LOCAL STUDIES OF MACHINED SURFACES

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1. Introduction

Chip removal ranks among the machining processes where higher surface quality is required. The surface used to be evaluated to a very limited extent, mostly involving roughness characteristics. Nowadays, tools, instruments and experience are available that allow comprehensive analysis of the state of surface and correlations with resulting properties. The author of this paper has been dealing with comprehensive examination of machined surfaces. It was based on state of the art knowledge which is often summarized in the surface integrity concept. The techniques included scratch testing, nanoindentation hardness measurement, cyclic impact testing and local corrosion testing. Description of surface is more accurate if it includes not only Ra roughness but also additional surface characteristics, in particular the areal roughness.

2. Application of Surface Integrity Knowledge

At the author's department, great attention is paid to surface integrity. This is given by the set of instruments at the department and by the cooperation with the Department of Machining Technology at the Faculty of Mechanical Engineering of the University of West Bohemia in Plzeň. This cooperation expands to include practical applications thanks to scientific and industrial projects concerning both machining accuracy and the state of surface. Four years ago, there was only one company on the European market offering defined finishing of machined surfaces, the Baublies AG [1]. Its contribution consists in developing a standalone roller burnishing tool which offered numerous advantages. One of the most important ones is the fact that it is adjustable within a certain range of diameters and this adjustability is useful for worn rollers as well. On the other hand, it also has its drawbacks: the drilled hole must have certain characteristics related not only to accuracy but also surface morphology and hardness. It cannot be used as a combination tool either. Another drawback is its high price which is many times higher than the prices of drills and even broaches. Despite these drawbacks, this company's range of products has no competitor in Europe. This company can boast not only market innovations but also scientific contribution, as it was its product range which introduced the surface integrity concept into engineering practice. Although the American standard on surface integrity, ANSI B211.1 1986, has been presented three years ago, it has been used very little in practice.

The purpose of this article is not to detail the individual factors whose theoretical aspects are covered in the standard. That type of knowledge has been presented in a number of papers [2 - 4]. This study aims to describe a specific evaluation of machined surface of cast iron, focusing both on the resulting accuracy and other surface integrity aspects. Application of surface integrity to practical issues requires a very cautious approach. First, the results obtained are extensive and may not be always relevant to practical use. Second, they might be conflicting. The state of surface used to be described by means of roughness characteristics. Surface and sub-surface defects received some attention as well. In more profound studies, these were even correlated with the material's fatigue behaviour. The comprehensive nature of those results requires that they are treated in an appropriate context and with proper correlations. Measurement of residual stresses may serve as an example. A number of publications have been devoted to residual stress measurement, not only by the author of this paper [2, 4] but by other experts as well [5, 6]. First problems arise in selection of a method of determining residual stresses with certain (in)accuracy. Others are related to its interpretation and usability in practice. In the real world, problems might occur with the usability of solely residual stress-based findings for rejecting non-conforming products or for predicting service properties. This is why the author and his team have aimed the experiments and analyses at broader description of individual properties. At first sight, these may lead to conflicting findings but in wider context they will be more accurate than mere residual stress measurement whose interpretation is difficult and often impossible.

3. Surface Integrity Factors

This study was aimed at the surface integrity of drilled holes with the depth of 3D where the required tolerance grade was IT6 – IT7. The material was gray cast iron. The tools included those of the company HOFMEISTER s.r.o. own design and other competitors' drilling tools. The cylinders had the following dimensions: d = 26 mm, l = 36 mm. After drilling the holes, the cylinders were cut to specimens along their axis to allow analysis of the machined surface.

Experiments and factors monitored included the following: surface topography measurement, surface roughness measurement, surface microstructure observation, microhardness measurement, nanoindentation hardness testing, scratch testing, corrosion tests, impact testing.

3. State of Surface in Drilled Holes

The specimens were documented using light microscope to allow comparison of drilled holes. Micrographs of surfaces of holes were compared visually and by means of image analysis software.

The surface of the hole drilled with one of the competitors' tools (A) exhibited dark spots where the machined surface was pulled out during drilling, and light areas where no extraction occurred. Sharp edges of graphite flakes are locations of high stress concentration, contributing to the pull-out of graphite particles or even parts of surface attached to them (see Fig. 1). Analysed surfaces showed conspicuous parallel markings running at about 30° to the axis of the cylinder, regardless of the tool used. These are probably traces of surface deformation caused by the tool flank while the tool was being removed from the hole. These irregularities can be regarded as undesirable effects impairing the quality of the machined surface. This condition of the surface cannot be detected by other means than by observation and documentation. These surface irregularities do not affect roughness values. That is why the roughness data cannot be regarded as conclusive, as it does not reflect the actual condition of the surface. Despite this fact, a number of authors accept roughness values as decisive data for description of surface state. The author's department has found a proven method of documenting the surface using light or scanning confocal microscope, evaluating its features by image analysis and measuring areal roughness.

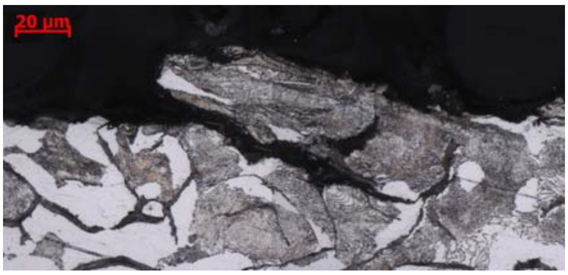

Fig.1 – **Mechanism of pull-out of surface in the drilled hole.**

The amount of extracted surface depends on the stress state and on the forces between the tool and machined surface. It is assumed that the higher the internal stress (particularly the tensile stress) in the machined surface, the greater the amount of graphite pulled out with the matrix by the drilling tool and the greater the depth from which the material is extracted. The quality of the machined surface is impaired by this process. This finding indicates that the time-consuming measurement of residual stresses, which is difficult to interpret, is not necessary to obtain the relevant information.

4. Surface Microstructure

The study of the surface is necessary not only for its relief but also for revealing the internal structure. It is the heterogeneous microstructure of grey cast iron for which this approach proves effective, as the location of material pull-out is governed by the location of graphite under the surface (Fig. 1). The surface relief is affected by the state of microstructure in a definite manner. This microstructural condition changes in dependence on the introduced stress and temperature. These relations proved true mainly during drilling of D2 tool steel when, with certain machining parameters, the drilled surface re-hardened and its hardness increased markedly again (Fig. 2).

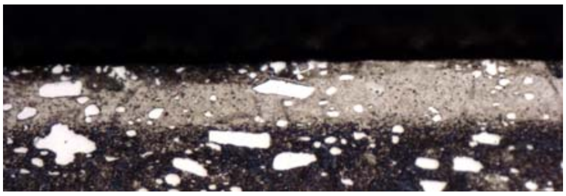

Fig.2 – **Surface hardened to the depth of 30µm. D2 steel with surface hardness of HV0.01 =1,107.**

5. Surface and Subsurface Microhardness

Higher hardness is often required to improve the resistance of surface to contact loads. In shaft-hole clamp joints, hardness is also related to the structure's stiffness. Drills of the Hofmeister company's own design were intended for drilling high-precision holes for these very applications. For this reason, the experiments were focused on hardness and related properties.

Microhardness of specimens was measured along two parallel lines located about 50 µm apart and in the same distance from the surface. The first line was just beneath the machined surface and was planned to include the plastic deformation zone created by the cutting tool. The second line was to show the hardness of unaffected material. By comparing average hardnesses along both lines and average standard deviations, one can assess the state of the material surface after machining. Hardness was measured as HV0.015 microhardness in all cases. Compared with C45 steel which was also tested in the present project, the increase in the amount of deformation in cast iron is much smaller.

The results show that changes in hardness of the material were not consistent. In some cases, hardness of the machined surface decreased, despite the expected influence of plastic deformation. In this case, certain impact of the tool wear cannot be ruled out, as under normal conditions, i.e. normal machining temperature, cast iron should not exhibit softening. The decline may also be explained by the effects of the cutting process, which does not introduce sufficient amount of strain or even lacks the parameters to make the material strengthen above its initial level. The tool A retained its initial parameters throughout the cutting process. The tool B lost its ability to cause work hardening in the material at the end of the drilling process. The Hofmeister tool, on the contrary, caused the material to harden gradually. In this case, results of measurement confirmed the results of previous metallographic observation. The special tool with its special geometry proved beneficial as well.

6. Nanoindentation Measurement of Microhardness

Nanoindentation measurement has a number of advantages over conventional microhardness measurement. They include the accuracy and a number of outputs providing reliable description of the state of surface and hardened surfaces in particular. Nanoindentation curves offer corrected values with regard to the indenter used and results which are comparable with those of conventional hardness testing. Availability of information on elastic-plastic behaviour of the surface is useful as well. In this case, such information proved important in assessing the differences between holes made by different tools.

The measurement was carried out in the base material, i.e. in the region unaffected by drilling (a). Another region was the machined surface (b). In this case, unlike in the results of previous conventional microhardness measurement, the effect of hardening was found in all surfaces of drilled holes. The average increase in nanoindentation microhardness HIT when moving from the region "a" to the region "b" was the same in the case of the Hofmeister tool and the B tool: 47%. With the tool A, this increase was 55%. From the viewpoint of elastic-plastic strain ratio, highest values were found for the tool B: 27.2 %. For the Hofmeister tool, the elastic-plastic strain ratio was smallest (24.2%).

7. Surface Analysis by Scratch Testing

This scratch-based test is a typical modern method for assessing the adhesive-cohesive behaviour of thin film-substrate systems. Using this method for evaluation of homogeneity and hardness of machined surface resulted from its historical basis employed by Mohse in comparing hardnesses of different materials. The purpose of measurement was not only to determine the surface hardness but also the surface uniformity along the entire hole depth of 36 mm. Two 18 mm scratches were created on the surface under a constant load of 40 N. Scratch channel volumes were measured using Olympus Lext 3100 confocal microscope at the magnification of 200.

Volumes of scratch channels on the machined surface of the cast iron show that the largest value (indicating the lowest surface hardness) is associated with the element machined by the tool A. In contrast, the lowest scratch channel volume was found in the element drilled with the tool B. Scratch channel volumes are not very different. The differences are within the measurement error range, which is why these results do not confirm the conclusion that the tool A produces the softest surface.

Results of this analysis have been included in this paper on purpose, although they do not correspond to the above findings and are in contradiction to the assumption that scratch channels are less deep in materials with higher hardness. These contradictory results illustrate the difficulties inherent to characterising comprehensive properties of real-world surfaces in relation to surface integrity.

8. Corrosion Resistance Tests

Cast iron is a heterogeneous material consisting of tough metal matrix with embedded graphite particles represented by flakes in this case. These particles disrupt the coherence of the matrix. For this reason, creating surface films is more limited in this case than in case of steels. The purpose of the corrosion test was to assess the impact of the state of machined surface on the corrosion behaviour. This simple corrosion test does not clearly indicate if the dominant aspect is the surface relief or the activation energy increased by plastic deformation. The most rapid corrosion was seen in specimens drilled with the tool B. The other drilled holes showed very similar results. After finding additional correlations, it was shown that the surface created by the tool B contains more defects, pull-out regions and higher hardness. In this case, the surface relief proved more significant than the plastic strain introduced, as the latter was minimal in the machined surfaces.

9. Cyclic Impact Test

Impact resistance of surfaces of holes drilled by three tested types of tools was evaluated by means of the cyclic impact test. It consists in cyclic impact loading of the surface. The blows are repeated with certain pre-defined frequency and energy.

The examined surfaces were subjected to identical loads consisting in 5,000 impacts with the lowest energy available in the setup. The purpose of the test was to measure the properties of those surface areas where different effects of the cutting tools were expected. The test created an impact crater which was then examined. The crater dimensions were measured and characteristics of degradation processes were determined (surface layer delamination, cracks). These results were correlated.

The craters were measured in a light microscope. The state of the material in craters was documented using a scanning electron microscope.

The dimensions of craters did not differ significantly. It is due to the fact that the state of machined surfaces does not vary in such a manner which could be detected under the presently used impact test conditions. Upon more detailed examination of dimensions and nature of defects in the crater, the surface machined with the Hofmeister tool was found to be of higher quality than those created by the other two tools. Detecting the state of machined surfaces more accurately would require much lower energy of the impact body than in the current test. As the results show, a surface machined with high-quality tools has no significant impact on degradation processes under impact loads in ordinary service.

10. Conclusions

The concept of surface integrity encompasses various results which are intended to provide a comprehensive image of the state of machined surface. Unfortunately, some results can be conflicting and difficult to classify without contradictions. This may be due to lack of accuracy of measurement but one cannot exclude effects of unknown factors which have different impact in different types of measurement. The former cause can be eliminated by larger number of measurements and by statistical processing of results, taking account of the standard deviation. The latter causes are difficult to identify. It can only be eliminated through more profound understanding of principles and readings of measurement. This applies to, for instance, the corrosion tests where the results depend on competing principles and on domination of some of them. Despite these difficulties, valuable findings have been obtained. They are valuable not only from the academic but also from the practical standpoint. In this case, it applies to evaluation of surfaces created by specially designed "finishing" drills. These tools have been developed and manufactured in the company HOFMEISTER s.r.o. On the basis of the above mentioned wide-ranging cooperation between the academic sphere and manufacturers and users of cutting tools, the findings and results building a comprehensive picture of the surface integrity concept will be further developed.

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Abstract

In some areas of science and industry, the concept of surface integrity is becoming a strongly preferred approach to describing the surface being created. The term surface integrity represents a comprehensive characterization of all influences bearing on the surface properties and the end-use properties of a product.

This paper focuses on specific influences in relation to end use properties of a product and their practical application in describing a surface. This paper also describes a practical application of the concept of surface integrity to holes drilled in gray cast iron with special tools.