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# Surface Characterisation Based Tool Wear Monitoring in Peripheral milling

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**Abstract**: The progress of surface metrology in the last decade has led to improved 3D characterisation of surfaces which offers the possibility of monitoring manufacturing operations to give highly detailed information regarding the machine tool condition. This paper presents a case study where areal surface characterisation is used to monitor tool wear in peripheral milling. Due to the fact that tool wear has a direct effect on the machined workpiece surface, the machined surface topography contains much information concerning the machining conditions including the tool wear state. Through analysing the often subtle changes in the surface topography the tool wear state can be highlighted. This paper utilises areal surface characterization, areal auto-correlation function (AACF) and pattern analysis to illustrate the effect of tool wear on the workpiece surface. The result shows that: (1) tool wear, previously difficult to detect will influence almost all of the areal surface parameters; (2) the pattern features of AACF spectrum can reflect the subtle surface texture variation with increasing tool wear. The authors consider that, combined analysis of the surface roughness and its AACF spectrum are a good choice for monitoring the tool wear state especially with the latest developments in on-machine surface metrology.

**Keywords***:* surface metrology; tool wear; areal surface texture parameters; areal auto-correlation function

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## 1 Introduction

With increasing demands for higher productivity and quality, there have been increased interests in monitoring all aspects of the machining process. As tool wear directly affects the precision and surface finish of the product, it is important to monitor the state of cutting tool if precision is to be maintained over time [1].

Metal Cutting is achieved through shear mechanisms and the relative motion between the workpiece and the cutting tool. As a result of the cutting motion the surface of workpiece will be influenced by cutting conditions (cutting parameters, cutting force, cutting tool state), and the surface topography of the workpiece will include much information pertaining to the cutting process [2-6]. Thus, through monitoring the machined surface topography of the workpiece and extracting the relevant information the cutting process and tool wear state should be able to be monitored and quantified. This paper proposes a surface metrology based tool wear monitoring methodology through analysing the change of the surface topography features during tool wear. The work forms part of a large study where surface metrology is being used to measure all aspects of the machining in combination with an on-line metrology tool.

## 2 3D Surface Analysis Techniques

### 2.1 3D Surface Parameters

The traditional surface evaluation methods use surface profile evaluation based on a section profile of the surface. Cutting process however are in Euclidean space, the information concerning tool wear must be three dimensional in nature, but default surface profile evaluation can only recover limited information (2D) from the cutting process and will be limited in its ability to monitor development of tool wear for example.

Recent advanced techniques have taken place in the ability to measure and characterise areal surface topography [7-12]. A set of areal surface roughness parameters have been defined and as shown in Fig.1. The areal surface texture parameters not only describe the statistical amplitude properties, but also reflect texture distribution properties. As discussed earlier, tool wear will influence both the surface roughness and the texture distribution. In this paper, the use of areal surface texture parameters to characterise the machined surfaces of workpieces in order to evaluate the tool wear is outlined. Clearly not all of the areal parameters will reflect the tool wear state significantly, and the aim here is to define a subset of parameters for the purpose of tool wear monitoring.

### 2.2 Areal Autocorrelation Function (AACF)

The autocorrelation function is a very useful tool for processing random signals. It describes the general dependence of the topographical values at one position on the topographical values at another position. For areal surface evaluation, it can not only describe the spatial relation dependences of the surface topography, but also describe the direction and periodicity of the surface texture [7-8].

From the authors previous research, the AACF has been used to describe different machining methods as each has very different surface textures patterns and consequently very different patterns for their AACF spectra. Furthermore, the AACF spectra can reflect the texture periodicity and directionality more clearly than visualisation of a surface topography map. The authors have previously used the AACF to monitor the development of chatter in peripheral milling. It was observed that with different degrees of chatter the surface texture on the workpiece showed which were more apparent than simple visualisation. AACF analysis of machined surface has the capability to reflect the information of the machining state more clearly than observing the raw data. Consequently in this paper the pattern features of the AACF spectrum of machined surface are used to monitor the tool wear state.

## 3 Simulated Tool Wear Experiment

Under normal conditions, tool wear develops over a period of time. In the present study however tool wear has been “induced” by using a diamond lap to manually wear the tool edge and hence control the amount of tool wear. The procedure in detail is as follows: measure new tool→machine a set of workpieces→measure the workpiece→lap the tool to induce wear→measure the tool wear→machine a new set of workpieces→measure the workpieces→lap the tool to induce wear→measure the tool wear→repeat……. Through this procedure a full set of machined workpieces were obtained under defined amounts of tool wear.

To eliminate the influence of random factors and to enhance comparability, eight groups of cutting conditions as shown in table 1 were selected (all the parameters selected according to the recommendation of the tool’s manufacturer). In the table, nomenclature of the machined workpieces is as follows: “TWnC”, “TW” represents “tool wear”, the number “n” represents the tool wear amount of each group of tests, n is 1,2,3,4, and 1 represents the new tool, the first wear, the second wear and the third wear level; the last character represents the different combination of the cutting parameters in each group of cutting tests, from A to H. The material of the workpiece is EN8 with hardness 243Hv. The peripheral milling cutter is an SSM2200 (radius 20mm, two teeth and $30^0$ helix). For each cut the same position on the cutter was used, a Talysurf PGI was used to measure the tool wear amount, and for each tooth four positions at 10mm intervals from the tip were selected for measurement. All machining was carried out on a Cincinnati Arrow2-500 machine centre.

To measure the machined surface a Talysurf PGI was used, the evaluation area was $6*10mm^2$, with a sample spacing of 10um, polynomial fitting was applied to remove form errors firstly and then a Gaussian regression filter was applied to obtain the surface texture, the cutoff wavelength of the filter $\lambda_c$ was 2.5mm.

# 4 Analysis of the simulated tool wear

## 4.1 Measurement of Tool Wear

Figure 2 shows the section profile of the tool in the new, first wear, second wear and final wear state, the amounts of the tool wear are approximately 0um, 90um, 110um and 130um. Tool wear is defined as the departure from idealized tip geometry and is measured using the form Talysurf PGI.

## 4.2 Variation of surface texture

Fig.3 compares the 3D surface topography under different tool wear conditions. It is observed that the surface topography has good texture in feed direction, the surface is very flat and has low levels of waviness when tool is new; with increasing tool wear the regular texture loses “strength” with scuffs and furrows appearing, with further tool wear, the surface appears very irregular having alternate rough and smooth zones.

## 4.3 Areal Surface Texture Parameter Analysis

Figure 4 shows the variation trend of the 3D amplitude parameters Sq, Ssk, Sku, S5z with the increase in tool wear. Sq, the areal root mean square roughness, increases with tool wear increase, with the amplitude of the roughness rising with the increasing tool wear. i.e between tw1 and tw2, the tool wear changes 90um while between tw3 to tw2 and tw4 to tw3 only changes 20um. Ssk is the measurement of asymmetry of surface deviations about the mean /reference plane. This parameter can effectively be used to describe the height distribution of surface topography. From the figure, Ssk is near zero when the cutter is in good condition, which means that the surface height distribution curve is very like a standard normal distribution and a symmetrical distribution. When the tool is worn, Ssk becomes increasingly negative, due to the fact that the height distribution curve is changed to an asymmetrical distribution with a negative skew, which shows that the height of the surface is mainly above the mean plane with the surface tending towards having a “flatter top” with some deep valleys below the mean surface plane. Sku characterises the spread of the height distribution. These curves indicate that the Sku is near 3 when cutter in good conditions, which shows that the surface height distribution is very close to a Gaussian distribution. When tool is worn, the machined surface has greater “peakedness”, with the Sku being are far bigger than 3. The parameter S5z increases with the tool wear, which indicates that some random scores and deep furrows occur on the surface and surface quality deteriorates.

From the combined analysis of the amplitude parameters, it can be concluded that the surface quality deteriorates with the increasing tool wear. Additionally when the tool is worn, the blunt cutter edge has a rubbing effect on the surface that results in the surface tending towards a plateau type surface with a relatively flat tops and some deep scored valleys.

Figure 5 shows the variation of the areal spacing parameters Sds, Str, Sal with tool wear increase. The spacing parameters refer to the spatial properties of surfaces. Sds is the number of summits of a unit sampling area. The curve indicates that the number of the random peaks and valleys on surface increases with a tool wear increase. Str is defined as the ratio of the fastest to slowest decay to 0.2, of the AACF of the surface area. The Str is used to identify texture strength i.e. uniformity of the texture aspect. From fig.3 the surface has a strong directionality in feed direction when cutter is new; when the tool is worn, the texture distribution strength in feed direction is weakened. With the increasing tool wear the effect of randomly occurring deeper furrows along the feed direction on the machined surface is more apparent. A large value of Sal denotes that the surface is dominated by low frequency (or long wavelength) components, while a small value of the Sal denotes the opposite case. So from the figures it is clear that, with increasing tool wear distinct waviness appears on the surface. This could be due to the Built Up Edge effects along the tool edge and consequent inconsistent cutting of deep furrows on the surface along the feed direction as well as ploughing zone of lower roughness indicating poor cutting zones.

Compared with the amplitude parameters, the spacing parameters can reflect the tool wear’s effect on surface texture distribution more distinctly.

Figure 6 shows the variation of hybrid parameters with increasing tool wear. The hybrid parameters are parameters based on both amplitude and spatial information. Sdq is the root mean square value of the surface slope with the sampling area, Sdr is the ratio of the increment of the interfacial area of a surface over the sampling area, and Ssc is defined as the arithmetic mean of the principal curvatures of the summits within the sampling area. They define numerically hybrid topography properties such as the slope of the surface, the curvature of high spots, and the interfacial area. Any changes that occur in either amplitude or spacing may have an effect on the hybrid property. From these figures, it is clear that most of the hybrid parameter Sdq, Ssc, Sdr will increase with increasing tool wear. This reflects the development of random deep scores smearing and possible BUE formation.

### 4.4 AACF spectrum analysis

Figure 7 shows the variation of the AACF of the machined surfaces. Relative to the original surface texture, the AACF spectra can show the varying trend of the surface texture with increasing tool wear. In fig.7a, the tool is new and the AACF has the same periodicity as the original surface texture along the feed direction. In fig.7b, the strength of the periodicity distribution along feed direction is weakened, and the regular machined surface lay is somewhat destroyed with increasing tool wear. In fig.7c, new periodical waviness components appear in the vertical direction these are the result of inconsistent cutting along the feed direction because of the probable presence of BUE. In fig.7d, the periodicity distribution along feed direction has almost disappeared and that in the vertical direction is also weakened, this shows that at this stage the tool wear is very serious and less real cutting of the surface is occurring and the rubbing effects of the tool edge radius are becoming much more significant.

The AACF illustrates clearly the main features of the surface texture and its pattern reflects the tool wear state. From the extraction and recognition of the pattern features of the AACF it is feasible to monitor the state of tool wear, and this is the subject of ongoing research.

Of the methods outlined in this paper it appears that the AACF technique shows the clearest indication of tool wear and the authors would recommend this technique. Numerical analysis of the AACF however requires further methods. The method currently under investigation by the authors is Pattern analysis of the AACF data [13]. This technique allows the development of trends in the AACF data to be extracted and further analysed to investigate subtle changes in surface topography to be quantitatively characterised and expressed numerically.

## 5 Conclusions

In the present investigation the affect on surface texture of tool wear have been investigated via changing tool edge radius under accelerated wear conditions. The increase of the tool edge radius and the tool surface roughness has a two fold effect on the surface roughness. One is that it will lead to possible BUE’s formation, growth and break down and the irregularity of the tool edge, thus developing furrows on the surface and increasing the general roughness. On the other hand, increasing the tool edge radius produces a rubbing effect on the machined surface and the surface will possesses an irregular variation of the rough and smooth zones. Thus, BUE's effect will increase the roughness in the initial phase of tool wear, with the rubbing effect becoming apparent as a later wear phenomena

Clearly, the surface topography reflects tool wear state. Tool wear will influence almost all the 3D surface parameters. Sq, Sds, Sdq, Sdr have the same varying trend with the tool wear state; Ssk and Sku reflect the surface amplitude distribution, with a new tool the surface amplitude distribution has a standard normal Gaussian distribution and with a worn tool it will departs from the Gaussian distribution; Str can reflect the variation of the surface texture direction. Thus, a subset of surface texture roughness parameters including Sq, Sds, Str, Sdq, Sdr is recommend as the indication to monitor the tool wear state.

Overall, the 3D surface parameter's variation can quantify the tool wear effects on the surface, the pattern features of AACF spectrum can reflect the surface texture's variation with tool wear increase. Thus, combined analysis of the surface roughness and its AACF spectrum can be a choice to monitor the tool wear state and can be used to monitor other machine states and could therefore provide a means to optimise the machining process.

The authors recognize that online 3D surface measurement of machined surfaces has yet to be realized and a fast optical data capture technique appears to be the only option in this case. However the above analysis is essential when such a data capture device is finally developed and this is currently the subject of research by the present authors [14]. In addition the authors also recognise the artificial nature of the generated tool wear. They are however confident that the observed effects would be replaced for a “real' tool during wear. In fact the reported analysis techniques have now been applied to real tools and this work will be reported in the near future.

## 6 Acknowledgements

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## FIGURE CAPTIONS

Fig.1 3D parameter set

Fig.2 Development of accelerated tool wear across tool edge

Fig.3 3D surface topography in different tool wear amount (a) 0 μm, (b) 90 μm, (c) 110 μm, (d) 130 μm

Fig.4 variation of 3D roughness amplitude parameters with tool wear

Fig.5 variation of 3D roughness spacing parameters with tool wear

Fig.6 variation of 3D roughness hybrid parameters with tool wear

Fig.7 variation of the of AACF with tool wear (a) 0 μm, (b) 90 μm, (c) 110 μm, (d) 130 μm

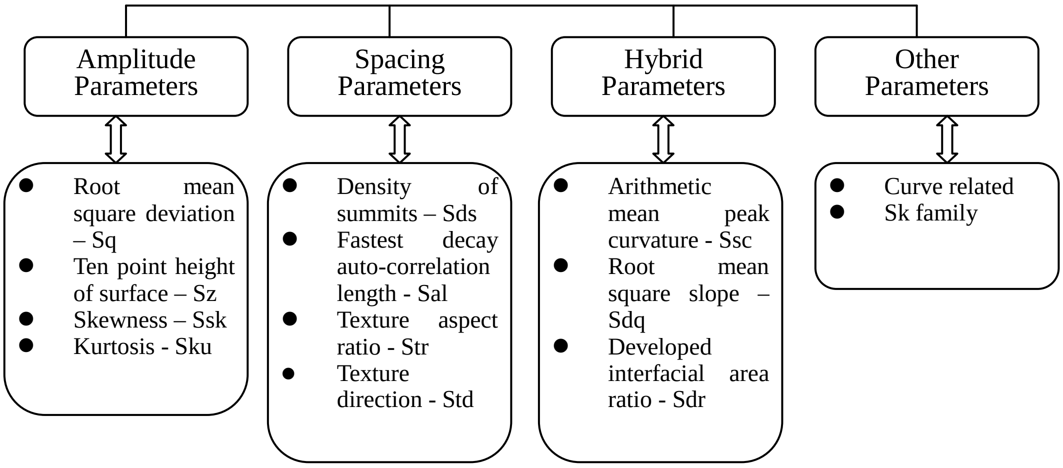
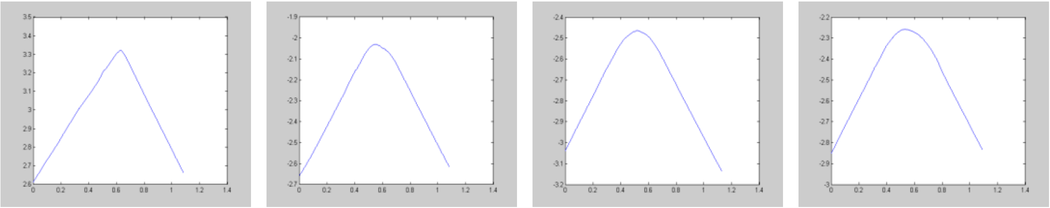
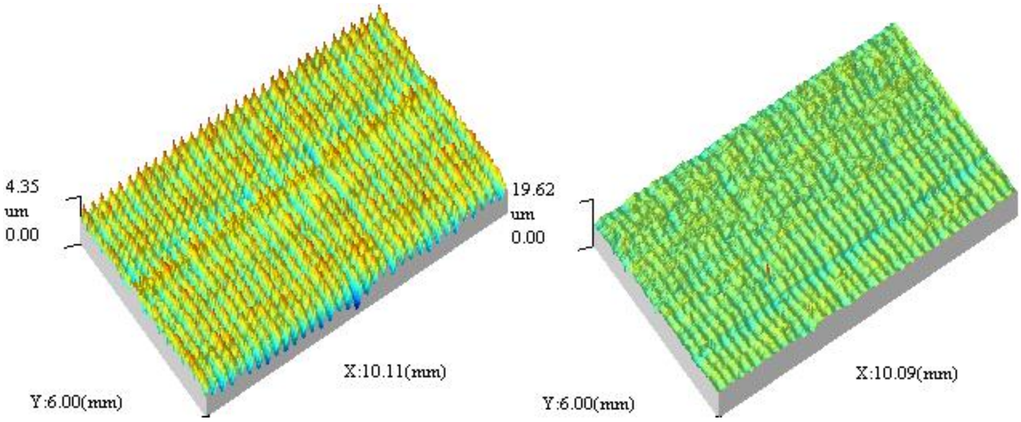


Fig.1 3D parameter set

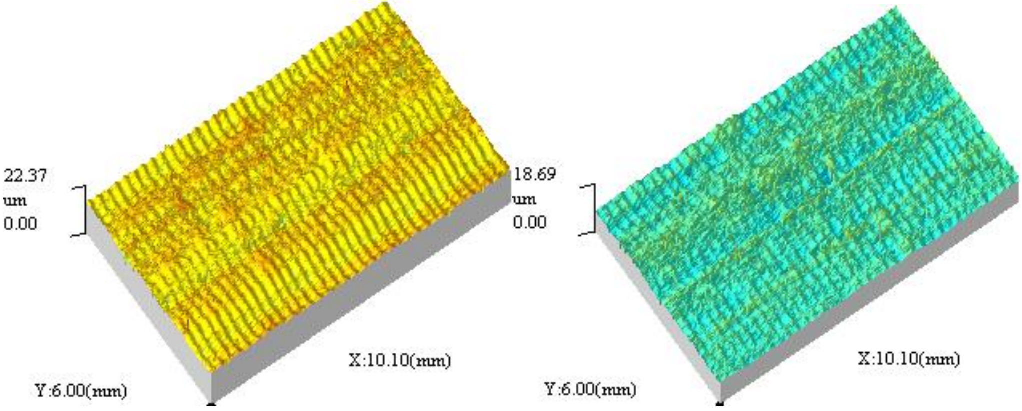


(a) 0 μm (b) 90 μm (c) 110 μm (d) 130 μm

Fig.2 Development of accelerated tool wear across tool edge



(a) 0 μm (b) 90 μm



(c) 110 μm (d) 130 μm

Fig.3 3D surface topography in different tool wear amount

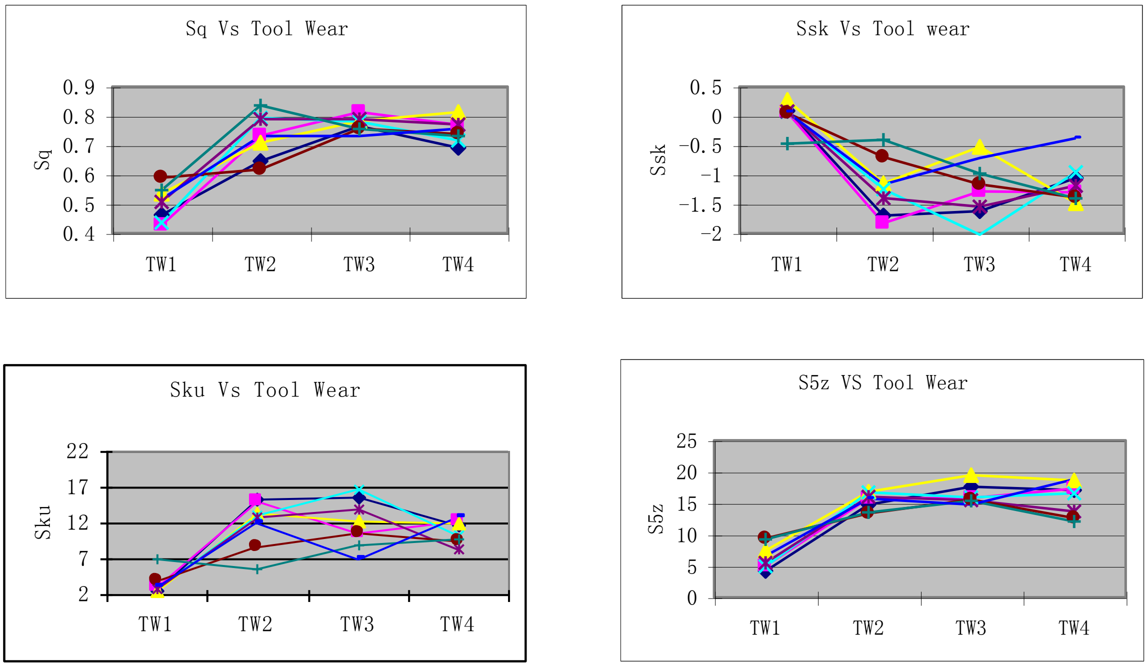


Fig.4 variation of 3D roughness amplitude parameters with tool wear

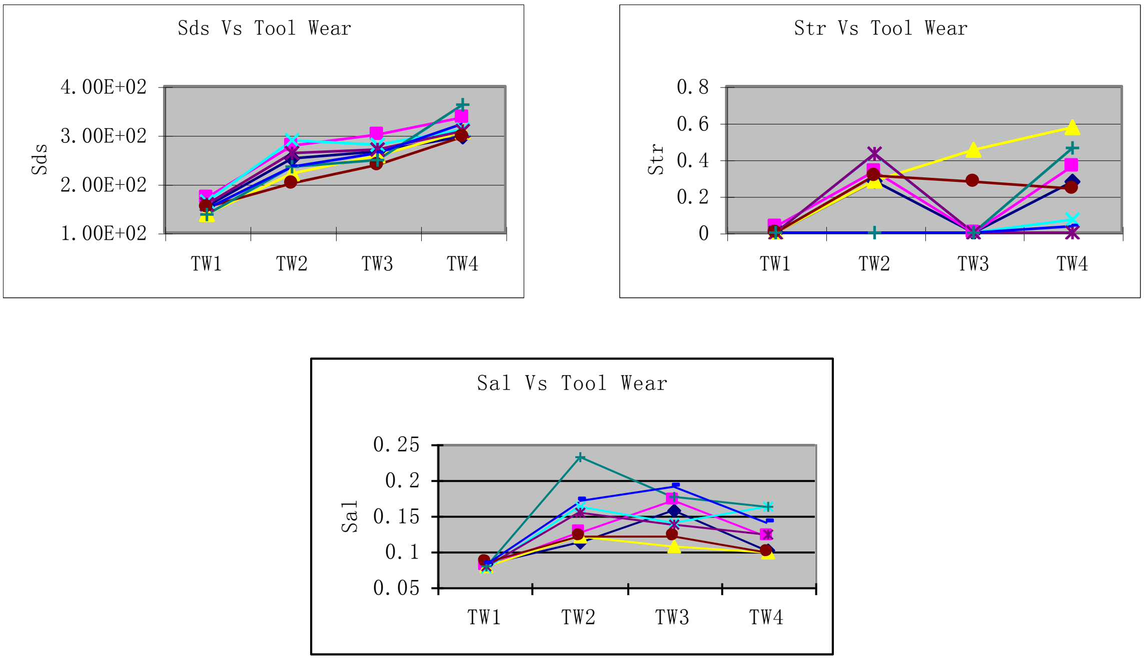


Fig.5 variation of 3D roughness spacing parameters with tool wear

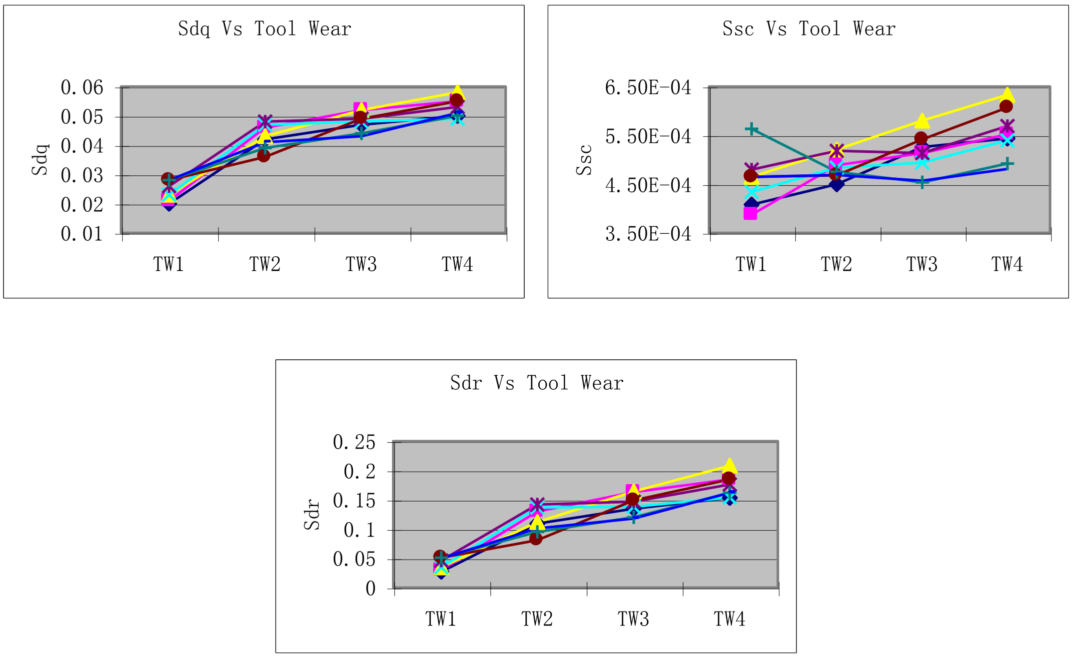
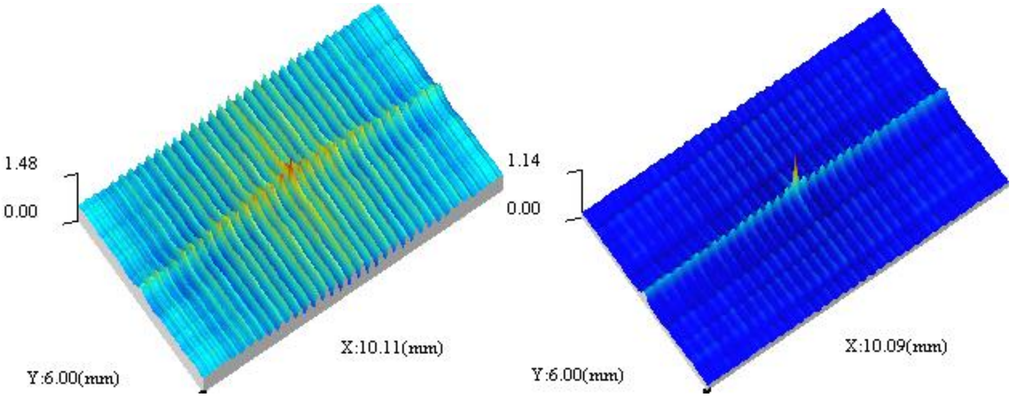
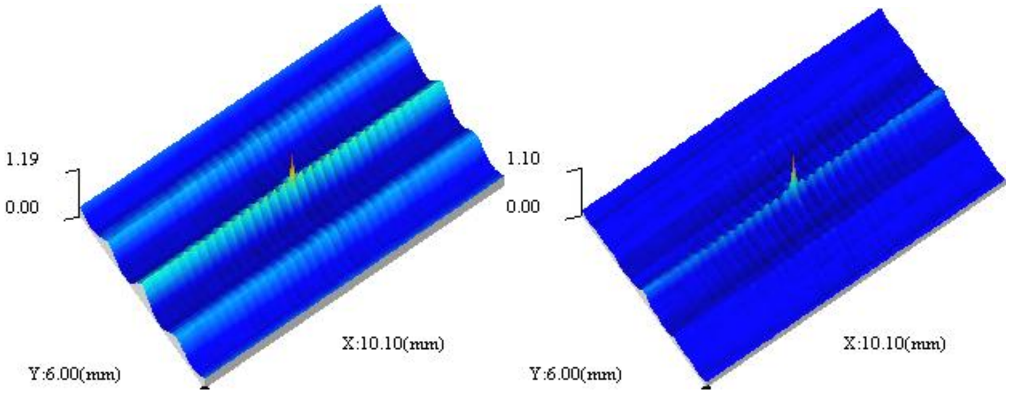


Fig.6 variation of 3D roughness hybrid parameters with tool wear



(a) 0 µm (b) 90 µm



(c) 110 µm (d) 130 µm

Fig.7 variation of the of AACF with tool wear

Table 1 Cutting parameters

| surface name | TWnA | TWnB | TWnC | TWnD | TWnE | TWnF | TWnG | TWnH |
|---|---|---|---|---|---|---|---|---|
| spindle speed(rpm) | 796 | 796 | 796 | 796 | 796 | 796 | 796 | 796 |
| radial depth(μm) | 200 | 200 | 200 | 200 | 200 | 200 | 600 | 200 |
| axial depth(mm) | 15 | 15 | 15 | 15 | 15 | 15 | 10 | 10 |
| feedrate(mm/min) | 239 | 215 | 271 | 215 | 239 | 271 | 239 | 239 |