A quantitative method to estimate high gloss polished tool steel surfaces

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Abstract

Visual estimations are today the most common way to assess the surface quality of moulds and dies; a method that are both subjective and, with today’s high demands on surfaces, hardly usable to distinguish between the finest surface qualities. Instead a method based on non-contact 3D-surface texture analysis is suggested. Several types of tool steel samples, manually as well as machine polished, were analysed to study different types of surface defects such as pitting, orange peel and outwardly features. The classification of the defect structures serves as a catalogue where known defects are described. Suggestions of different levels of ‘high surface quality’ defined in numerical values adapted to high gloss polished tool steel surfaces are presented. The final goal is to develop a new manual that can work as a ‘standard’ for estimations of tool steel surfaces for steel producers, mould makers, polishers etc.

Keywords: Tool steel, Replication, Surface analysis, Surface characterisation

1. Introduction

Quality controls and/or specifications of the surface condition of injection moulding tools are commonly based on qualitative estimations where reference surfaces are compared to actual ones. Most often even simple roughness parameters like the Ra-value (the arithmetic mean deviation of the assessed profile [1]) are used to better describe the surface condition. However, these kinds of procedures are subjective, and 2D measurements often lack in their ability to describe surface structures. More objective (and standardised) methods for surface evaluations of ‘mirror-like’ tool steel surfaces are, to the authors knowledge, not existing, therefore new methods/procedures are suggested; well-known surface criteria of tool steel surfaces, collected via visual estimations, were translated into quantitative parameters based on 3D surface measurements.

The first idea is based on the concept to divide the geometrical features on the surface into three components; form, waviness and roughness (see Fig. 1), depending on their spectrum of wavelength. This separation make it possible to distinguish between different types of defect structures, thus a detailed surface characterisation can be performed where type, dimension and distribution of defects can be detected.

The second idea is to build up the surface topography by hills, dales and saddle points (see Fig. 2), which is more comparable to visual estimations [3]. A way to visualise useful information is the change tree, which shows the relationships between hills, dales and saddle points; to avoid irrelevant data, Wolf pruning is applied which reduce the amount of hills/dales by merging small contiguous hills/dales into larger ones. In this case, the output values are ‘accepted’ or ‘not accepted’ surface quality where the limit values are based on known surface structures and visual estimations of the test samples.

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2. Experimental work

Tool steel samples produced via different process routes (powder metallurgy - PM, ingot casting - IC, continuous casting - CC and electro slag remelting - ESR), heat treated to various hardness levels (48 to 60 HRC), were included in the study. The samples, all plane surfaces, were either manual or machine polished in order to achieve a high gloss surface appearance, i.e. a ‘mirror-like’ surface. A typical surface preparation sequence include one grinding step to secure a plane surface, one to six grinding steps (e.g. with aluminum oxide stones), and finally three to five polishing steps with various diamond abrasives.

2.1 Evaluation technique

A Phase Shift Technology MicroXam™ optical interferometer operating in the phase-shifting mode (quoted vertical resolution: 0.1 nm; sampling: 1 µm) was used to measure and examine the surfaces at different magnifications. Surface analysis based on the 10x-images (measurements with the magnification of 100) were made in MountainsMap® Premium® and SurfStand v5.0.1; all images were levelled with respect to the least squares plane and a form removing step (polynomial fitting of order 2) was applied to get rid of any remaining curvatures. Surface parameters included in this paper are [1] [3] [4]:

- \( S_q \) - Root-mean-square deviation of the surface [nm]
- \( S_k \) - Kernel roughness depth (roughness depth of the core) [nm]
- \( S_{tt} \) - Texture aspect ratio (values near 1 means isotropic surface, values is near 0 means anisotropic surface)
- \( S_{dd} \) - Number of dales per unit area [1/mm²]
- \( S_{sv} \) - Five point pit height [nm]
- **Mean height of islands (MHoI)** - Sum of the maximal heights of the islands above a threshold (which in this case is defined as 2xSk in height from the mean plane) divided by the number of islands [nm]
- **Mean surface of islands (MSol)** - Sum of the surfaces of the islands above the threshold (which in this case is defined as 2xSk in height from the mean plane) divided by the number of islands [µm²]

| Numerical value | Qualitative evaluation scale | Quality level |
|-----------------|-----------------------------|---------------|
| 1               | Surface in very good condition without pitting | Good surface quality |
| 2               | Surface in very good condition with min. pitting | Good surface quality |
| 3               | Surface in good condition with min. pitting | Good surface quality |
| 4               | Surface with min. structure with min. pitting | Accepted surface quality |
| 5               | Surface in good condition with some pitting | Accepted surface quality |
| 6               | Surface in good condition many pitting | Accepted surface quality |
| 7               | Surface with structure and many pitting | Non-accepted surface quality |
| 8               | Surface with structure and many deep pitting | Non-accepted surface quality |
| 9               | Surface with deep structure and pitting all over | Non-accepted surface quality |

Table 1: Summary of the ranking-scale used for the visual estimation (no instruments were used); low values correspond to ‘good surface qualities’, high values to worse ones. Adapted from [SR lic].
All parameter values given in the tables are average values based on five, randomly chosen measurement points from each sample (except the parameter values given in figure 4, 5 and 6 which are based on one single value - the actual measurement point). A similar study reported that 5-10 measurements were needed to get stable mean values for most parameters (±20% at the 95% confidence level) [3]. The visual estimation, used as a reference to the measurements, was based on two criteria, the condition of the surface structure (e.g. relief and orange peel) and pitting. Part of the samples was estimated in a well-known polishing shop, part of them at Halmstad University. To be able to compare this qualitative evaluation to the calculated surface parameters, the results were translated into numerical values (see table 1).

3. Results and discussion

3.1 Defect classification – defining the geometry of a defect

Based on interviews, questionnaires [5], literature studies (e.g. [6-9]) and analyses of test samples a summary of defect structures was presented in [2]. That work has further been developed into a more complete defect classification in this study (see Fig. 3). All defect structures are presented as shown in the example for the inwardly directed defect pitting (Fig. 3, right). This particular defect is a well-known problem within industry and, as it is often spread over the majority of the surface, it is relatively easy to detect by a trained (naked) eye. One way to separate pitting from other inwardly defects is to calculate the MHoI, describing the mean height of the defects (note: the images are inverted), and MSoI, describing the mean defect area. As can be seen in figure 4 the pitting are smaller than the holes (have lower MSoI values), however they are not always more shallow as in the example in figure 3.

Figure 3: Left; a schematic view of included defect types, from the left: inwardly directed defects, outwardly directed defects, areas that appear different compared to its surrounding, and wavy textures. Right; an example of how ‘pitting’ can be described in a defect chart.

Figure 4: An example of how pitting can be separated from holes by the MSoI value (lower images inverted). *Given Sk values are based on filtered surfaces; Robust Gaussian, cut-off 150 µm.
3.2 Quantitative method for extraction of defects

This stepwise analysis method is described in figure 5, where a non-accepted sample is serving as an example; after the levelling and form removal operation, the image is further modified to separate any wavy textures from out- and inwardly directed defects. This enables a detailed study of the defect structures included in the defect chart with one exception - the ‘areas that appear different compared to its surrounding’, which need to be further studied.

![Image of defect chart](image_url)

Figure 5: Based on one single interferometer measurement, a sample ranked as 7 (see table 1) in the visual estimation, due to orange peel and pitting in the surface, was analysed in three steps. The table shows suggested acceptance levels; grey cells correspond to the values of the example surface – i.e. it fails due to orange peel and inwardly defects.

Figure 5 also presents numerical values for three acceptance levels of high gloss polished tool steel surfaces in order to define an objective estimation of the surfaces. The values are chosen with respect to the visual estimations of the samples, i.e. they are based on the opinions of the polisher. Table 2 summarises results based on included samples, which cover both accepted and non-accepted surface qualities. As can be seen, different numerical values correspond to different types of defect structures; coloured cells point out interesting values.

![Image of table](image_url)

Table 2: Summary of analysed samples; numerical values, acceptance levels and defects are presented sample by sample.

3.3 Quantitative surface estimation

To get a more general evaluation of the surface, i.e. to limit the output to one single value - accepted or non-accepted – the procedure in figure 6 can be used. The surface is modified in the same way as before, but instead of using a Robust Gaussian filter, Wolf pruning is used which in this case marks the borders between dales. Defect free (or nearly defect free) surfaces consist of many small dales, surfaces with defects of less and bigger ones (provided a Wolf pruning of 10%). To separate accepted and non-accepted surfaces the S5v value (= valley depth) is divided by the Sdd value (density of dales) – a value below 1 means an accepted surface quality. This is because deeper inwardly or outwardly directed defects affect the segmentation, and so lower the Sdd value and increase the S5v value; the quotient will exceed 1. A summary of the results are presented in table 2 above; the method fails in some few cases where no values are presented - it needs to be further improved.
Figure 6: Based on one single interferometer measurement, a sample ranked as 7 (see table 1) in the visual estimation, due to orange peel and pitting in the surface, was analysed in two steps. Suggested acceptance levels are presented; grey cells correspond to the values of the example surface – i.e. it fails due to too extensive defect structures.

4. Conclusions

Even though further analyses are needed it can be concluded that the methods presented can be used as objective surface estimations; non-accepted defect structures were detected with help of interferometer measurements and defined by a few surface parameters. E.g. pitting, which is an inwardly directed defect, could be defined by calculating the MSOl- and MHol values.

5. Future work

Reference samples and moulds, with defined defect structures, will be studied in order to measure in what extend the defects are transferred into different types of plastic plaques; the goal is to find the size/shape limit where the defects do not affect the final quality of the plastic surfaces. Further studies will also include the ‘areas that appear different compared to its surrounding’, and improvements of the suggested methods.

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