Towards robust polishing strategies for moulds and dies

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ABSTRACT

This paper summarises several experiments performed in order to increase the knowledge about the polishing process (e.g. to better understand the origins of different defect structures) and to develop new polishing strategies for dies and moulds with high demands on surface quality, i.e. glossy and ‘defect free’ surfaces. The polishing strategies are not only a help to avoid unwanted surface structures, they will also work as the base for automated polishing systems, which have several advantages compared to manual polishing; vibrating hand tools and monotonic work can be avoided, dust and noise levels as well as total process time can be reduced, and more consistent surface finishes from tool to tool can be achieved.

A selection of steel samples, polished with different techniques, were analysed to study how the final surface quality was influenced by e.g. the process route, the degree of purity and the microstructure. The surface quality was here represented by roughness values and SEM-images. It could be concluded that the degree of homogeneity and the purity level of the steel materials were crucial to final surface qualities; the lower amount of inclusions, the better the surface quality. Further, a classification of occurred defect structures made.

Keywords: polished tool steel, defect structures, surface roughness

1. INTRODUCTION

Polished steel moulds with high precision surfaces, often with the demand of mirror finishes, are being used in a variety of branches today [1]. The polishing process, representing the last manufacturing step of the moulds, strongly influences the properties and functions of the final parts as well as the efficiency and robustness of the whole process chain. Such properties are e.g. abrasion and corrosion resistance, tribological and optical properties, and haptics as well as visual impressions of the final components.

To be able to improve the surface quality, the fundamentals of the polishing process have to be understood; especially the origins of different types of defects and defect structures (such as pull-outs, inclusions and ‘orange peel’) which still miss for sufficient explanatory models. Further, this gives rise to the need of a metrology framework for accurate surface characterisation. Earlier studies have shown that non-contact 3D-surface texture analysis is a sufficient way to characterise high gloss polished surfaces [2] [3], but to our knowledge no standardised methods exist for this category of surface finish.

In the context of this research work, process strategies for manufacturing ‘defect free’ high gloss polished tool steel surfaces have been developed in purpose to end up in robust strategies for avoiding any defects and/or giving tips about what to do when surface defects appear.

2. METHODS AND MATERIALS

Various process technological experiments on tool steels were performed to get better explanations to the origin of defects. From Dambon [4] it is known that different influencing parameters exist, such as steel composition, microstructures, steel manufacturing processes (e.g. degree of purity), and different polishing kinematics and systems, that affect the polishing result. For this reason these parameters, beginning with the steel composition, were considered in a project founded by the German Research Association, Deutsche Forschungsgemeinschaft (DFG).

The results are summarised into robust process strategies for generating ‘defect free’ surfaces in order to:

- support manual polishers to avoid defect structures and to reduce the polishing time
- be transferred into a robot assisted polishing system, which is also part of the research work at the Fraunhofer IPT. The final goal is to find a system that
will minimize the manual polisher’s often monotonous work in unhealthy conditions [5]. An automated polishing system will also reduce the dependency of the skills and experience of individual polishers.

The polishing experiments were accomplished on three different polishing machines; one from the optics industry for polishing spherical geometries (Fig. 1), one from the metallography for plane samples (Fig. 2) and one typical manual polishing system (Fig. 3) to be able to compare manual work of a polisher to more automated systems.

The samples were estimated visually with a light optical microscope to get a good overview of the whole surface of the samples, scanned with a SEM (Scanning electron microscope) to get a closer look on any defect or defect structure, and measured with a white light interferometer to get detailed 3D images and height information which in turn can be translated into different 3D parameters, e.g. the roughness parameters $S_a$ and $S_z$ (Arithmetical mean height and Maximum height of the surface) [6].

The first experiments were centred on different steel compositions and microstructures. Ten different steel grades were analysed, of which four are included in this paper; see Tab 1.

### Table 1: Selection of examined tool steels

<table>
<thead>
<tr>
<th>Material No.</th>
<th>DIN - Symbol</th>
<th>Hardness</th>
<th>Remelted</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2343</td>
<td>X35CrMoV5-1</td>
<td>48-50 HRC</td>
<td>ESR</td>
</tr>
<tr>
<td>1.2367</td>
<td>X38CrMoV5-3</td>
<td>48-50 HRC</td>
<td>No</td>
</tr>
<tr>
<td>1.2083</td>
<td>X42Cr13</td>
<td>52 HRC</td>
<td>No</td>
</tr>
<tr>
<td>1.2379</td>
<td>X153CrVMo12</td>
<td>60 HRC</td>
<td>No</td>
</tr>
</tbody>
</table>

### 3. RESULTS AND DISCUSSION

The main focus during all experiments was the final surface quality, which below is discussed in correlation to different ‘influence factors’.

#### 3.1 Microstructure and composition vs. $S_a$ & $S_z$

As can be seen in Fig. 4, the 1.2379 steel has the highest roughness values and well defined inclusions (Fig. 5). The explanation for this is its high carbon content which on the one hand gives a good wear resistance for the material, but on the other hand, that is an important point for the polishing process, gives rise to many hard and large primary carbides in its basic matrix (see Fig. 5, left). This steel has a high chromium content which is added for the corrosion resistance, but as chromium has a high affinity to carbon, this results in chromium carbides, which can be seen in the results from the SEM/EDX-analysis in Fig. 5, bottom.
Despite lower roughness values, the 1.2083 steel has also chromium carbides in its material structure. But because of the lower carbon content, the amount of the carbides is not that high and the polished surface quality becomes better.

Concerning the steel grades 1.2343 mod. and 1.2367 there is no clear evidence for the influence of the steel composition. Here the polishing results are more affected by the microstructure. As can be seen in Fig. 6, the 1.2343 mod. has an optimal martensitic structure, while the 1.2367 shows, despite a martensitic structure, dense segregations with primary carbides.

Figure 5: Chromium carbides - steel grade 1.2379

Figure 6: Microstructure Contrast - Etching with 3% Nital

3.2 Classification of surface defects

Another focus towards robust process strategies is the classification of surface defects. Fig. 7 presents different kinds of surface defects detected during the experiments. The defect structures were divided into three groups depending on their shape and dispersion; ‘Defects affecting wide areas’, ‘Line shaped defects’ and ‘Defects locally affecting the integrity’. A similar classification of defects was made in [2].

Figure 7: Classification of surface defects

More detailed information (such as size/shape of the actual defect and clear pictures of it) and suggestions of possible avoidance strategies shall be given for every defect type in a future ‘defect chart’ for high gloss polished tool steels. Below a selection of the defects presented in Fig. 7 are discussed.

Defects affecting wide areas

Waviness and roughness can be combined with form deviations into “figure deviations” (DIN 4760) [7], but are usually analysed separately. However, the transition where form deviations pass into waviness, and waviness into roughness are smooth and application dependent.

Waviness is here defined as the deviation of the original geometry in the range of mm - µm. It often appears during the manual polishing because of non-uniform pressure distribution. The consequence of the appearance is a high post processing effort. It can only be avoided if the pressure distribution is even, which in turn requires a great experience in the manual polishing process.

Roughness, in contrast to waviness, is the unevenness in the range of µm – Ångström. It is here on the one hand considered as a defect since smooth surfaces are vital for high quality tool steels, i.e. the goal of the polishing process is to minimize any “mountains” and “valleys” in the surface. If that is not properly done, the surface roughness is too high (traditionally measured with profilers) which means that the surface is too rough compared to the requirements – it is a surface defect. However, the roughness can not
really be avoided, only minimized (it is a matter of the scale, as discussed in [8]), and so it could be on the other hand considered as a surface property rather than a defect.

Orange-peel can be described as many flat gaps side by side whereby an effect of an orange-peel (or like an irregular pattern of a golf ball) occurs (See Fig. 8).

It often appears after too long polishing times, if too high pressures are applied and/or if too soft or wrong sized carriers are used. Thus, since this defect seems to be an aspect of chosen polishing technique rather than a material problem, the knowledge and experience about polishing strategies are vital to avoid ‘over-polishing’ which lead to the described orange peel structure.

Line shaped defects

The difference between scratches and grooves is the direction of the tracks. While scratches have no direction and appear because of the polishing (diamond) grain, grooves are directed, often deep and in most cases from the pre-preparation steps (e.g. grinding or turning), see Fig. 9.

Scratches are the nature of the mechanical polishing and too deep scratches occur when too high pressures or wrong carriers have been used. The polishing grain breaks into the surface and pulls a track behind itself. The smaller the polishing grain, the softer the tool is and the lower the pressure is, the smoother the scratch and so the surface roughness.

Pull-outs might be the most interesting defects, as they appear as peaks on injection moulded plastic parts. Pull-outs occur, as the name indicates, when carbides or non-metallic inclusions break out of the steel matrix. Five different scenarios are imaginable for the interaction between a diamond grain and a steel matrix containing carbides (see Fig. 10); 1. A typical mechanical abrasion of steel caused by a diamond grain (no carbide particles involved), 2. A diamond grain strikes a large primary carbide, which stays in the surface as it is still enclosed by the steel matrix, 3. Secondary carbides, which are smaller than the diamond grain, are removed out of the steel matrix and will not affect the surface quality, 4. and 5. Carbides having the same size as the diamond grain, or are even larger, are not easily removed out of the steel matrix, but will be cut into pieces or pulled-out by the diamond grain. The last scenario is generating the undesirable defects on mirror finished surfaces; spread over larger areas, i.e. scattered pull-outs, commonly known as pitting.
Another reason for the pull-outs are non-metallic inclusions (NMI), e.g. oxidic and/or sulphidic particles occurring as line shaped or globular inclusions. NMI can, as the carbides, break out and leave holes or stay in the steel matrix, but in some cases only the softer material around the NMI is removed leaving a “stuffed hole” with the disadvantage that water can enter, ending up in corrosions around actual inclusion (see Fig. 11).

Figure 11: Non-metallic inclusions

3.3 Degree of purity vs. Sa & Sz

One steel grade – 1.2343 – remelted with four different methods was analysed. The first steel was open melted in an electric arc furnace without any remelting afterwards. The second one was remelted with the “Electro Slag Remelting” (ESR) method. With this remelting method the carbide precipitations and the NMI are minimized. An even more homogenous material is achieved with the third remelting method, the “Pressure Electro Slag Remelting” (PESR). The difference to the ESR technique is that the steel is remelted among an inert gas atmosphere, which minimizes the NMI (especially the oxides) in the steel material even more than the ESR technique. The last remelting method included in the study was the “Vacuum Arc Remelting” (VAR). The remelting process takes place under vacuum to reduce the content of gases, e.g. oxygen and nitrogen.

All samples were manually polished and tested for their degree of purity (represented in the K0/K1 value) in order to find a correlation between the roughness values and the K0 and K1 value [9].

Fig. 12 shows the roughness values Sa and Sz of the polished samples. It is clear that the roughness values are low for all four manufacturing processes. Compared to the degree of purity (Table 2) a correlation can be stated; the better the degree of purity, the lower the roughness values. But this statement is only valid for the average roughness values. Studying the statistical spread, the difference of the roughness values is not definitely given.

Table 2: Comparison of the purity values with the roughness values

<table>
<thead>
<tr>
<th></th>
<th>K0</th>
<th>K1</th>
<th>Sa</th>
<th>Sz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open</td>
<td>2.25</td>
<td>0.75</td>
<td>1.8</td>
<td>17.8</td>
</tr>
<tr>
<td>ESR</td>
<td>6.3</td>
<td>3.8</td>
<td>2.1</td>
<td>21.8</td>
</tr>
<tr>
<td>PESR</td>
<td>1.0</td>
<td>0</td>
<td>1.8</td>
<td>19.7</td>
</tr>
<tr>
<td>VAR</td>
<td>0.9</td>
<td>0</td>
<td>1.9</td>
<td>17.9</td>
</tr>
</tbody>
</table>

In contrast to the purity and roughness values, the visual estimation of the samples by a light microscope and a SEM visualise an important difference between their surface qualities. While the VAR polished steel seems to have almost no defects, the ESR remelted steel and the open melted steel possess many NMI.

With help of a MATLAB-tool, developed at Fraunhofer IPT, it was possible to count the defects (even very small ones up to two pixels) and display the area of the defects in histograms (Fig. 13).
The histograms in Fig. 13 are based on 15 light microscope pictures per sample. Every picture is converted in a black/white picture and the black pixels are counted. In these diagrams, it can be seen that the VAR steel has the lowest amount of defects, while the open melted steel shows more than 3000 small defects.

These results give new questions to the metrology, since it is assumed that the roughness values, which are considered here, are not informative enough to characterise every surface defect (also pointed out in e.g. [2] and [3]).

4. CONCLUSIONS AND FUTURE

With the first results of the influence parameters “steel composition” and “microstructure”, a first step towards the understanding of the polishing process was made. The following factors are important for the polishing result:

- The steel composition, especially the amount and size of primary and secondary carbides.
- The microstructure of the steel – to achieve a mirror finished surface, a homogenous microstructure is required.
- The choice of the manufacturing process, since it controls the purity level and the amount of non-metallic inclusions in the material; the “impurities” in the steel matrix can not be completely avoided, only minimized with special process routes and manufacturing processes of the steels.

Further it could be concluded that roughness values alone can not fully describe the surface quality of a high gloss polished steel surface.

In future work other parameters influencing the polishing result, such as polishing kinematics and systems, will be examined to get a broader understanding of this complex process.

Parallel to the development of new and automated polishing systems, new surface analysis methods are required to get more accurate and objective surface quality controls. One step towards a common vocabulary for surface defects on polished steels is the classification table, which will be further discussed within both academia and industry. The goal is to develop ‘a new polishing standard’ including instrumentation, methods and estimation criteria’s for surface evaluation of high gloss polished tool steels.

5. ACKNOWLEDGEMENT

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6. REFERENCES