material removal's depth was obtained while using the same set of polishing parameters, proving immediately the veracity of the above mentioned theory.

While polishing soft steel with the polyurethane LP-66, which has a cerium oxide filler, the same material removal's depth could not be achieved while using the same set of polishing parameters. In this case the hardness of the soft steel (211 Vickers) was higher than the filler of the polyurethane LP-66 (102 Vickers). However, when the polyurethane GR-35, which has a zirconium oxide filler, the same material removal's depth could be obtained as long the polishing parameters stood constant. In this situation, the hardness of the polyurethane's filler GR-35 (535 Vickers) was higher than the soft steel's hardness (211 Vickers) proving once again the veracity of this theory.

While polishing hardened steel with the polyurethane GR-35, the reproducibility of the same material removal's depth was only achieved two times but with different material removal rates. Comparing the both hardness's, the hardened steel's hardness (615 Vickers) was higher than the zirconium oxide filler's hardness (535 Vickers). For this reason the polyurethane LP-99, which has a silica filler, was used. During the polishing attempts on hardened steel using the polyurethane LP-99 the same material removal's depth was obtained as expected. In this case, the hardness of the polyurethane's filler LP-99 (982 Vickers) was higher than the hardened steel's hardness (615 Vickers).

It was found that the filler of the polyurethane was relevant when it comes to obtain the same material removal's depth while using the same set of polishing parameters. In order to control the material removal by obtaining the same depth, while the polishing parameters stay constant, the hardness of the polyurethane's filler needs to be higher compared to the material's hardness that will be polished.

The next goal is to correct the geometrical shape of flat hardened steel samples. As the same material removal's depth could be constantly reproduced over and over, the correction of the geometrical shape of samples is now possible. A reference measurement will be conducted with the objective to know the spots where the surface deviates from the desired shape. After knowing where the surface deviates a tactical material removal will be used in order to remove more material on the necessary spots bringing the actual shape closer to the desired shape.

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Disclosure statement

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