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Prediction of thermal contact conductance based on the statistics of the roughness profile characteristics

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Abstract

The roughness profiles of some common machined surfaces were measured. Four different criteria for determining contact peaks are presented. The distributions of the roughness profile height and the contact peak height were calculated. Based on the statistics of roughness profile characteristics, the thermal contact conductances for surfaces with different roughnesses were predicted. The results showed that the contact peak's criterion is crucial to the calculation of the distribution of the contact peak height. It has, however, limited influence on the prediction of thermal contact conductance. On the other hand, using several statistical roughness parameters or a single roughness profile is not adequate to describe the topography of the contact surface because of the contact surface's anisotropy. The values of predicted thermal contact conductance for surfaces with different roughness profiles form a steady prediction strip.

Keywords: Roughness profile; Contact peak; Thermal contact conductance; Surface anisotropy

1. Introduction

Most machined surfaces are rather rough when viewed microscopically. When two rough surfaces are brought into contact, actual contact only occurs at certain discrete spots. The present study only considers the conductance of solid contact spots; it does not deal with gap conductance. Thus the heat flow is limited to only the actual contact spots, resulting in thermal resistance at the interface known as thermal contact resistance. Heat transport between contacting surfaces is often discussed as a thermal contact conductance (TCC), which is the inverse of thermal contact resistance. TCC has attracted many scholars' attention because contact heat transfer is of great importance in fields such as automated manufacturing, microelectronic technology, superconductivity, and aeronautics and astronautics [1]. Since the 1960s, many TCC models have been proposed by different scholars. These models mainly differ in their descriptions of surface topography and assumptions of summit deformation.

It is difficult to directly describe three-dimensional surfaces. Therefore, the summit of a three-dimensional surface is usually considered to be related to the peak of its two-dimensional profile, and the summit height distribution can be obtained using peak height. Greenwood and Williamson were the first to propose that the peak height of the roughness profile should match normal distribution [2]. This conclusion was adopted

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Nomenclature

A_{app}	nominal contact area of contact surface	T	temperature (K)
a	contact radius of summit (m)	Y	material yield stress of softer material in contact (Pa)
b	radius of curvature of summit (m)	λ	coefficient of heat conductivity (W/(m K))
E	Young's modulus of elasticity (Pa)	λ_s	effective coefficient of heat conductivity (W/(m K)), $\frac{2}{\lambda_s} = \frac{1}{\lambda_1} + \frac{1}{\lambda_2}$
H_c	microhardness of softer material in contact (Pa)	v	Poisson ratio
h'	thermal contact conductance of single contact spot (W/K)	σ	root-mean-square deviation (m)
h_c	thermal contact conductance per unit area (W/(K m^2))	φ	contact resistance factor
m	mean slope of surface profile	*Subscripts*	
P	contact force of single summit (N)	1, 2	solids in contact
p_{app}	apparent contact pressure (Pa)	i	individual
p_m	mean contact pressure of single summit (Pa)		

by many scholars and used in many TCC models [3–6]. Later, Cooper et al. proposed that the peak height does not match normal distribution and discussed the spatial distribution and the size distribution of summits [7]. Polycarpou and Etsion indicated that the Gaussian distribution of roughness height can be approximated by an exponential distribution, and a simple analytical expression was derived for the real contact area and the number of contacting summits [8]. In these models, some statistical parameters such as root-mean-square deviation, mean radius of curvature and mean slope of surface profile are used to describe the surface topography. These parameters are related to the precision of the measurement instrument. On the other hand, some research has shown that the change of roughness height is a non-stationary random process [9]. Based on the fractal theory, Majumdar and Bhushan proposed that the fractal parameters which are independent of the measurement scale can be used to describe the surface topography [10]. The description of surface topography is very important to the establishment of the TCC model, and researchers still hold divergent views on surface topography. So an accurate description of contact surface topography is of primary importance to the establishment of a TCC model.

There are three different types of deformations for common metal materials: elastic, elastoplastic and plastic [11]. Three types of summit deformation assumptions have been proposed according to the deformation which occurs for most summits in contact. These three assumptions are elastic, plastic and elastic–plastic. Some scholars think that most summits deform elastically based on the Hertz theory [4]. This is the elastic deformation assumption. Some other scholars think that the contact pressure exceeds the elastic limit for most summits, and the plastic deformation is predominant [7,12]. This is the elastic deformation assumption. The elastic–plastic deformation assumption was developed after the 1970s. It can be divided into two categories. One assumption is that the summit is considered to deform elastically or plastically [2,13,14]. The other assumption is that the summit deformation is considered to be elastic, elastoplastic or plastic, changing as contact pressure increases [5,15–17]. Deformation occurs in contact spots, and it can be elastic, plastic or elastoplastic not only depending on the load and the material's physical property but also on the description of the surface topography. Because of this, the first step in predicting TCC is determining the size and number of summits.

The peak height distribution (or the roughness profile height distribution) is considered to be normal in the classical TCC models [3–6]. The number of contact spots or the actual contact area is integrated. However, this method has two problems. First, the method is unable to use statistical roughness parameters to describe the anisotropy of machined surfaces. Secondly, the method does not consider the size distribution and spatial distribution of summits on machined surfaces. Recently, Madhusudana and coworkers [16] and Singhal et al. [17] proposed that each peak in the roughness profile (or each equivalent peak in small regions) can be calculated, even if the peak height distribution (or the roughness profile height distribution) does not agree with a function. The TCC of individual summits can be calculated to get the TCC of the whole contact surface. They related the statistical characteristics of roughness profiles to summit deformation. This is a new method to establish the TCC model. However, they did not show how to calculate the peaks in the roughness profile and did not consider how the peak criterion influenced the results. Furthermore, the effect of the anisotropy on prediction results was not considered for anisotropic surfaces. In this paper, the roughness profile is extracted from the original profile, and the influence of roughness profile characteristics on the TCC prediction is studied based on the contact peak criterion (peaks that may contact other surfaces are called contact peaks here in order to distinguish them from the usual definition of a peak).

The framework of this paper is as follows. Section 2 is devoted to measurement and testing methods. The content of this section includes the method used to measure the original profile of machined surfaces, the method used to filter waves, the method used to test the normality and the influences of different factors on statistical results. Section 3 analyzes the roughness profile characteristics. Section 4 introduces the TCC prediction method. Section 5 analyzes predictions resulting from the TCC method. Some factors which may affect the TCC prediction value are discussed, such as the contact peak criterion, the transformation method from contact peak to summit and the anisotropy of surfaces. The conclusions are summarized in Section 6.

2. Measurement and characterization of roughness profiles

2.1. Measurement of original profile

2.1.1. Test plates and processing method

The materials of the test plates consisted of stainless steel S304 and copper H62. The diameter of the contact surface was 52 mm. Each material produced ten test plates using market-bought plates. For each material, four test plates were sandpapered using two types of sandpaper, and four test plates were mechanically polished using two types of emery wheels (only one surface was machined for each plate). Then four types of rough surfaces were produced for these eight test plates for each material. The surfaces of the other two test plates which were not sandpapered and polished were considered to be the same roughness grade for each material. So each material was machined to produce five grades of roughness.

2.1.2. Instruments

The original profiles of the test plates were obtained using the SRAT-1 type roughness automatic profilometer (made by the Instrument Development Center of the Chinese Academy of Sciences). This instrument was an electronic probe type, and the probe diameter was 2 μm. The minimum height resolution was 0.01 μm. The minimum sampling interval (scanning resolution) was 1.25 μm.

2.1.3. Procedures and results

Every test plate was marked with a serial number. They were labeled with four diametric lines (named A, B, C and D) on the back of the contact surface, as shown in Fig. 1. The corner dimension of two adjacent lines was 45°. The original profiles were sampled along the marked lines. The plates were sampled centrosymmetrically along lines A and C, and the measurement starting point was 1/4 diameter apart from the edge along B and D.

The statistical parameter σ (root-mean-square deviation of the profile) was obtained for every plate surface in accordance with ISO4287/1-1984. The mean results were calculated using three random positions on the surface, as shown in Table 1. The length of each original

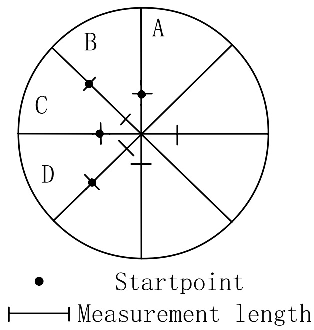

Fig. 1. Surface of test plate.

Table 1
The results of surface roughness measurements

No.	σ (μm)		Machining method
	S304	H62	
1	0.045	0.049	Iron oxide polishing paste
2	0.056	0.049	
3	0.023	0.019	Chromium oxide grinding grease
4	0.018	0.021	
5	0.332	0.563	240# waterproof abrasive paper
6	0.377	0.610	
7	0.192	0.139	600# waterproof abrasive paper
8	0.131	0.322	
9	0.115	0.437	Rolled plate
10	0.082	0.286	

profile was measured at points 8 mm from the line along each labeled line. The sampling interval was 1.25 μm.

2.2. Wavelet transform method

The original profile consists of three types of errors: errors in geometrical form, waviness and roughness. Observations show that the deviation of a surface from its mean plane is a non-stationary random process [9]. As a new mathematical tool, the wavelet transform has the unique ability to analyze the local characteristics of non-stationary random objects and has experienced rapid development since 1986. Wang et al. proposed a method to evaluate the fractal characteristics of original profiles for machining surfaces [18,19]. Decomposing and filtering the original profile are basic abilities of the wavelet transform. In this paper, the Daubechies wavelet base was used to decompose each original profile into 12 orders of the wavelet spectrum, and the roughness profile was reconstituted by discarding the original three orders of the wavelet spectrum.

2.3. Test of normality

The test of normality judges whether a set of data comes from a normal population. In this paper, the skewness and kurtosis of data were used to test the data's normality. If both the skewness and kurtosis of data are in the required range of normal distribution, the distribution of these data should be normal. This range must be determined by two factors: the sample size and the significance level [20]. In this paper, the significance level was 0.01, which meant the qualification for normal distribution had a wide range.

2.4. Factors influencing the test of normality

2.4.1. Sample size

In order to ensure the accuracy of the test of normality, the sample size of data should be as large as possible. But the number of sampling spots for the profiles is usually limited by the accuracy of the measurement instrument. According to the comparison of normal distribution data and roughness profile data, a sample size of 4000 is large enough to meet the requirements of the test of normality for each profile.

2.4.2. Orders of wavelet spectrum

Errors in geometrical form, waviness and roughness of the original profile correspond to different wavelet spectrums from low frequency to high frequency. In order to determine the roughness cut-off frequency, the original profile measured was filtered and reconstituted step by step. In this process, the number of previously discarded wavelet spectrums was increased gradually. Then the skewness and kurtosis of the reconstituted original profile were calculated in each step. The results show that, with the increasing of previously discarded wavelet spectrums, the skewness and kurtosis of the reconstituted original profile drive were constant. For the same original profile, the roughness profile characteristics should be constant. According to this thinking, the roughness cut-off frequency was the highest frequency of discarded wavelet spectrums when the skewness and kurtosis of the reconstituted profile drive were constants. In this paper, the reconstituted profile was considered as the roughness profile without considering the original three orders of the wavelet spectrum.

2.4.3. Number of times wave filtering is repeated

The results showed that increasing the number of times wave filtering was conducted had little influence on the skewness and kurtosis of the reconstituted profile when other conditions were unchanged. In this paper, the roughness profile was considered to be the original profile filtered only once.

3. Roughness profile characteristics

3.1. Test of roughness profile height

The roughness profile height is defined as the deviation between the original profile and the reference line, which is obtained by wavelet transform. First, all original profiles were filtered to obtain the roughness profiles. Second, the skewnesses and kurtoses of roughness profiles were calculated to verify the normality of roughness profile height distribution. The results show that for most of the machined surfaces in our study, the roughness profile height did not have normal distribution. But the histogram indicates that the distribution had some normality, which is in agreement with the opinion of Greenwood and Williamson [2].

Recently, Leung et al. [21,22] indicated that the profile height distribution and summit height distribution of isotropic surfaces have some normality based on Boltzmann's statistic theory. But the roughness profile height distribution varies from the normal distribution for an average machined surface. More research should be conducted to determine why the roughness profile height is not normal.

3.2. Test of contact peak height

Two actual surfaces come into contact on discrete summits which are associated with peaks in the roughness profile. It is very important to analyze the peak height distribution. However, not all of the peaks participate in contact heat transfer. In this paper, peaks that possibly contact the other surface are called contact peaks. Since previous TCC prediction methods have not defined any general criterion for contact peaks, we proposed four contact peak criteria (as shown in Appendix A). The contact peak height was considered as the deviation between the measured height and the reference line.

Using four criteria, we identified the contact peaks for all roughness profiles, and analyzed the distributions of contact peak heights.

Fig. 2 shows the positions of the contact peaks. These positions were identified according to the four criteria for the same roughness profile. In Fig. 2, the points show the positions of contact peaks, and the line indicates the roughness profile. Single peaks in the roughness profile were classified and filtered according to different criterion. For example, single peak A is a contact peak that was identified using all four criteria, whereas single peak B is a contact peak identified only according to criterion 1, as shown in Fig. 2. Using the four criteria for the same roughness profile, it is clear that the number of contact peaks and their positions vary widely.

Fig. 3 shows contact peak height distributions using four criteria for the same roughness profile. In Fig. 3, (a) is close to a normal distribution; some "strips" are noticeably absent in contrast to the normal distribution shown in Fig. 3(b) and (d); a critical height is present in Fig. 3(c).

Fig. 4 shows the skewnesses and kurtoses of contact peak heights for all roughness profiles. For a roughness profile with a length of 6 mm, the results of calculation show that the number of contact peaks is usually 400–1000 according to criterion 1, while there were only 100–500 contact peaks according to the other three criteria. It should be noted that the sample sizes for testing the normality of contact peak height were different for different roughness profiles. In Fig. 4, the range of skewness and kurtosis for normal distribution for the highest sample size is represented by a broken square, and the range for the lowest sample size is represented by a solid square. There are few points located inside the squares in Fig. 4(a) and (c). However, Fig. 4(b) and (d) show quite a few congruent points. So the contact peak criterion is a possible reason for the great differences in predicting thermal contact conduction using different mechanistic models.

When different criteria were used, the contact peak height characteristics varied greatly for the same roughness profile.

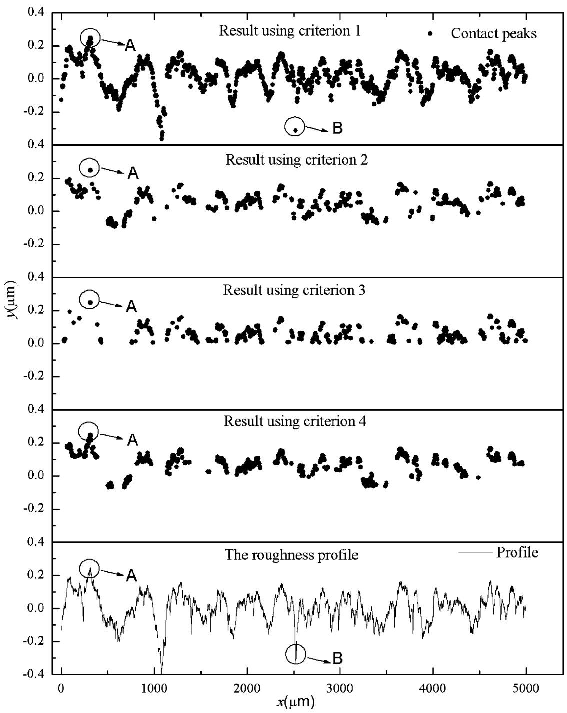

Fig. 2. Positions of contact peaks using four contact peak criteria.

3.2.1. Criterion 1

The skewness and kurtosis of the contact peak height distribution were very close to the skewness and kurtosis of roughness profile height for most profiles. Using this criterion, the histograms showing the contact peak and roughness profile heights were also similar to each other. This indicates that the single peak height characteristics are similar to the roughness profile characteristics.

3.2.2. Criterion 2

Some strips were absent compared with normal distribution in the histogram for contact peak height, especially in the negative skewness range, as shown in Fig. 3(b). These absences were caused by the presence of a reference line, which was calculated based on each sample segment of the roughness profiles. All of the single peaks that were lower than the reference line have to be discarded. This resulted in a decrease in data in the negative skewness range for contact peaks.

3.2.3. Criterion 3

There is a critical height for contact peaks, and the histogram seems to be half of the mitriform, as shown in Fig. 3(c). This is due to the fact that in this criterion, the reference line is calculated according to the whole roughness profile, not according to each sample segment, as was the case in criterion 2. All of the single peaks which are lower than the reference line should be discarded. Obviously, the critical height is the height of the reference line.

3.2.4. Criterion 4

The results obtained using criterion 4 were similar to those obtained using criterion 2. Single peaks that are lower than the reference line were discarded. The reference line was also calculated based on each sample

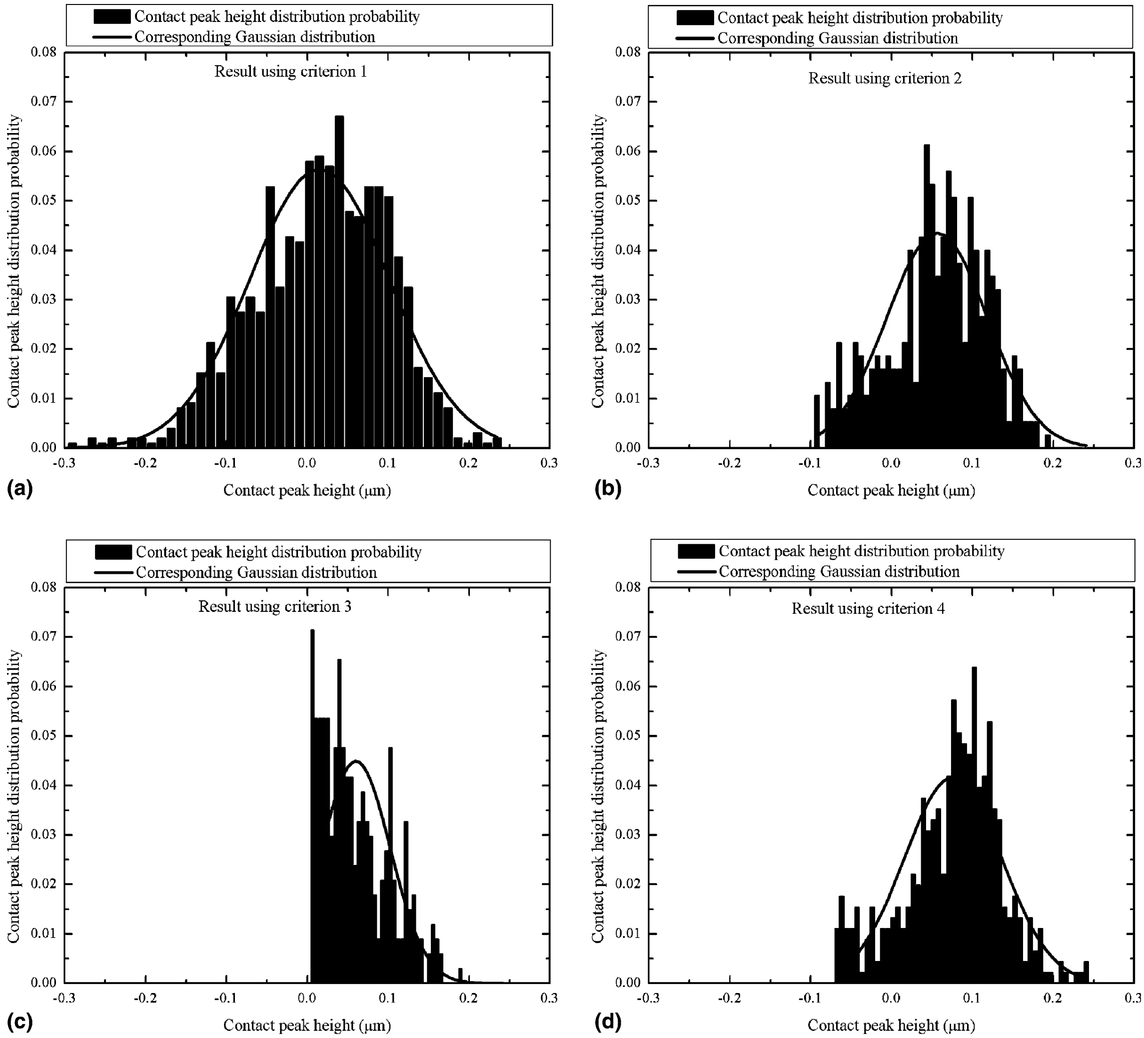

Fig. 3. Roughness profile height distribution.

segment of the roughness profiles, and there were also the absences of strips in the histogram of contact peak height distribution.

4. TCC prediction method

As described in the previous section, the contact peak criterion is critical to the contact peak characteristics which are required to evaluate the number and size of the contact spots. The TCC is the sum of the conductance of several discrete spots that exist on the interface. The actual radii of these contact spots as well as their number can be determined by means of surface topography and deformation analysis. So the TCC can be finally determined as a function of surface parameters, material properties and contact pressure.

Based on a single roughness profile, the contact peak distributions can be obtained by the method described in the previous section. It is further assumed that summits are directly correlated with contact peaks. There are two methods for transforming contact peaks into summits, as detailed in Appendix B. These methods were used to obtain characteristics for the size and number of summits. An ideal TCC mathematical model for a single contact spot was used.

4.1. Single summits in contact with a flat surface

This study assumed single summits were in contact with an ideal smooth flat surface. The equation to calculate the

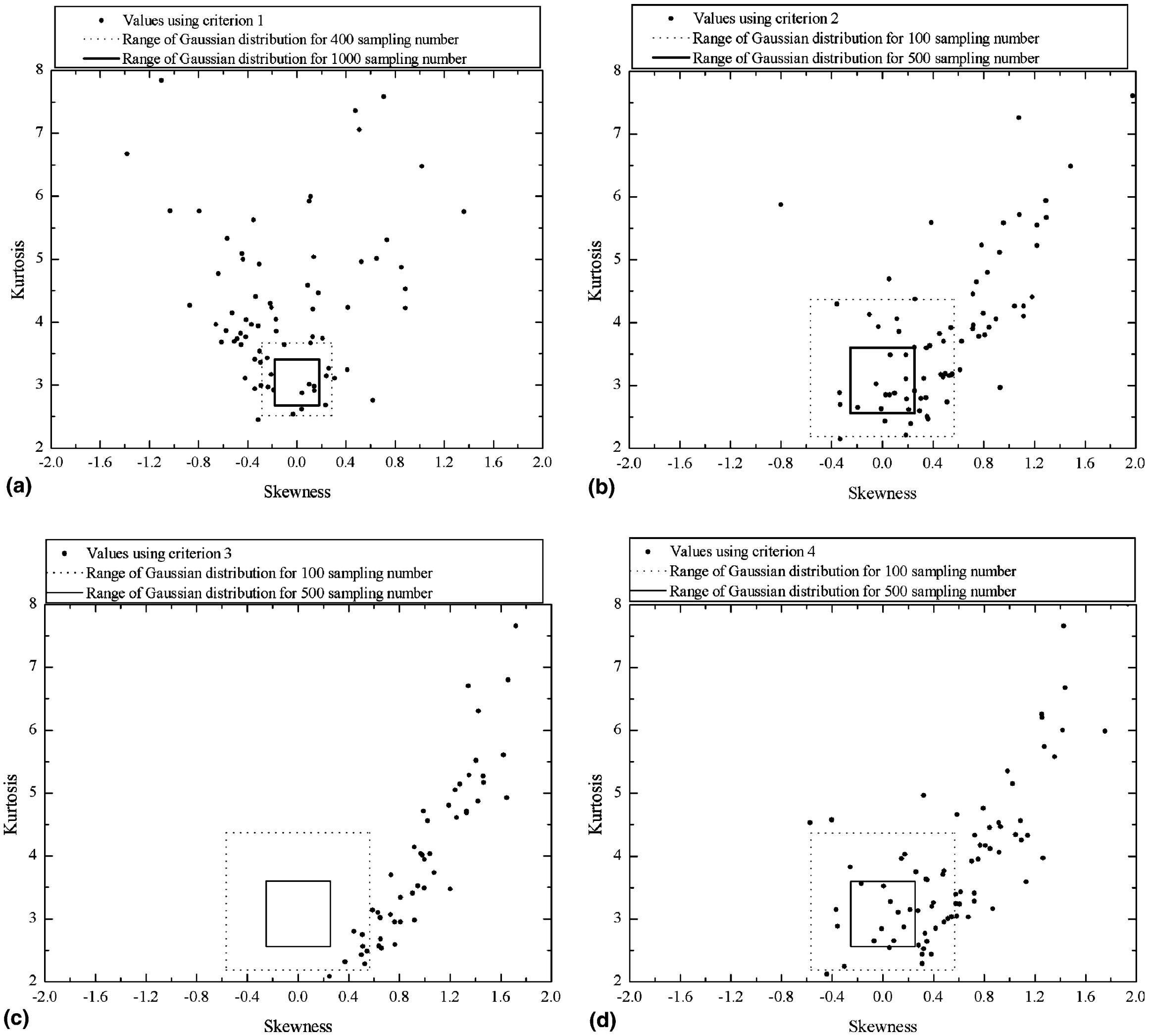

Fig. 4. The skewnesses and kurtoses of contact peak heights.

TCC of single contact spots was derived from a sphere model. It is expressed as:

$$h' = \frac{2a\lambda_s}{\varphi} \tag{1}$$

where a is the contact radius of summit; b is the radius of curvature of summit; φ is a function of a/b. The expression of φ varies with the value of a/b [7]. To simplify the problem, φ was calculated using Eq. (2):

$$\varphi = \left(1 - \frac{a}{b}\right)^{1.5} \tag{2}$$

In order to evaluate the contact radius of the actual spot, it is first necessary to determine whether a summit's deformation would be elastic, elastoplastic or plastic. For the present study, the effect of the description of surface topography on TCC prediction was discussed primarily. So the summit deformation assumption was chosen arbitrarily. Then the plastic deformation assumption was chosen; namely, the deformations of all summits were assumed to be plastic. For a given surface separation, the contact radius of a summit was calculated by Eq. (3) [16,17]:

$$a = \sqrt{2\delta b} \tag{3}$$

The mean contact pressure can be expressed as Eq. (4) [16,17]:

$$p_m = H_c = 3Y \tag{4}$$

In Eq. (4), the value 3 was the approximation of 2.76 [5].

4.2. Actual contact between two rough surfaces

These two rough surfaces were assumed to be made of the same material and to be uniform in their surface topography. They could be used as a model of the contact of a smooth and equivalent rough surface. The prediction method included the following procedures:

(1) For a single original profile for a rough surface, the roughness profile is extracted using the wavelet transform. Then the position and number of contact peaks for this roughness profile were obtained using the four contact peak criteria.
(2) Each radius of curvature of contact peak, namely the radius of the summit on a three-dimensional surface, was calculated. Then the equivalent curvature radius for two contact peaks in contact was equal to $\sqrt{2}$ times a single radius according to the rule of equivalent parameters that characterized the topography of the two surfaces [15].
(3) For a given separation distance between two surfaces, each contact peak height was used to judge whether this contact peak was in contact with the smooth surface. If contact occurred, the contact radius a and mean contact pressure P_m of this contact peak could be calculated using Eqs. (3) and (4), and then the contact force P of this contact peak was calculated as:

$$P = p_m \pi a^2 \tag{5}$$

(4) The number and the size of the summits which were in contact were calculated using two different methods for transforming contact peaks into summits. The contact conductance and the contact pressure of the whole surface were sums of all of the summits, assuming these summits were parallel to each other. Then the contact conductance per unit area h_c and apparent contact pressure p_{app} can be calculated by Eqs. (6) and (7):

$$h_c = \sum h_i' / A_{app} \tag{6}$$

$$p_{app} = \sum P_i / A_{app} \tag{7}$$

(5) Step 3 was repeated for different separation degrees. Then the relation between TCC and apparent contact pressure was obtained.

5. Results and analysis

This study used test plates made of stainless steel 304. Table 2 shows the conditions and material parameters. The calculation results are shown in Figs. 5–9 by the relation of dimensionless TCC ($h_c\sigma/m\lambda_s$) and dimensionless apparent contact pressure (p_{app}/H_c). The roughness parameters of m and σ were calculated for each roughness

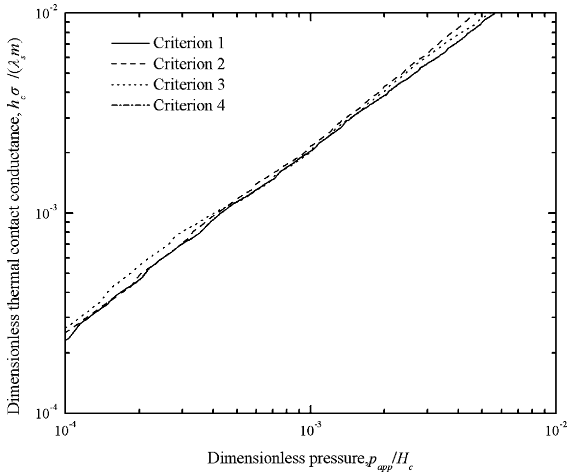

Fig. 5. TCC of roughness profile A for test plate 1.

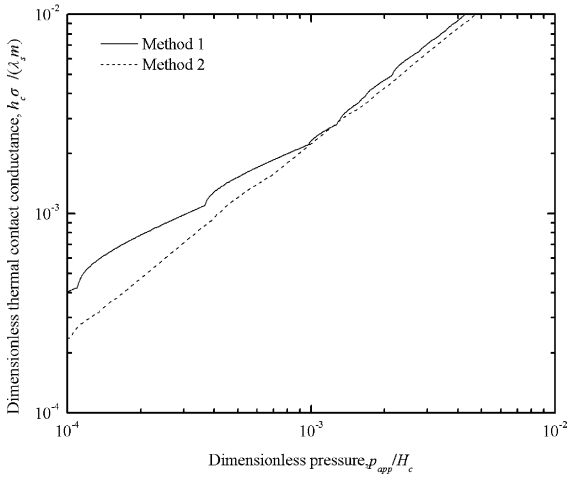

Fig. 6. Effect of methods for transforming contact peaks into summits.

Table 2
Conditions and material parameters

T (K)	p_{app} (Pa)	λ (W/m K)	H_c (GPa)	E (GPa)	ν
273.15	10^5–10^7	13.8	2.3	193	0.28

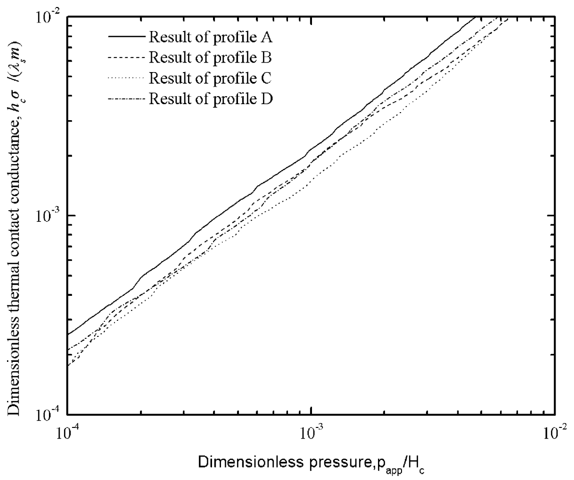

Fig. 7. TCC prediction strip for test plate 1.

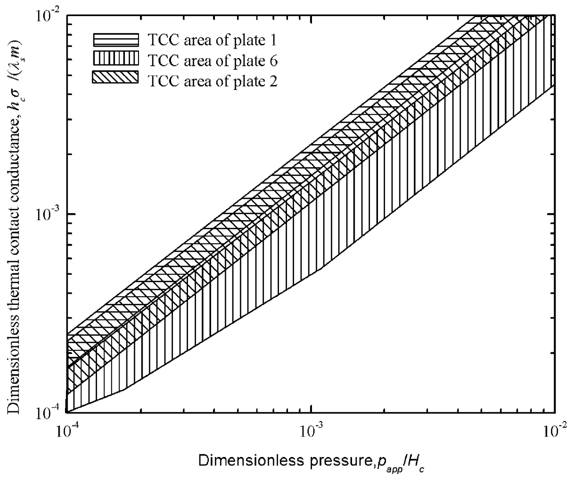

Fig. 8. TCC prediction strips for different test plates.

profile, but because of the limits of this paper's length, their values are not listed here.

5.1. Effect of the contact peak criterion

In this paper, peaks that may contact other surfaces are called contact peaks in order to distinguish them from the usual definition of a peak. The existing TCC models do not distinguish contact peaks from ordinary peaks. So four criteria are proposed to evaluate the contact peaks in this paper. The contact peak criterion greatly affects the statistics of contact peak height distribution, as discussed in Section 3.2. This explains the divergent views held by different scholars for the distribution of contact spots. In this section, the effect of the contact peak criterion on TCC prediction is discussed. The number of contact peaks for four roughness profiles for test plate 1 was calculated, as listed in Table 3, according to four contact peak criteria. Fig. 5 shows the TCC prediction results of roughness profile A.

The results showed that the TCC prediction values obtained using the four criteria were different for the same roughness profile. But the differences were not significant. This is due to the fact that the contacts mainly occur among contact peaks with large heights under the given apparent contact pressure, and these contact peaks can be obtained using every criterion. This shows that the contact peak criterion has limited influence on TCC prediction values.

5.2. Effect of the method for transforming contact peaks into summits

Some scholars have calculated the relationship between the quantity of summits and of peaks [6]. But their calculations did not consider the relationship of summits and peaks in regard to height distribution. So, in this study, we propose two methods to transform contact peaks into summits and obtain the characteristics for the size and number of summits, as detailed in Appendix B. In this section, the effect of the method for transforming contact peaks into summits on TCC prediction is discussed.

The contact conductance of roughness profile A for test plate 1 was calculated using two methods for transforming contact peaks into summits, as shown in Fig. 6. Using different methods produced significantly different results. Curves relating the TCC and apparent contact pressure fluctuated greatly when calculated using method 1. This was due to the fact that when method 1 was used, the number of contact spots increased greatly as the separation decreased. These two methods are assumptions about the relationship of contact peak and summit.

Table 3
Contact peaks for roughness profiles of test plate 1 using different criteria (number/mm)

Line no.	Criterion 1	Criterion 2	Criterion 3	Criterion 4
A	159.83	48.17	43.00	72.50
B	168.67	43.00	42.17	74.00
C	172.33	46.67	44.83	68.50
D	154.17	51.83	45.50	72.83

In order to provide a more proper method for transforming contact peaks into summits, a more accurate description of three-dimensional surface topography is necessary.

5.3. Effect of RMS and anisotropic property

Fig. 7 shows the prediction results for four roughness profiles for test plate 1. Though the contact peak numbers for different roughness profiles from the same test plate were close to each other (Table 3), the TCC prediction values were quite different and formed a prediction strip of a certain width. The formation of a prediction strip was caused by the fact that the contact surface was anisotropic, and the strip reflected the difference in characteristics between different roughness profiles (such as the contact peak height distribution). This reveals that a single roughness profile cannot be used to describe the topography of a whole surface. Furthermore, the calculation results showed that the widths of prediction strips vary for different test plates. More research should be conducted to confirm whether an exact calculation of the TCC prediction strip is possible for a test plate, and how many roughness profiles should be used.

The TCC prediction strips for test plates 1, 2 and 6 are presented in Fig. 8. The results showed that the widths of prediction strips were quite different for different test plates. Furthermore, the prediction strips could be overlapped for two test plates with very different RMS values, as was the case for test plates 2 and 6. This revealed that several statistical roughness parameters are not sufficient to describe the topography of a whole surface.

6. Conclusions

1. The contact peak criterion is a key element to calculate the number and position of contact peaks. The results obtained using different criteria were very different. This explains the divergent views held by different scholars for the distribution of contact spots. However, the contact peak criterion has limited influence on TCC prediction results.
2. The TCC prediction values for different roughness profiles were different for the same machined surfaces because of anisotropy. A single roughness profile is insufficient to describe the topography of the whole surface. If several roughness profiles are used, the TCC calculation results for different roughness profiles form a steady strip. Furthermore, the prediction strips may be overlapped for two contact surfaces with different RMSs. It is also inadvisable to use several statistical roughness parameters to describe the topography of the whole surface. More experimental data should be obtained to validate the predictive model, and determine the prediction strip.

In order to establish a more effective model for predicting TCC, a three-dimensional numerical calculation of the topography of the contact surface should be included in the model. Further research is planned to describe the three-dimensional topography of contact surfaces.

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Appendix A. The contact peak criterion

Spots that are higher than their neighboring spots can be considered as single peaks, and the converse is true for single valleys. The outline of the exterior (from material to medium) along the mean line between the two nearest meeting points (profile and mean line) is named a profile peak, and the converse is a profile valley according to ISO4287. The distance from the highest single peak of a profile peak to the mean line is called the profile peak height. The distance from the lowest spot of a profile valley to the mean line is named the profile valley depth. In a sampling length, the sum of the maximum profile peak height and the maximum profile valley depth is named the maximum height of the profile. As shown in Fig. 9, A, B and C are profile peaks; R_P is the profile peak height of profile peak A; a, b, c, d, e and f are single peaks of profile peak A; h and i are single peaks of the profile valley; and R_Z is the maximum height of the profile in this sample segment.

The aforementioned mean line is the reference line which is used to calculate the roughness of the original profile (the wavelet reference line was used in the current work). The mean line must be calculated based on each sample segment, and the length of a sample segment is decided by the roughness of the surface according to ISO 469-1982. The average values of the roughness height within a sample segment are not zero for different parts of the same roughness profile obtained using a wavelet filter. Therefore, the mean line should be calculated a second time. In this study, the arithmetical mean line was used.

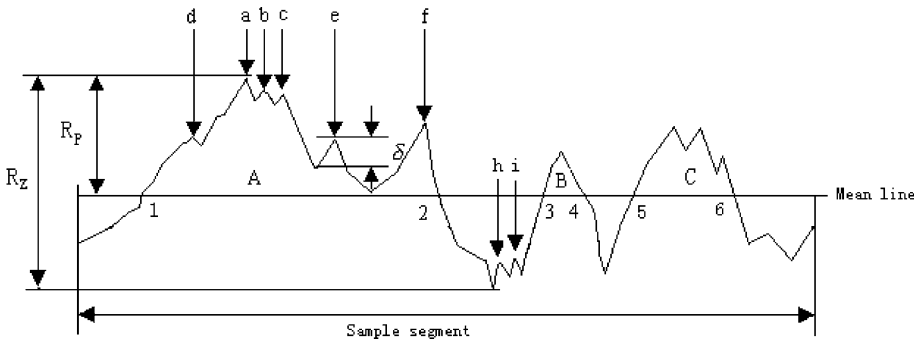

Fig. 9. Single peak and profile peak.

We introduced four different contact peak criteria as shown below.

A.1. Criterion 1

When two surfaces are in contact, it is assumed that all single peaks may be contact spots; that is, single peaks are contact peaks.

A.2. Criterion 2

It is assumed that not all single peaks can contact the other surface; only the single peaks of profile peaks may contact the other surface. If the difference in height between a single peak and the nearest taller single valley is more than 10% of the profile peak height for a profile peak, this single peak can be considered as a contact peak [23]. The profile peak should be evaluated by the mean line, which is calculated within each sample segment.

A.3. Criterion 3

In order to study the influence of the mean line, the mean line is calculated within the whole length of the roughness profile, not within a sample segment as is the case in the criterion 2. Other consideration about contact peaks are the same as in criterion 2.

A.4. Criterion 4

Only the height resolution was considered for the contact peaks in criterion 2 and 3. In fact, very narrow single peaks have little influence on the contact heat transfer. So the least separation between two contact peaks should be more than 1% of the length of a sample segment according to ISO 469-1982. Furthermore, a single peak with a height that is greater than 10% of the maximum height of the profile within a sample segment would be considered a contact peak. The mean line is also calculated within a sample segment.

The positions and number of contact peaks can be calculated using these criteria. The contact peak heights for the same roughness profile still show some deviation between measured spots and the wavelet reference line in TCC calculations.

Appendix B. Methods for transforming contact peaks into summits

It is supposed that the density of summits is 1.2 times that of peaks [6]. This can only illustrate the relationship between the quantity of summits and of peaks. The relationship between summits and peaks in regard to height distribution is unknown. Two methods for transforming contact peaks into summits were proposed in this paper.

First of all, the surface was supposed to be isotropic, meaning that the statistics for the roughness profile characteristics were uniform in different positions and directions. x and y represented two directions which were orthogonal on the contact surface. In x-direction, the number of contact peaks for a roughness profile with the length l was supposed as n. The following two methods were used to calculate the number of corresponding summits in the $l \times l$ rectangular area for each contact peak of a roughness profile in x-direction.

B.1. Method 1

It was supposed that each contact peak of a roughness profile in x-direction corresponded to $1.2n$ summits in the $l \times l$ rectangular area. In other words, the parameters of these summits should be calculated using the parameters of this contact peak if it is in contact with the other surface. Accordingly, the total number of summits is $1.2n^2$.

When the separation distance d has been determined, the number of contact peaks n_c which are in contact with the other surface can be calculated according to the height of each contact peak. Accordingly, the total number of summits which are in contact is $n_c \times 1.2n$ under this separation distance.

B.2. Method 2

The number of contact peaks which were distributed in k equal intervals between the least height z_0 and the greatest height z_k was calculated according to each contact peak height z: n_1 $(z_0 < z < z_1)$, n_2 $(z_1 < z < z_2)$, n_3 $(z_2 < z < z_3) \cdots n_{k-1}$ $(z_{k-2} < z < z_{k-1})$, n_k $(z_{k-1} < z < z_k)$.

If the separation distance d agrees with the condition $z_{x-1} < d < z_x$, each contact peak which agrees with the condition $z > z_{x-1}$ in x-direction corresponds to 1.2 $(n_k + n_{k-1}+n_{k-2} + \cdots + n_{x-1} + n_x)$ summits in contact. In other words, the parameters of these summits should be calculated using the parameters of this contact peak. Accordingly the number of all of the summits which are in contact in the $l \times l$ rectangular area is 1.2 $(n_k + n_{k-1} + n_{k-2} + \cdots + n_{x-1} + n_x) \times (n_k + n_{k-1} + n_{k-2}+ \cdots + n_{x-1} + n_x)$ under this separation distance. Obviously, the total amount is also $1.2n^2$ when all of the summits are in contact with the other surface in the $l \times l$ rectangular area.

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