Comprehensive consideration for classification of micro-nano surface and sub-surface integrity

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Abstract: Surface alterations may include mechanical, metallurgical, chemical and other changes. These changes, although confined to a small surface layer, may limit component quality or may, in some cases, render them useless. A basic understanding of the changes in the condition of the surface is required if further product improvement is to be attained. This paper presents a comprehensive consideration for classification of micro-nano surface and subsurface integrity.

Keywords: surface, surface integrity, surface assessment

1. Introduction

The term “surface integrity” was first coined by Field and Kahles in 1964[1], and is defined as “the inherent or enhanced condition of a surface produced in a machining or other surface generating operation”. As the requirements for surface quality have increased, so has the need to explore new techniques for the assessment of surface and subsurface integrity.

A tremendous amount of work has been presented in the CIRP or other publications over the past years in terms of methods to characterize surface integrity. For example, seminal keynote papers by Field and Kahles[2] addressed the surface integrity of machined components and methods for measuring surface integrity[3]. Bryan reported on the functional characteristics of surface and the requirements placed on surface roughness[4], microhardness and residual stress measurement by Tönshoff and Brinksmeier[5], and measurement of residual stress by Brinksmeier et al[6]. Characterization of the surface microtopography was addressed by Lonard et al[7], and uses of the STM and AFM were presented by Vorburger et al[8].

Especially, Lucca, Brinksmeier and Goch presented the keynote paper “Progress in Assessing Surface and Subsurface Integrity” in 1998 CIRP[1], which summarized a variety of techniques employed for the characterization of surface and subsurface integrity. The 1st international conference and general meeting of the euspen held in Bremen, Germany, 1999, included also a number of papers dealing with assessment of surface and subsurface integrity. For instance, Carr et al. assessing subsurface damage with AFM[9]. Goch et al. noncontact measure topography using near-field acoustic microscopy[10]. Thomas described the directional properties of roughness on machined surface[11], and Westkamper et al. presented a theoretical consideration for a new tolerance system to characterize technical surfaces in the micro- and nanometer scale[12].

Although there are great progresses of measuring and assessing techniques of surface and subsurface integrity, and some summarization and research have been made; not much attention has been paid to the integrity performance of micro-nano surface and subsurface, in the past few years. Based on the machining, usability, and structure characterization of engineering surface, this paper classifies the surface and subsurface integrity into four kinds of performance parameters. In addition, some aspects of surface topography, such as roughness, pit, and micro-hardness etc., have

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been measured and assessed experimentally with WYKO instrument, SPM and SEM.

2. Classification of micro-nano surface and subsurface integrity

Today, sub-micro and machining techniques, such as hard cutting, LIGA, coating, sputtering and probe et al. produce the surface structure almost down to an atomic level. At the same time, the emergence of nanometer measurement instruments, such as STM, X-ray interferential microscopy etc., make it possible to describe the microsurface structure at an atomic lever.

Whereas measuring and manufacturing tools are continuously improving, the tolerance systems, measurement strategies and parameters to describe surface properties have remained more or less the same for several decades. In the measurement and characterization of nanoscale, parameters and strategies differ from that of milli- and micro-scale, and should be first transformed from 2D to 3D application, and then downsized to the nanometer scale[12]. In addition, not only the geometrical properties of workpiece surface, but also the properties of physical, chemical and material of subsurface play an important role on the usefulness of workpiece.

Taking machining, using and structure characterizing into consideration, this paper classifies surface and subsurface integrity into geometrical, mechanical, physical and chemical properties at nanoscale. The most of them are evaluated quantitatively. The complication that follows is by no means meant to be comprehensive, but rather to provide a starting point for further studying surface and subsurface integrity. A detail classification is shown as follows.

- **Geometry properties**
  - 3D roughness
  - motif
  - waviness
  - micro-defect (crack, scratch, pit, …)
  - anisotropy
  - unhomogeneity

- **Mechanical properties**
  - friction, wear, lubrication
  - corrodibility
  - residual stress
  - dislocation
  - fatigue
  - brittle

- **Physical properties**
  - hardness
  - conduction
  - magnetoconductivity
  - reflection
  - interatomic force

- **Chemical properties**
  - crystal component
  - crystal grain size
  - element distribution
  - element purity

Above-mentioned parameters may not be reasonable possibly in practice, so they should be studied further in the future.

3. Some experiments on integrity

3.1 Roughness

In this experiment, the sub-micro surface topography of workpieces glass, ceramic, silicon and horniness alloy were measured with RSTPlus interference microscopy made by WYKO, in Changchun Precision Optical-Mechanical Institute, the Academy of Science of China. The measuring principle of interferential microscopy is the same
as WYKO TOPO interferential microscopy, its vertical resolution is 0.1nm, repeatability is 0.01nm (RMS), measuring range 0.1-0.15nm. In the experiment, the magnification used by the microscopy is 10×, scan area 603.6µm×448.4µm, sampling interval 1.64µm. After sampling, the measuring surface data were processed by the computer. The image of surface topography and the measured height values were obtained immediately (shown in Fig.1). Then sampling some curves on corresponding surface topography, we can find the roughness parameters values seen in Table 1 respectively.

(a) ground glass (BK-7) surface  
(b) ground ceramic surface  
(c) ground single crystal Si surface  
(d) ground horniness alloy surface  

Fig.1 Surface topography

<table>
<thead>
<tr>
<th>Sample material</th>
<th>Machining method</th>
<th>Roughness parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>glass</td>
<td>Fine grinding</td>
<td>Ra(nm)</td>
</tr>
<tr>
<td>ceramic</td>
<td>Fine grinding</td>
<td>2.45</td>
</tr>
<tr>
<td>single crystal Si</td>
<td>Fine grinding</td>
<td>12.98</td>
</tr>
<tr>
<td>horniness alloy</td>
<td>Fine grinding</td>
<td>3.02</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.45</td>
</tr>
</tbody>
</table>

3.2 Assessing micro defects with SPM

Here, the micro defects (pits) of ultra-precision grinding and cutting surface were measured with NanoScopeIII Dimension 3100 SPM made by DI, in Precision Engineering Research Institute, Harbin Institute of Technology. In contact measuring mode, the SiN probe was used, the curvature radius of probe tip 20-60nm, the length of cantilever 100 and 200nm, scan area was 80µm×80µm, 256×256 data points were measured in each scan, and the scan speed was 1.57Hz.

The 3D surface topographies obtained by SPM are shown in Fig.2. We can find the maximal pit and measure its 3D sizes by SPM. The results are tabulated in table 2.
The experiment results show that the pits on ultra-precision ground glass surface are the most among the measured samples; the pits on cutting Al surface are little and big; ones on the Ge and Si surface are many and stain.

3.3 Microindentation of brittle material surface

In single point diamond cutting, roughness parameters and sub-surface plastic deformation are the main evaluation indexes for integrity. In damage layer, the residual stress of near field surface caused by plasticity may lead to the change of surface performance. Whereas the depth of the damage layer can be determined by micro-hardness, taper section form and residual stress are measured by microindentation. In this paper, the experiments of microindentation on brittle materials were made with metal microscopy hardness meter by use of Vicker-diamond head. To obtain the perfect optical surface, the single crystal Si was lapped and polished first. The experiments were loaded by 0.01-1N. In each kind of load, ten indentations were made, and the best indentation was selected as research object.

The SEM photographs of samples loaded by 0.02N and 0.04N are shown in

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**Table 2** The measuring results of micro-defects by SPM

<table>
<thead>
<tr>
<th>Sample material</th>
<th>Machining method</th>
<th>Micro-defects (pit)</th>
<th>Length(µm)</th>
<th>Width(µm)</th>
<th>Depth(nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass BK-8</td>
<td>Fine grinding</td>
<td></td>
<td>1.280</td>
<td>0.847</td>
<td>441.67</td>
</tr>
<tr>
<td>Al</td>
<td>Fine cutting</td>
<td></td>
<td>1.416</td>
<td>1.263</td>
<td>434.07</td>
</tr>
<tr>
<td>single crystal Ge</td>
<td>Fine cutting</td>
<td></td>
<td>4.696</td>
<td>2.274</td>
<td>1263.4</td>
</tr>
<tr>
<td>single crystal Si</td>
<td>Fine cutting</td>
<td></td>
<td>0.815</td>
<td>0.582</td>
<td>619.90</td>
</tr>
</tbody>
</table>
Fig. 3(a). According to the Fig, there are only two plastic deformation pits on each sample surface.

In Fig. 3(b) is the SEM photography of sample surface indentation loaded by 0.06N, and we can see that there were micro radial cracks in the indentation diagonal. This means the start of brittle damage in single crystal Si.

From the SEM indentation photographs loaded by 0.5N and 0.8N (respectively shown in Fig. 3(c) and Fig. 3(d)), we can find that there are obvious cracks in the pyramid indentation edges, and the inner residual stress and the depth of increase with the load.

The deformation, crack and hardness of microindentation of single crystal Si after loading are tabulated in Table 3.

| Tab. 3 Deformation, crack and hardness of the indentation of loaded single crystal Si |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| parameters | Load(N) | 0.02 | 0.04 | 0.06 | 0.08 | 0.10 | 0.20 | 0.30 | 0.50 | 0.80 | 1.00 |
| a(µm) | - | 1.50 | 1.60 | 2.10 | 2.40 | 2.70 | 3.50 | 4.00 | 5.10 | 6.00 | 7.10 |
| c(µm) | - | - | - | 5.00 | 6.00 | 7.00 | 12.0 | 15.0 | 18.0 |
| d(µm) | 0.40 | 0.45 | 0.56 | 0.80 | 0.87 | 1.00 | 1.20 | 1.40 | 1.70 | 2.00 |
| hardness(Gpa) | 4.44 | 7.87 | 6.80 | 6.94 | 6.85 | 8.16 | 9.37 | 9.61 | 11.11 | 9.92 |

In the table, parameter ‘a’ denotes diagonal length of indentation, ‘c’ the length of crack, ‘d’ the impressing depth of sample subsurface.

4. Conclusion

This paper presents a simple classification for the integrity of micro-nano surface and subsurface. Some integrity experiments, such as on Si, Ge, glass, alloy and Al,
have been done by SPM, WYKO interferential microscopy and SEM. Certainly, there is a long way to go for establishing comprehensive and reasonable assessing system.

**References**