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Analysis of defect mechanisms in polishing of tool steels

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Abstract

The polishing process in the mold and die making industries is nowadays still predominantly done manually. As a consequence of this the quality of the mold strongly depends on the worker's skill, experience and also on his form on the day, patience and concentration. Furthermore, polishing is in most cases the last manufacturing step of the process chain and occurring surface defects are critical and often a "knock-out-criterion". Until now there exists no systematical acquisition or explanation for the appearance of this polishing defects. This paper shows the results of experiments describing the polishing process and defect mechanisms in order to generate process strategies for manufacturing "defect-free" high-gloss polished tool steel surfaces. Ten different steel grades were analyzed in order to see how the final surface quality is influenced by e.g. the polishing system, the degree of purity or the microstructure. The surface quality is represented by roughness values and SEM-images. It could be concluded that the degree of purity and the homogeneity of the steel material are crucial to the final surface quality. The lower the amount of inclusions, the better the surface quality. Furthermore, a classification of the occurred defects during the polishing process is shown in this paper.

Keywords Production process · Polishing · Defect mechanism

1 Introduction

Polished steel molds with the demand of mirror finish, are being used in a variety of branches [1] and the polishing process represents the last manufacturing step of the mold. This process step is still a handcraft and the surface quality depends on the experience of the polisher. In addition this manual work is very time consuming, not predictable or plannable and from the experience of mold and die making companies the most expensive step in the whole process chain.

The mold and die making industry in Europe is currently facing a low-cost competition with Asia and other low-wage countries. This new competitive situation forces the mold and die making industry to produce faster and more cost effective. One solution, for reaching this aim, is the improvement of manufacturing processes by the automation of the ever increasing demands of polishing.

For this purpose, the fundamentals of polishing have to be understood; especially the origins of different types of defects and imperfections, as well as their structures (such as pull-outs, inclusions and 'orange peel') which are still missing for sufficient explanatory models. In the context of the research at Fraunhofer IPT, process strategies for manufacturing "defect- free" high gloss polished tool steel surfaces have been developed. The purpose is to elaborate guidelines to avoid defects and about what to do if surface defects appear.

2 State of the art

Several approaches for explaining the material removal mechanisms of polishing exist [2–7]. The most common

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models for steel can be summarized into three main hypotheses (Fig. 1).

The *Abrasion Hypothesis* describes the removal mechanism as an abrasive process. Roughly speaking this mechanism is similar to the grinding process but employing very small grains. Since the abrasive particles in the polishing fluid are much smaller than the grains during the grinding process and only temporary bound in the soft polishing tool, the roughness is smaller and the surface smoother.

In the *Flow Hypothesis* it is assumed that the peaks of roughness are driven or melt into the valleys of the surface because of local pressure and temperature peaks. By this process a smoothing of the surface is achieved.

The *Chemical Hypothesis* is based on the theory that during the polishing process chemical reactions between the boundary layer of the workpiece and the polishing suspension proceed.

The polishing process can be an interaction of these 3 hypotheses, so that mechanical and chemical influences are responsible for the removal rate and the surface quality of a polished sample. They describe the removal rate during the polishing process, respectively the appearing interactions, but give no exact quantitative characterization for the removal rate. For this purpose several empirical process models exist. The most common model for the prediction of the removal rate is the *Preston Hypothesis* [9].

$$\frac{dz}{dt} = K_P \cdot p \cdot v_R$$

This equation shows that the removal rate (dz/dt) is proportional to pressure and relative velocity and the constant K_p named the Preston Constant. K_p includes all chemical and mechanical interactions between tool and boundary layer of the workpiece. p is the pressure per unit area, v is the velocity between polishing tool and sample and dz/dt is the rate of material removed (cutting depth per unit time).

If on the one hand the equation is simple, but on the other hand the coefficient K_p is difficult to determine. There are a lot of different parameters which interact

Fig. 1 Removal mechanisms in steel polishing [8]

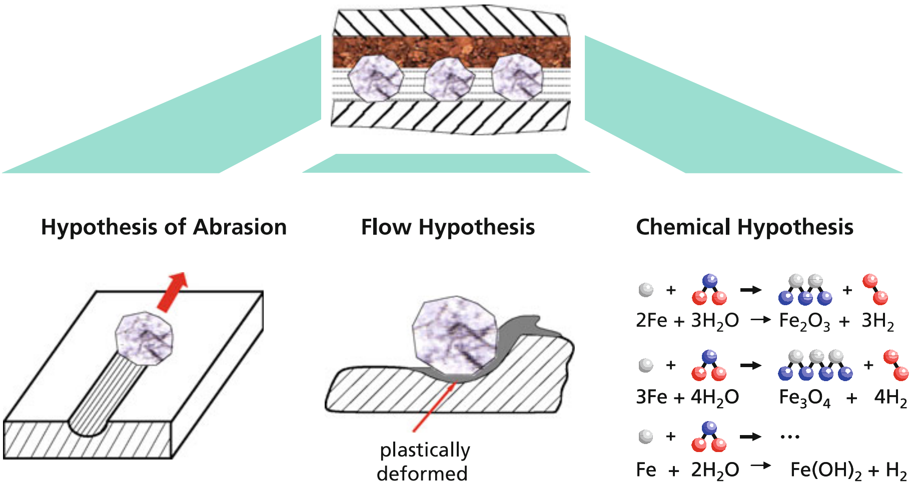
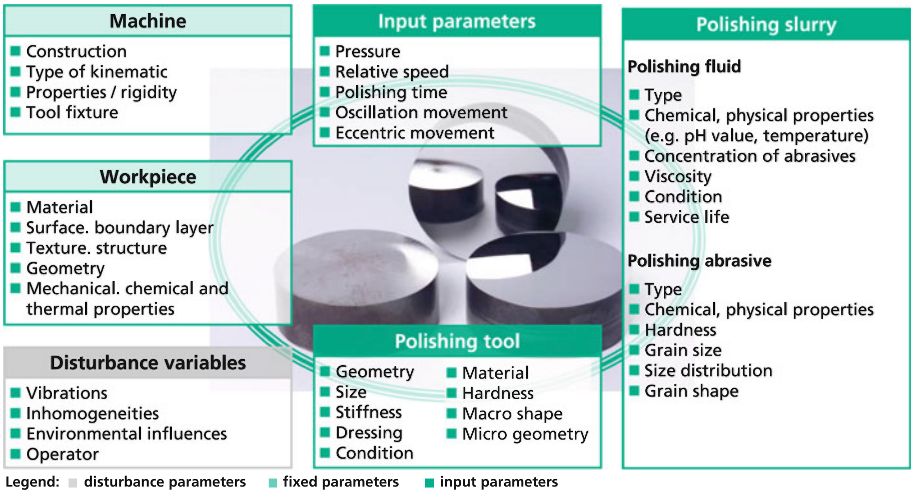


Fig. 2 Influencing parameters during the polishing process [10]



during the polishing process. Figure 2 gives a short overview of these parameters.

In addition it is a fact that during polishing of steel with diamond slurry the removal rate is dominated by the abrasion hypothesis [8].

2.1 Removal behavior of tool steels

From other publications [10, 11] it is known, that the hardness of the steel is an important influencing parameter. The softer the steel, the lower the removal rate and the higher the roughness values.

This behavior can be explained because of the steel's ductility. During the polishing process plastic deformation processes cause a displacement of the material but no removal. This is why the energy input for softer steel grades is higher and the removal rate lower, as the polishing process starts with a deformation of the soft material until the abrasive process starts.

2.2 Interaction between the polished steel surface and polishing abrasives

At the polishing system "steel and diamond suspension", the material is removed in the area between the steel surface and the polishing grain. The hard polishing grain gets into the workpiece surface and removes material from the surface. This abrasive removal process can be described by a model from Zum Gahr [12]. Four different interactions between the abrasive particles and the material are described in this model (Fig. 3).

Microploughing shows that the polishing grain after getting in contact with the surface, pushes the loosened material along, which finally agglomerates at the sides of the groove. Ideally no material is removed with the micro ploughing. But if more and more polishing grains get to the same area, the material is again and again pushed to the sides, until it breaks out. This phenomena is called microfatigue. During the microcutting the grain gets deep into the material and due to the maximum forming ability of the material a chip is formed, which matches in the best case to the groove. Microcracking is the result of high tensions, which are put into the material from the abrasive particles. This mechanism exists at brittle materials (e.g. ceramics), while microcutting and microploughing mainly appear at ductile materials (e.g. steel).

According to [8] it can be said that during the polishing process of hardened steel the mechanism of microcutting is dominant, while microploughing appears during the polishing of soft steel structures. Regarding the achievement of high surface qualities, the mechanism of microcutting should be preferred, since the material is cut off far cleaner from the surface. In contrast to this, during the microploughing the roughness value even raises because of the accumulated material at the side of the grooves.

Despite of many experiments in the field of steel polishing, the reason of appearance of imperfections is still not clear and logical explanatory models for describing them are missing. This research work starts on the basis of this knowledge with the goal to analyze and explain the defect mechanisms in polishing of tool steels.

3 Experimental setup

The polishing experiments were accomplished with two different polishing machines. The first machine (Fig. 4) is a

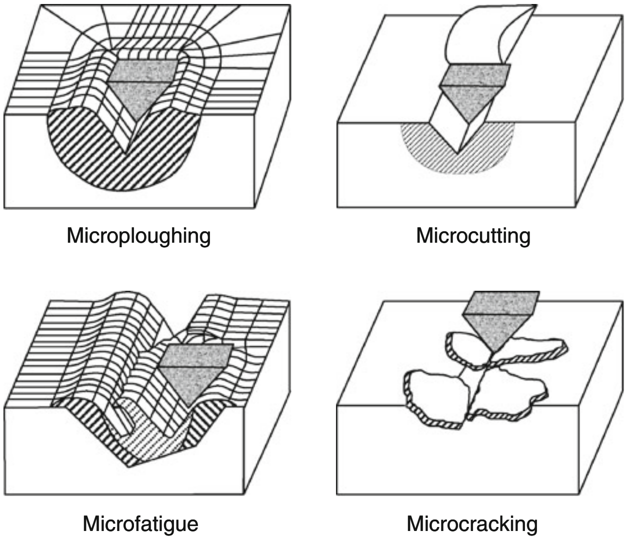


Fig. 3 Different interactions between abrasive and steel surface [12]

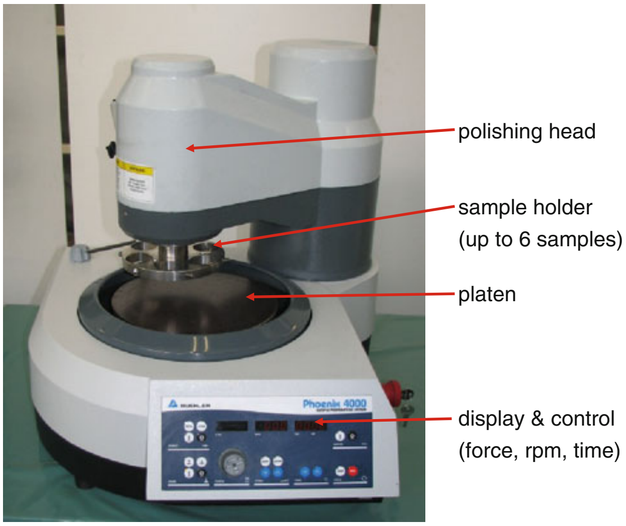


Fig. 4 Table polishing machine for finishing of plane samples

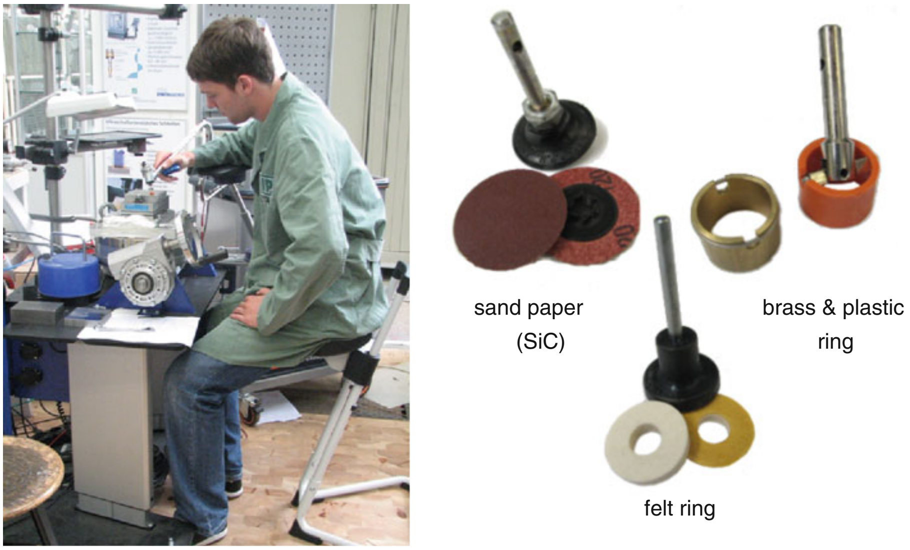


Fig. 5 Manual polishing device (*left*) and a selection of common polishing tools (*right*)

standard grinding and polishing machine for metallographic applications—a Phoenix 4000 V/1 by Buehler GmbH. This machine is able to polish up to six plane samples simultaneously. The polishing head rotates at a constant rate of 150 min^{-1}, while the rotational speed of the polishing disk can be varied between 50 and 600 min^{-1}. During the experiments the rotational speed of the polishing disk was constant set to 150 min^{-1}.

The second machine, which was used to gain knowledge of the manual work of a polisher, was a manual polishing system JOKE® Ergo-Work from JOKE® (Joisten & Kettenbaum, Fig. 5 left).

The manual polishing can be realized by different hand pieces, brass or plastic rings, lapping stones, polishing pads and several diamond pastes for polishing with rotational or translational tool movement (Fig. 5 right).

The samples were evaluated visually with a light microscope to get a good overview of the whole surface of the samples and scanned with a SEM (scanning electron microscope) to get a closer view on defects. Additionally, measurements with a white light interferometer were accomplished to provide a detailed overview of the surface and roughness parameters, e.g. Sa and Sz (arithmetical mean height and maximum height of the surface) [13].

Ten different tool steels were analyzed (Table 1), of which nine are commonly used in the mold and die making industry for gloss and mirror finish. Although one steel grade (1.2379) is no typical polishable steel, it was analyzed on purpose, in order to clearly see the influence of different composition. The four bold marked steel grades will be discussed further in this paper as a discussion of all examined steel grades would blast the extend of this text.

Table 1 Examined tool steels

Material no.	Abbreviation (DIN)
1.2083	**X40Cr14**
1.2311	40CrMnMo7
1.2316	X36CrMo17
1.2343	X38CrMoV5-1
1.2343mod.	**X35CrMoV5-1**
1.2367	**X38CrMoV5-3**
1.2379	**X153CrMoV12**
1.2738	40CrMnNiMo 8.6.4
1.2738mod.	26MnCrNiMo 6.5.4
1.2767	X45NiCrMo4

4 Results and discussion

The main focus of the experiments was the surface quality, which is discussed in the following chapters in correlation to different influencing factors.

4.1 Influence of the steel composition and microstructure

The measured values and SEM images were compared to the composition and microstructure of the different steel grades in order to find correlations to the polishing results. To keep track of the results, four chosen steel grades (bold in Table 1) polished with the table polishing machine are shown in the pictures below.

As can be seen in Fig. 6, the 1.2379 steel has the highest roughness and well defined inclusions (Fig. 7). The explanation for this is the high carbon content which leads to many hard and large primary carbides in the basic matrix

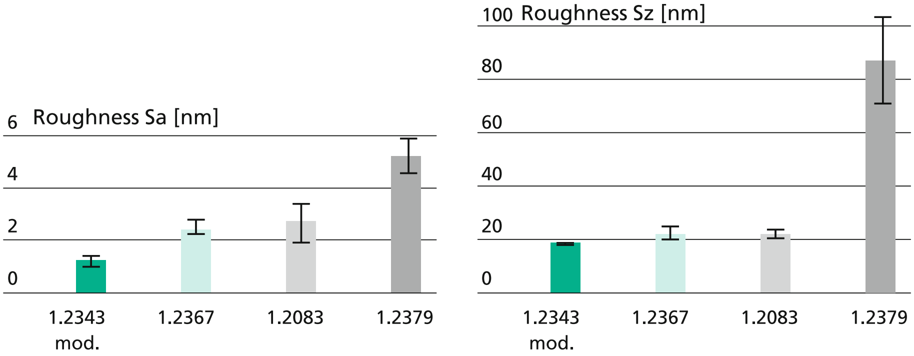


Fig. 6 Roughness of polished tool steels

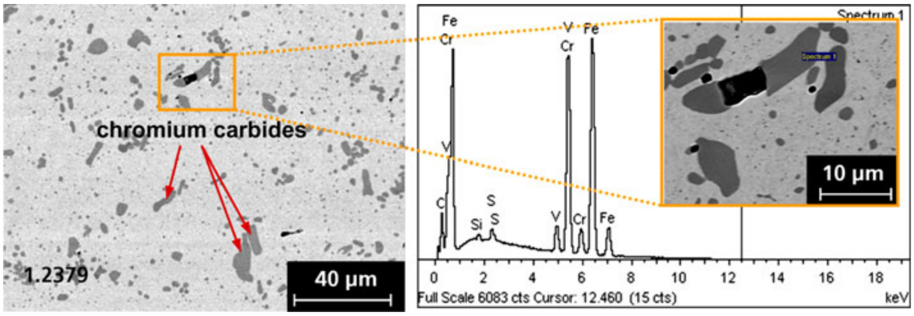


Fig. 7 Chromium carbides of the steel grade 1.2379

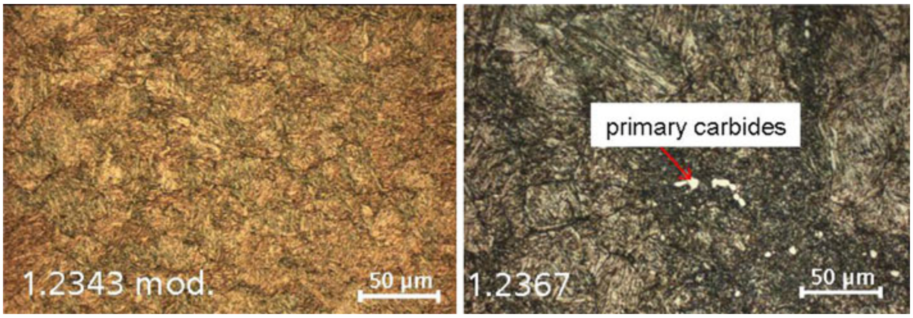


Fig. 8 Material structure contrast—etching with 3% Nital

(see Fig. 7, left) and in the following polishing process to pull-outs.

Steel 1.2379 has a high chromium content which was added for 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 EDX (energy dispersive x-ray)-analysis in Fig. 7, right.

Despite low roughness values (Fig. 6), the 1.2083 steel also includes chromium carbides in its material structure. Because of the lower carbon content than 1.2379, the amount of the carbides is not that high and therefore the polished surface quality improves.

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 effected by the microstructure. As can be seen in Fig. 8, 1.2343 mod. has an optimal martensitic structure, while 1.2367 shows, despite a martensitic structure, dense segregations with primary carbides. These segregations are the reason for higher roughness, as they tend to break out during the polishing process.

4.2 Influence of the steel manufacturing process

The second experiment focused on the manufacturing process of steel. Only one steel grade—1.2343—remelted with four different methods, was analyzed.

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. According to this remelting procedure the carbide precipitations and the non-metallic inclusions (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

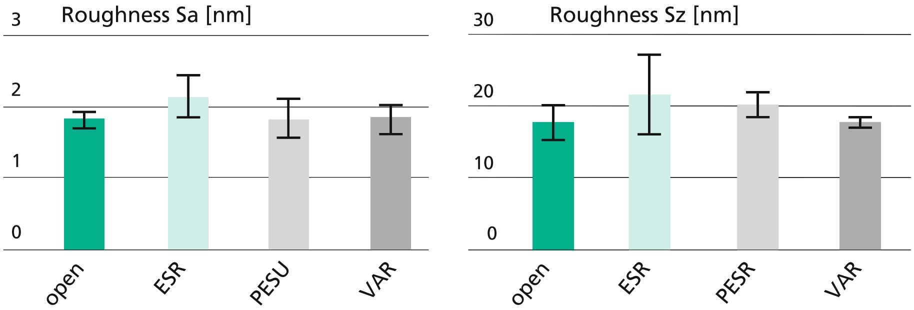


Fig. 9 Roughness of polished samples of 1.2343 with different degrees of purity

that the steel is remelted among an inert gas atmosphere, which minimizes the NMI (especially the oxides) in the steel material. The forth remelting method included in the study was the Vacuum Arc Remelting (VAR), which is done 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 values in order to find a correlation between the roughness values and the K0 and K1 value [14].

The K-value gives information about the amount of the surface ratio of the non-metallic inclusions. The smaller the number behind the letter K, the more “small inclusions” were considered for the measurement (according to special tables). K0 is the most accurate K-value determination, which is used for vacuum remelted steels.

Figure 9 shows the roughness Sa and Sz of the polished samples. It is clear that the roughness is low for all four manufacturing processes. Compared to the degree of purity (Table 2) a distinct correlation can be stated; the better the degree of purity, the lower the roughness. But this statement is only valid for the average roughness. Studying the statistical spread, the difference of the roughness is not definitely given.

In contrary to the missing clarity of the correlation between purity and roughness, the visual evaluation of the samples by light microscope and SEM prove an important difference between the surface quality. 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, it was possible to count the defects (even very small ones up to two pixels) and display the total area of the defects in histograms (Fig. 10).

The histograms in Fig. 10 are based on 15 light microscope pictures per sample. In these diagrams, it can be seen that the VAR steel exhibits the lowest amount of defects, while the open melted steel shows more than 2,000 small defects. These results give new questions to metrology, since it is assumed that the roughness parameters are not sufficient to characterize surface defects (also pointed out in e.g. [15] and [16]).

Table 2 Comparison of the results of the purity values K0 and K1 with roughness parameters Sa and Sz (Steel 1.2343)

	K0	K1	Sa	Sz
Open	2.3	0.8	1.8	17.8
ESR	6.3	2.1	2.1	21.8
PESR	1.0	0	1.8	19.7
VAR	0.9	0	1.9	17.9

4.3 Classification of surface imperfections

This leads to another important aspect, which is the classification of surface defects. The challenge is to find a common and precise vocabulary to classify the defects. As a first step towards an uniform polishing vocabulary, a defect chart was created on the basis of the European standard EN ISO 8785 [17]. A similar topic for micro-components was already analyzed at the institute for metrology, automation and quality science (BIMAQ) [18], where the detection of imperfections with different types of metrology characterization methods was the focus.

This defect chart (Fig. 11) concentrates only on high gloss polished tool steels and the occurring defects during the polishing process.

A couple of the defects presented in Fig. 11 are discussed in more detail below.

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. It often appears after too long polishing times, if too high pressures are applied and/or if too soft or wrong sized polishing tools are used. Thus, since this defect seems to be an aspect of the chosen polishing technique rather than a material problem, the knowledge of and experience in polishing strategies are vital to avoid “over-polishing”.

Waviness belongs to the form deviations (DIN 4760) [20] and is 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

Fig. 10 Histograms of counted defects on polished samples of 1.2343 with different degrees of purity

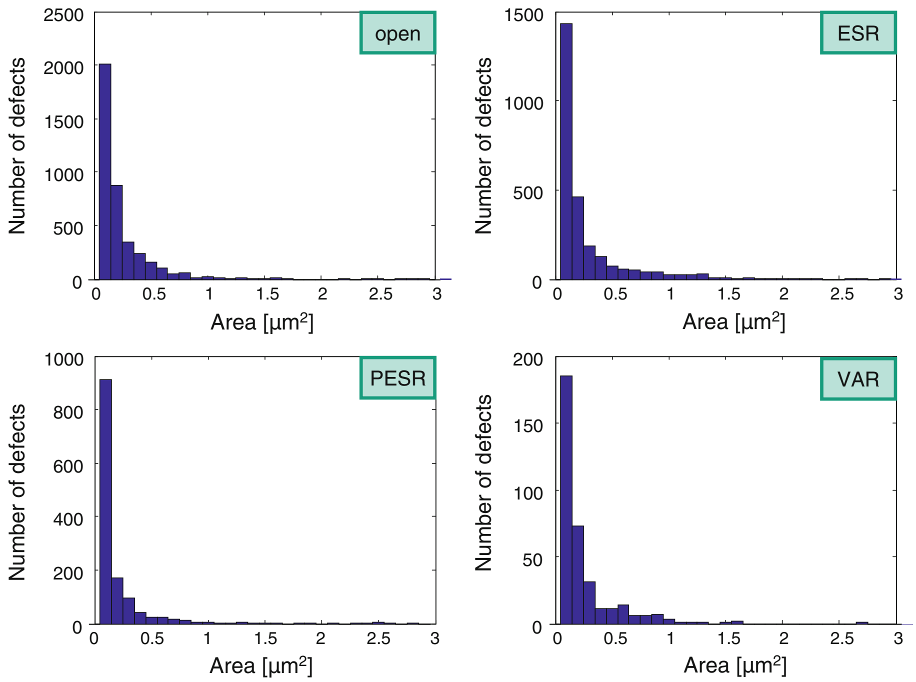
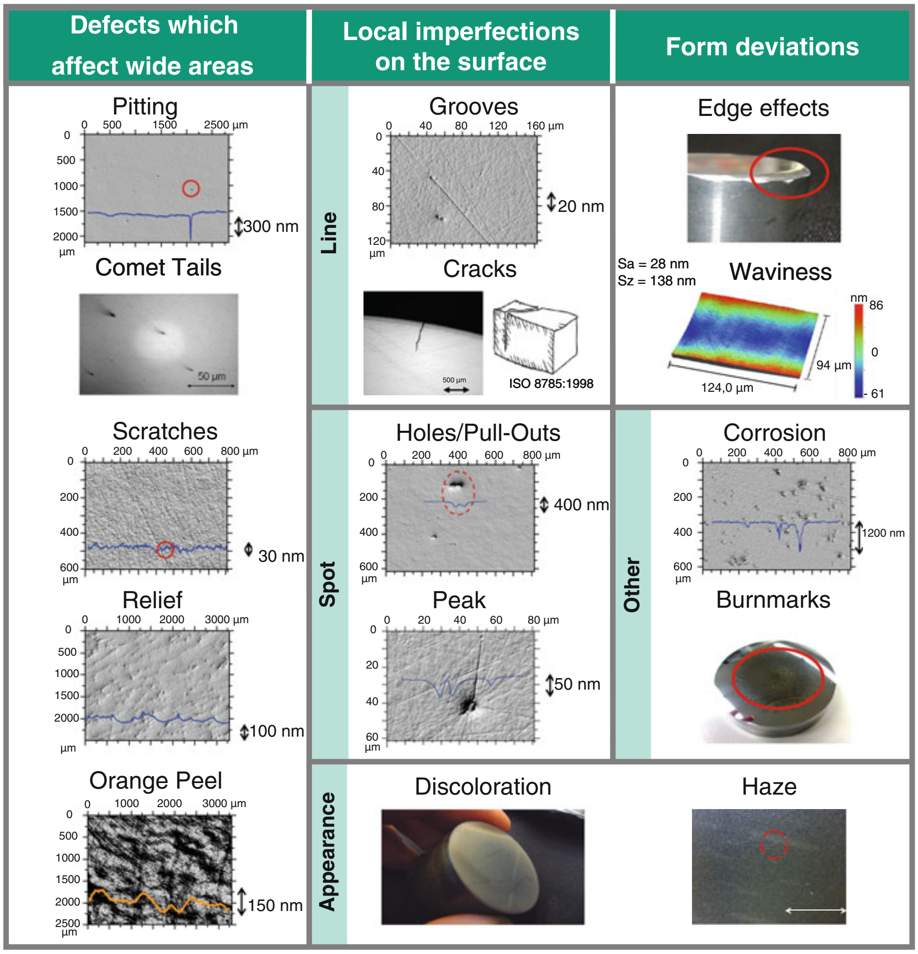


Fig. 11 Classification of surface imperfections [19]



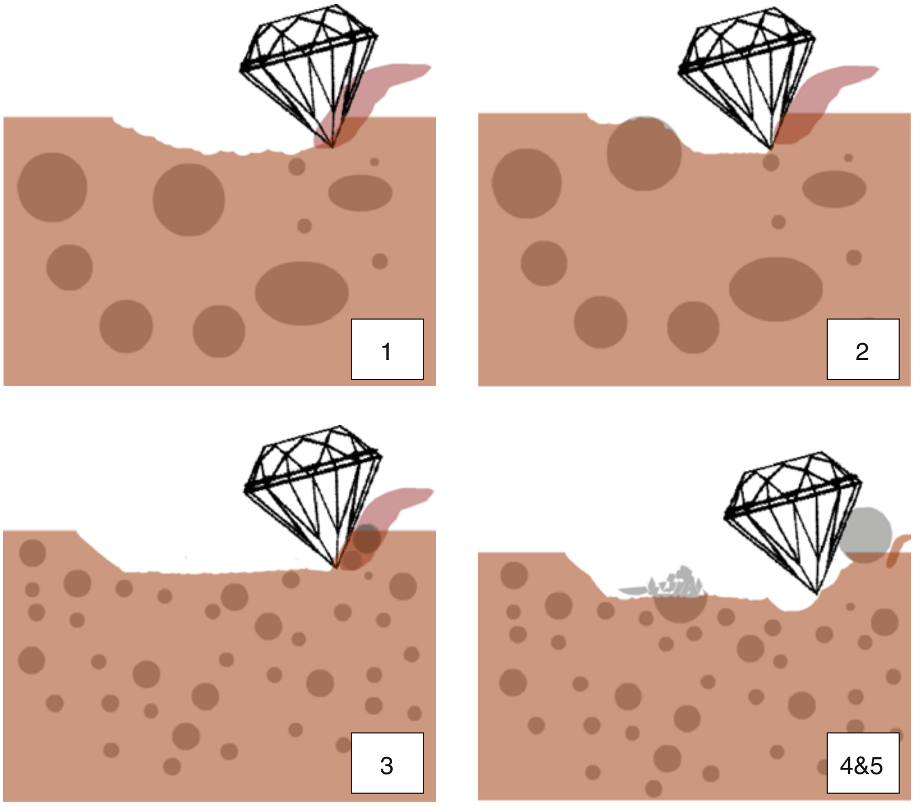


Fig. 12 Interactions with diamond grain and steel surface [8]

distribution is even, which in turn requires a great experience in manual polishing.

The difference between *scratches* and *grooves* is the direction of the tracks. Scratches have no specific direction since they appear because of the polishing (e.g. diamond) grains. Grooves are directed, often deep, and in most cases formed during the previous preparation steps (e.g. grinding or turning). Scratches are an inherent effect of the mechanical polishing and occur if high pressure or wrong tools have been used. The polishing grain gets into the surface and pulls a track behind itself. The smaller the polishing grain, the softer the tool and the lower the pressure, the smoother the scratch and so the surface roughness.

Pull-outs might be the most interesting defects, as they appear as peaks on injection molded plastic parts and are the reason for rejects, which may lead to judicial issues between polisher, mold maker, steel manufacturer and end user. Pull-outs occur, as the name indicates, when carbides or non-metallic inclusions are pulled 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. 12);

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 from 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 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.

On basis of this defect table and the according manifold experiments, polishing strategies for various examined steel grades were formulated and will be presented on the SFB/TR4 homepage.

5 Conclusions and future research

For the technological experiments of polishing tool steels, different influencing factors were considered. In this publication the influences of steel composition, microstructure and steel manufacturing process (degree of purity) on the polishing quality were shown.

It can be concluded that the following factors are important for the polishing result:

The steel composition, especially the carbon and chromium content. On the contrary small differences in the alloying elements such as manganese, molybdenum and vanadium have no effect to the polishing result.

The microstructure of the steel—to achieve a mirror finished surface, a homogenous microstructure (without segregations) 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 can be concluded that roughness measurements alone can not fully describe the surface quality of a high gloss polished steel surface. 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.

The classification table of surface imperfections provides a first common vocabulary of the polishing process.

The results of all influencing factors are finally summarized to polishing strategies for generating defect free surfaces. These strategies will help the polisher to avoid defects and to save time. Furthermore these strategies can be transferred to a robot cell with an integrated force-controlled polishing spindle in order to automate the polishing process [21, 22].

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