THE SURFACE: WHAT IS THE WAY TO BETTER UNDERSTANDING?

Antonín KŘÍŽ

University of West Bohemia, Univerzitní 22, 30614, Plzeň, Czech Republic, kriz@kmm.zcu.cz

Abstract

The concept of surface integrity represents a new and, in some areas of science and industry, 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. It explores the capabilities of measurement of individual factors and brings comments on its accuracy and implications.

The paper also describes a practical application of the concept of surface integrity to holes drilled with special tools. The resulting properties were examined with the aid of both corrosion and contact loading tests and residual stress measurement.

1. INTRODUCTION

Final properties of products are significantly influenced by the properties of their surface and their subsurface layer. Despite the present level of knowledge of the relationship between the surface and fatigue degradation, fatigue failures still comprise more than 90% of in-service failures. Fatigue failure of material is typically initiated on the surface of the part. Exceptions include substantial microstructural and metallographic defects and engineering design deficiencies (inclusions, cracks, excessively hardened surface, recesses and others) which may shift the point of initiation into the material and farther from the surface. For these reasons, the surface properties must receive sufficient attention. A comprehensive methodology has been created recently for describing the state of surface, taking into account a number of factors which are more interrelated than previously thought. It became the core of the surface integrity concept. Its practical application has to be handled very carefully for the following reasons. The first one concerns the complexity of the methodology and its capacity to provide usable results. 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 to the material’s fatigue behaviour. As shown in the following chapter on the surface integrity, these are not all the factors affecting the behaviour of the part. 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. To this topic, a number of publications have been devoted, not only by the authors of this paper [1, 2] but by other experts as well [3, 4]. First problems arise in selection of a method for determining residual stresses with certain (in)accuracy. Others are related to its interpretation and usability in practice. In the real world, problems will occur with the use of such findings for rejecting non-conforming products or for prediction of service properties. Although a number of publications have dealt with the surface integrity, the findings have not been embraced by engineering companies and cannot be integrated into product quality criteria.
2. **THE SURFACE INTEGRITY CONCEPT**

At present, the surface integrity and all related factors being monitored are included in the ANSI B 211.1 1986 standard. In the United States, this standard has already been used for describing the state of surface. It has its own symbol in drawings and its specifications.

The purpose of surface integrity analysis is to obtain a comprehensive description of the state of surface, as there are many factors affecting the resulting properties of a component. These factors operate simultaneously. They may be classified as internal and external ones.

*External factors:*

Mechanical (in-service stress)

Chemical (corrosion)

Physical (radiation, stray currents and others)

Combination of multiple factors (stress corrosion, electrochemical corrosion and even manufacturing processes, such as chip removal, heat treatment, forming)

*Internal factors:*

Residual stresses

Surface morphology (roughness)

Material and mechanical properties of the surface (hardness, effects of hardening, state of microstructure, surface treatment, such as films and coatings)

The presence of surface and sub-surface defects and heterogeneous microstructure (carbon in cast iron, inclusions, microporosity)

These days, the greatest attention in regard to surface integrity is paid to measurement of residual stresses. A number of studies are available which describe the impact of manufacturing processes on formation of residual stresses. Most effort is focused on machining, particularly on grinding (e.g. the study [5]). Some activities are aimed at residual stresses in the field of welding and heat treatment [6]. As described in the following section, measurement of residual stresses has certain difficulties. This is why the description of the state of surface requires greater attention spanning beyond the mere quantification of residual stresses – which may be very inaccurate and unreliable to interpret.

3. **RESIDUAL STRESSES**

These days, most attention is focused on determining residual stresses. Their analysis should be conducted with a number of related laws in mind. These include, in the first place, the principles of formation of stresses of different orders, methods of their measurement and the information they can provide. Residual stresses are in the centre of attention as they are induced during all manufacturing processes, particularly those employing heat and mechanical working. Metal cutting falls into this group of processes. The introduction of heat into the surface is non-uniform. This phenomenon alone leads to formation of plastic and elastic zones. Depending on the amount of heat, zones of plastic and elastic deformation develop [5]. If additional mechanical factors are taken into account, these zones become even more significant. Upon cooling of the workpiece, the energy used for elastic deformation is not recovered. The deformation remains in the surface,
resulting in residual stress. Residual stresses can be classified as either tensile or compressive stresses. The surface typically contains compressive stress but problems arise if tensile stress is present. The latter is often produced in the sub-surface layer. There are a number of other influences including elastic-plastic properties and the character of the stress. Rapid transition to tensile stress may produce undesirable conditions, possibly leading to sudden failure. Determining the character of stress and incorporating all other factors encountered in industrial applications is very difficult with existing measurement techniques.

3.1. Experimental Measurement of Residual Stresses

Development of a special drilling tool is pursued in cooperation with the company HOFMEISTER s.r.o. The purpose of the tool is not only to produce a hole with required accuracy but also to modify the topography of the surface, its structure and residual stresses. Preliminary experiments comprised drilling of holes with various parameters. Holes with the diameter of 30 mm were drilled in the material DIN C45. The specimens were subsequently sectioned and residual stresses were measured by means of X-ray diffraction analysis. Residual stresses ranged between -252 and -485 MPa and depended on the production process. All these stresses were compressive in nature. It is very difficult to assess individual processes on the grounds of these values. Another experiment consisted in measuring residual stresses along the circumference of a drilled hole. As Fig. 1 shows, even the stress within a single hole reaches different levels. The variance in stress within one hole is due to the heterogeneity of microstructure of the material used and due to changes in residual stress occurring even in the course of a steady-state process.

During experiments, residual stresses were measured in other instances as well. The Barkhausen noise and MMM (Magnetic Memory of Metals) techniques were used. Both techniques are primarily suitable for evaluation of compressive residual stresses. Despite that, the values obtained corresponded to those measured by means of X-ray diffraction analysis.

The findings indicate that in spite of a number of professional reports aimed meticulously at measured values of residual stresses, these outputs do not provide a basis for a clear-cut assessment of the state of surface. Constructing hypotheses on the real-world behaviour of a component with a given residual stress and predicting its end-use properties is thus utterly inconceivable.

![Fig. 1 - Residual stress distribution along the circumference of a drilled hole](image1)

![Fig. 2 - The actual state of the surface](image2)

4. SURFACE MORPHOLOGY

Description of the surface, and, consequently, its quality, and the assessment of quality of the entire process are often based on roughness numbers. The Ra
parameter is typically used. Roughness numbers can be obtained quickly and with necessary accuracy even by means of shop-floor profilometers. There are a number of correlations between the values obtained and their practical implications for end-use properties. Yet, the experiments carried out and long-term experience have shown that the Ra parameter, i.e. the arithmetical mean deviation of the profile, does not provide sufficient amount of information for a comprehensive representation of the state of the profile and the surface. As evidenced by Fig. 2, not only the height of surface features, but also their shape, such as the diameter and aspect ratio, and presence of cracks, are important. Under contact loading, these values are more important than Ra values. The description which is closest to the real surface is provided by the Abbott-Firestone curve.

Surface roughness characterization is nowadays carried out by means of a number of optical instruments offering surface mapping and evaluation of the so-called areal roughness. A laser scanning confocal microscope is available at the author's laboratory. The values of areal roughness obtained are different from linear roughness. These discrepancies are due to the technique (method) of measurement and the nature of the measurement. Fig. 3 shows the surface with the linear roughness of Ra 0.6 µm, the measured areal roughness of which was SRa = 0.3883 µm.

These values and findings suggest that another value which is often thoroughly examined as part of surface integrity analysis exhibits certain inaccuracy.

5. MATERIAL AND MECHANICAL PROPERTIES OF THE SURFACE

Inspection of surfaces produced in the project is primarily aimed at the state of the material. This is dictated by the author's focus, by the technical equipment of his laboratory and by the fact that these properties have the most significant impact on the resulting behaviour of a machined component.

Observation of microstructure on a transversal metallographic section proved an effective technique for capturing surface changes and, if applicable, the surface profile. Fig. 4 indicates that application of the special tool results in deformation of material down to the depth of 40 µm.

Fig. 4 – Transversal metallographic section of the drilled hole: distorted microstructure of the DIN C45 steel.

On the transversal metallographic section it is possible to assess microstructural changes possibly initiated by not only the tool force but also its thermal effects. Microhardness of the microstructure shown in Fig. 4 was measured in transversal direction. An increase from the original HV 0.01 = 242 ± 14 to 430 ± 23 was found. Evaluation of the surface profile showed that the amount of asperities decreased significantly. An important finding was the absence of surface laps or other defects resulting from large deformation of irregular surface.

Another well-tested method which provides more comprehensive characterisation of the state of surface is a cyclic impact test. It was described in detail in the paper [7]. The process of creation of impact craters on the
machined surface under various conditions of loading reveals those surface properties which are decisive in contact loading. These findings are very valuable for making precise holes used for precise fit of machine components. Components joined in this fashion are subjected to both contact wear and fatigue damage in service. Cyclic impact testing proved that in spite of the increase in surface hardness the fatigue behaviour of the component is improved. Surfaces of holes are drilled by conventional methods exhibit deeper craters and the nature of their failures indicates that they are more prone to fatigue degradation.

6.  CORROSION TESTING

The experiments provided a basis for creating a new methodology of describing the state of surface not only in terms of its topography but also surface activation energies. This methodology serves for evaluation of the state of surface in terms of its corrosion behaviour. Experiments aimed at the influence of plastic deformation and surface roughness on corrosion damage have been carried out. Their results have clearly proven that the surface roughness and topography have greater impact than the stress which had been introduced into the material. The greater the roughness and surface asperities, the more intensive the corrosion activity. The surface activity also increases with growing residual stress. Nevertheless, the prevailing compressive stress has less influence than the surface topography.

5.  CONCLUSION

Surface integrity analysis provides a comprehensive evaluation of the state of surface and its impact on the performance of the part. Obtaining reliable results requires that individual factors are treated with great attention. Fragmentary measurement, partial experiments and their results are not sufficient for evaluating final properties of a component. There are a number of experts engaged in research into this issue at the author’s place of work and at the Department of Machining Technology of the University of West Bohemia. In spite of this, or even for this reason, the author sees in the surface integrity concept both a great challenge and a risk, resulting from separation of individual results from the overall context. Embedding the surface integrity concept into real-world applications still is and will be a cumbersome task, not only due to issues related to transferability of the methodology but also with regard to measured values and their impact on the quality of the product. Another source of difficulties is the absence of a unifying theory which would enable comparison and quantification of individual factors of influence. Despite these problems, valuable findings have been reached both from the academic viewpoint and in terms of practical application and evaluation of surfaces newly created by specially developed “finishing” drills developed and manufactured by the company HOFMEISTER. 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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LITERATURE


