

Cutter mark cross method for improvement of contact stiffness by controlling distribution of real contact area

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Abstract

Contact surfaces do not make contact perfectly because such surfaces have a lot of asperities. The real contact area is much smaller than the nominal contact area, and the real contact areas has a non-uniform distribution because of the waviness in the contact surface. The contact stiffness is influenced not only by the deformation of the asperities, but also by the distribution of the real contact areas. In general, a contact surface with a uniform distribution of the real contact areas has greater contact stiffness. However, this requires a grinding finish and costs more than the cutting finish. In this study, a method for uniformly distributing the real contact areas easily, is proposed to improve the contact stiffness of a contact surface finished by cutting. The method is called the cutter mark cross (CMC) method. The allowable waviness in the CMC method is shown. In addition, the effect of the CMC method is investigated by experimentation. The results show that the real contact areas can be distributed uniformly using the CMC method. The horizontal and vertical contact stiffness can also be improved.

Highlights

- Cutter mark cross method (CMC method) is proposed.
- The distribution of real contact area can be controlled by CMC method.
- The contact stiffness is improved by CMC method.

Keywords

Contact stiffness, Real contact area, Distribution of real contact area, Cutter mark

1. Introduction

In recent years, there has been increasing demand for higher efficiency in high-precision machining. Because the stiffness of a machine tool greatly affects the machining accuracy, high stiffness machine tools are required. However, machine tools have many parts that are jointed, at each of which the stiffness decreases. Therefore, the stiffness of contact surfaces (contact stiffness) between various mechanical surfaces of the machine tool, including the bolt fastening part, decreases the machine tool stiffness, when high contact stiffness at a contact surface is required [1-5].

A contact surface has a lot of small-scale asperities and the contact stiffness is influenced by uncertain factors such as the shape and distribution of the asperities. Many studies have proposed models of the contact stiffness at a real contact surface. Greenwood and Williamson proposed the first contact stiffness model for contact between rough surfaces based on an asperity model (GW model) [6]. Whitehouse and Bush et al. further improved the GW model [7-13]. Moreover, Chang et al. extended the GW model to include the plastic and elastic deformation of asperities in contact, using an analytical approach [14]. In the more advanced model, the contact stiffness depends on three parameters: the standard deviation of the height of asperities, the distribution density of the asperities, and their mean radius. This model is focused only on the micro scale deformation of the contact surface. However, when considering the stiffness of the contacted parts, the macro scale deformation of a contact surface is also important. The macro scale deformation of a contact surface refers to the deformation due to the distribution of the contact pressure. On the contact surface, the real contact areas have non-uniform distribution. Therefore, the contact pressure also has a non-uniform distribution and the contact stiffness is influenced by the contact pressure distribution. Lei Wang et al. proposed an analysis of contact stiffness that included both micro and macro scale [15]. According to this analysis, considering the deformation of a contact surface at micro and macro scale, the stiffness of a contacted joint can be calculated precisely. In other words, there are micro and macro scale approaches for improving contact stiffness.

To improve the contact stiffness at micro scale, control of the height of asperities is important. Surfaces with less roughness have higher contact stiffness because the deformation of asperities is smaller. This tendency has been confirmed experimentally and analytically in earlier studies [16-18]. To improve the contact stiffness at macro scale, the distribution of the real contact areas is important because the three-dimensional (3-D) stress distribution near the contact surface depends on the distribution of the real contact areas. Moreover, the distribution of the real contact areas is greatly affected by the waviness of the contact surface [19,20]. The lower waviness results in greater contact stiffness because the distribution of the real contact areas is more uniform. However, making a contact surface with less roughness and lower waviness is expensive.

This study proposes the cutter mark cross (CMC) method, which is a simple method of improving the contact stiffness. This method enables us to distribute the real contact areas uniformly in the

nominal contact area and to improve the contact stiffness, even if the contact surface has a certain waviness. First, a method of distributing the real contact areas uniformly (CMC method) was proposed. Then the condition of waviness needed to distribute the real contact areas uniformly was calculated. Next, an experiment was conducted to verify that the real contact areas was distributed uniformly by the CMC method. Finally, it was verified that the contact stiffness was improved by the CMC method.

2. Method of improving contact stiffness

2.1 Cutter mark cross (CMC) method

Fig. 1 shows a schematic of a contact surface. The contact surface has a lot of asperities, so the contact surfaces cannot make perfect contact. The real contact areas are much smaller than the nominal contact area. Moreover, the distribution of the real contact areas is only part of the nominal contact area because the contact surface has waviness, as shown in Fig. 1 (b). The contact stiffness is influenced not only by the deformation of the asperities, but also by the distribution of the real contact areas. The distribution of the real contact areas depends on the waviness of the contact surface more than its roughness. The contact stiffness is greater when the distribution of the real contact areas is uniform (Fig. 1 (a)) than when the distribution of the real contact areas is partial (Fig. 1 (b)). To distribute the real contact areas uniformly, the contact surface needs to have minimal waviness. However, this requires a grinding finish, which costs more than a cutting finish alone. This is because the deformation of the asperities due to the normal preload is too small. The real contact areas are distributed uniformly when the deformation of asperities is greater than the waviness in the nominal contact area.

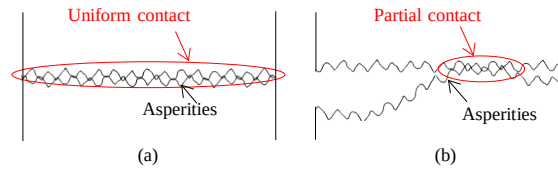


Fig. 1 Schematic of a contact surface: (a) No waviness, (b) With waviness

In general, a lot of contact surfaces are finished by cutting. A cutting surface has periodic cutter marks. In this study, a contact surface finished by cutting was considered. To distribute the real contact areas uniformly and to improve the contact stiffness, increasing the deformation of the asperities is effective. In this study, the cutter mark cross method is proposed for this purpose. In this article, the word of “cutter mark” represents traces after cutting, and cutter mark cross method is expressed as CMC method for the abbreviation. Fig. 2 shows a schematic of the CMC method. The CMC method is a way to make the distribution of the real contact areas more uniform by crossing cutter marks and making point contacts. This method can concentrate the real contact areas at the crossings of the cutter marks. The number of real contact points are limited and extreme plastic deformation occurs at the real contact points. Therefore, when the plastic deformation is larger than the waviness of the surface, this method can prevent uneven distribution of the real contact areas.

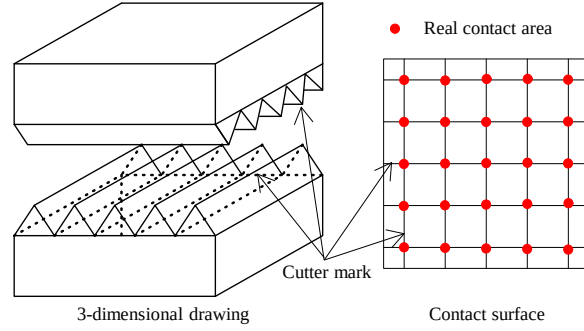


Fig. 2 Schematic of the cutter mark cross (CMC) method

2.2 Conditions for uniform distribution of the real contact areas using the CMC method

To make all cutter mark crossings come into real contact using the CMC method, it is necessary to calculate the allowable waviness. The elastic deformation is much smaller relative to the plastic deformation under the pressure of bolted joints between cutting surfaces. Therefore, in order to simplify the calculation, the allowable waviness is calculated considering only plastic deformation. The deformation of a contact surface is determined from the contact pressure and the plastic flow pressure of the material. The contact pressure depends on the contact load and the surface shape. In this section, the relationship among the allowable waviness, the contact load, and the contact surface shape is investigated.

The allowable waviness is determined from the plastic deformation of the contact surface. Fig. 3 (a) shows the deformation when the waviness of the contact surface is (ideally) zero, and Fig. 3 (b) shows the deformation when the waviness is large. In Fig. 3, the term d indicates the plastic deformation of the highest cusp, and w shows the waviness of the contact surface. Ideally, with $w = 0$ and uniform cusp heights, contact will occur at all cutter mark crossings, as shown in Fig. 3 (a). However, it is impossible to equalize the cusp heights perfectly because of the waviness in the actual cutting surface. On the other hand, as shown in Fig. 3 (b), when the plastic deformation of the cusps is smaller than the waviness of the contact surface ($d < w$), real contact does not occur at some cusp crossings.

The allowable waviness is obtained in the following manner. The material of both contacted surfaces is assumed to be same. First, the plastic deformation of the top of the cusps is calculated. The plastic deformation is determined from the total real contact area A_r . Contact starts at the highest point and the tops of cusps are plastically deformed. As the preload become larger, the contact height gets lower and total real contact area A_r increases while plastic deformation stops when the total real contact area A_r is satisfied according to Eq. (1):

$$A_r = \frac{W}{p_m} \quad (1)$$

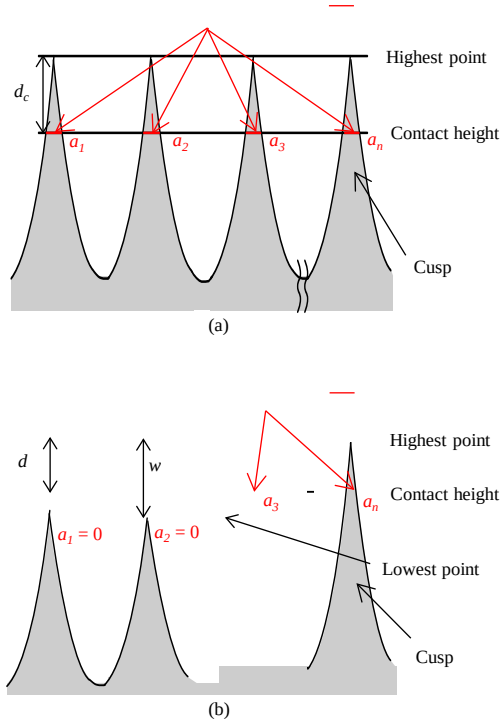


Fig. 3 Deformation at the top of the cusps: (a) $d \geq w$, (b) $d < w$

where W represents the preload, A_r represents the real contact area, and p_m represents the plastic flow pressure [21]. The plastic flow pressure p_m is a material parameter and almost equal to the Vickers hardness. The surface shape can be determined geometrically from the nose radius of the cutting tool and the pick feed on the cutting surface. When the surface shape of the contact surface is known, the plastic deformation can be calculated using Eq. (1) for the real contact area.

The case considered here, is where the deformation of the highest cusp d is the smallest. Because the real contact area is determined only from the preload applied to the contact surface and the plastic flow pressure p_m of the material, the total of the real contact area of each cusp crossing is equal regardless of its shape. Therefore, the total real contact area A_r satisfies Eq. (2):

$$A_r = \sum_{i=1}^n a_i \quad (2)$$

where a_i (≥ 0) is the real contact area at each cusp crossing and n is the number of cutter-mark crossings. The case where d is smallest, is the case where the maximum value of a_i reaches its minimum (Fig. 3 (a)). In this case, a_i satisfies Eq. (3).

$$a_1 = a_2 = \dots = a_n \quad (3)$$

In this case, the waviness is ideally zero and the all cusps have the same cusp height. The deformation of the highest cusp in this case is called the minimum contact deformation d_c . Even if the contact surface has large waviness, the highest cusp is guaranteed to be deformed to the minimum

contact deformation d_c or more. Therefore, if the waviness of the contact surface is smaller than the minimum deformation d_c ($w < d_c$), real contact can be realized at all cutter-mark crossings regardless of the condition of the contact surface.

2.3 Calculation of the minimum contact deformation and variation of the real contact areas

Here, the minimum contact deformation d_c is calculated for a surface finished using a tool with an R-shaped cutting edge. Fig. 4 illustrates the definitions of physical quantities and variables required for the calculation of d_c . From geometric conditions, the following equations hold.

$$h = R - \sqrt{R^2 - \frac{l^2}{4}} \quad (4)$$

$$x = R\sin(\alpha + \theta(x)) - R\sin\alpha \quad (5)$$

$$\sin\alpha = \frac{R - h}{R} \quad (6)$$

$$y(x) = l - 2R\sin\left(\frac{\pi}{2} - (\theta(x) + \alpha)\right) \quad (7)$$

where R is the nose radius of a cutting tool; l is the pick feed; and h is the cusp height. Fig. 5 shows a schematic of the real contact area after applying the CMC method. The upper and lower cusps deform by the same amount because both cusps have the same shape. Therefore, the real contact area $a(x)$ is assumed to be a square with side $y(x)$. The area $a(x)$ is given by

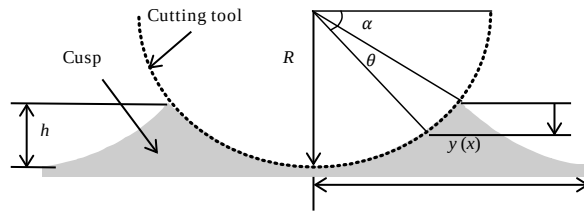


Fig. 4 Definition of the physical quantities and variables

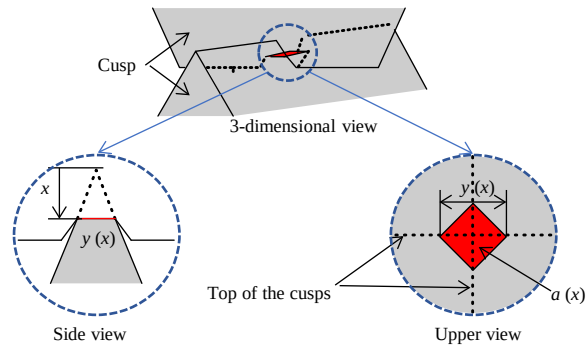


Fig. 5 Schematic of the real contact area after using the CMC method

$$a(x) = \frac{1}{2}y(x)^2 \quad (8)$$

The number of real contact surfaces are determined by the number of cusp crossing points n . The number of cusp crossing points n can be determined from the pick feed l . Here, n is given by

$$n = \frac{1}{l^2}A \quad (9)$$

where A is the nominal area of contact. The real contact area $a(d_c)$ per crossing when $x = d_c$ is given by

$$a(d_c) = \frac{A_r}{n} \quad (10)$$

where A_r is the total of the real contact areas. Substituting Eq. (1) and Eq. (9) into Eq. (10) yields:

$$a(d_c) = \frac{Wl^2}{p_m A} \quad (11)$$

Substituting Eq. (4)-(6) into Eq. (7) yields:

$$y(x) = l - 2R \sin\left(\frac{\pi}{2} - \sin^{-1}\left(\frac{x + R - h}{R}\right)\right) \quad (12)$$

From Eq. (8) and (11),

$$y(d_c) = \sqrt{2a(d_c)} = \sqrt{\frac{2Wl^2}{p_m A}} \quad (13)$$

The terms R and l are determined by the cutting condition, p_m is determined from the material, and W and A are determined from the contact conditions. Moreover, these values are constant. Therefore, from Eq. (12) and (13), the minimum contact deformation d_c can be calculated and is given by

$$d_c = R \sin\left[\cos^{-1}\left\{\frac{l}{2R}\left(1 - \sqrt{\frac{W}{2p_m A}}\right)\right\}\right] - (R - h) \quad (14)$$

Fig. 6 shows the calculated minimum contact deformation d_c . The x axis shows the cusp height and this value is determined from the contact surface shape parameter (R, l). The y axis shows the nominal contact pressure and this value is determined from contact condition (A, W). Making the waviness amplitude of the contact surface w smaller than d_c guarantees real contact at all cutter mark crossings with the CMC method. In the other words, Fig. 6 shows the limit of waviness amplitude when using the CMC method.

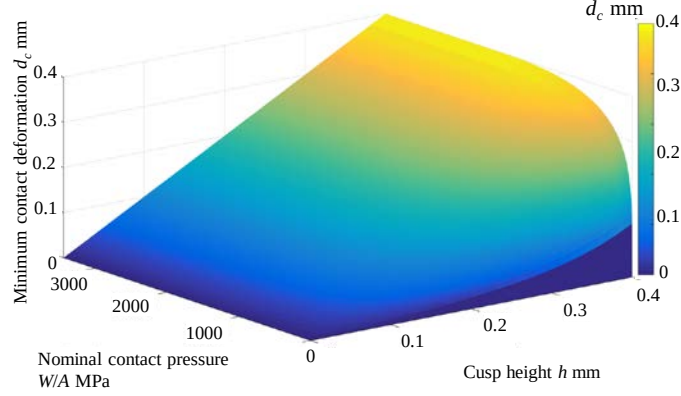


Fig. 6 Limit of wave amplitude in the CMC method ($R = 0.4$ mm, $p_m = 3430$ MPa)

Next, variation of the real contact areas is considered. If the waviness amplitude w is smaller than d_c , the real contact at all cusp crossings is guaranteed. However, even if real contact is guaranteed, the real contact area per contact point close to zero may be created. For this reason, the minimum the real contact areas per contact point must be considered. Setting the minimum real contact area per contact point enables us to prevent large variation of the real contact area. The minimum real contact area per contact point is determined by the waviness margin ε , which is a constant value and is satisfied by $w = \varepsilon d_c$ ($0 \leq \varepsilon \leq 1$). Fig. 7 shows the relationship between the real contact area per contact point $a(x)$ and cusp deformation x derived from Eq. (8). When the minimum real contact area per contact point is a_{min} , the waviness margin ε is obtained from Fig. 7. If the waviness amplitude w can be made smaller than εd_c , all the real contact areas per crossing becomes larger than a_{min} .

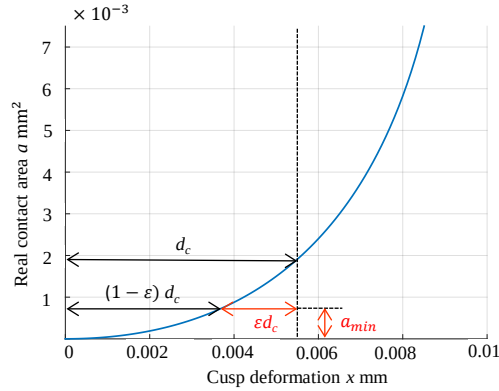


Fig. 7 Waviness margin

3 Experiment for controlling the distribution of the real contact area

3.1 Experimental method and condition

Section 2 describes the conditions for distributing the real contact areas uniformly in the nominal contact area using the CMC method. In this section, we report that the distribution of the real contact surface can be controlled successfully using the CMC method and that this was verified by experiment. Three specimens were made for the contact experiment, two top specimens and a base (bottom) specimen (specimen 1, specimen 2, and the base). Fig. 8 shows a schematic of the top specimens and the base specimen. Specimen 1 had minimal waviness within the condition of uniform distribution of the real contact areas. Specimen 2 had a step and did not satisfy the condition of uniform distribution of the real contact areas. The base specimen had the same surface shape as specimen 1. Surface contact was made by pushing the top specimens onto the base specimen and then applying a preload. The distribution of the real contact areas on these contact surfaces was investigated by measuring the plastic deformation of the contact surfaces with a laser microscope. The plastic deformation was measured by comparing the contact surface shape before and after the experiment. Table 1 shows the specifications of the laser microscope under the experimental conditions. The nominal contact area was a small square (2×2 mm) because observation of the plastic deformation was conducted at high magnification using a laser microscope.

Table 2 shows the specifications of the specimens. The specimens were made of carbon steel (JIS S45C) and the surfaces were plated with nickel phosphorus (Ni-P). The specimens were machined using shaper cutting with a single crystal diamond tool. Specimen 1 was machined with waviness about 1 μm in amplitude, and specimen 2 was machined with a 5 μm step.

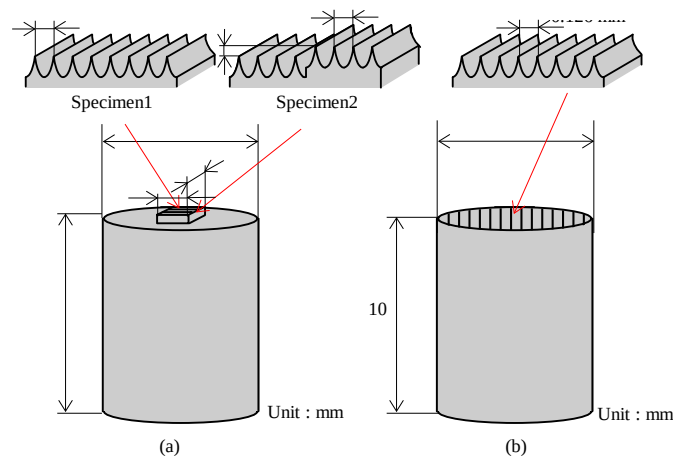


Fig. 8 Schematic of the two top specimens and the base specimen: (a) the two top specimens, (b) the base specimen

Table 1 Specifications of the laser microscope and force sensor under the experimental conditions

Laser microscope	Resolution	X: 0.625 μm Y: 0.625 μm Z: 0.002 μm
	Measurement range	X: 2.5 mm Y: 2.5 mm Z: 0.05 mm
	Accuracy	0.2 μm
Force sensor	Measurement range	26 kN
	Sensitivity	-3.8 pC/N

Table 2 Specifications of the top specimens

	Specimen 1	Specimen 2
Tool radius: R	0.2 mm	0.2 mm
Pick feed : l	0.126 mm	0.126 mm
Cusp height: h	10 μm	10 μm
Wavy amplitude: w	1 μm	5 μm
Nominal contact area: A	4 mm ²	4 mm ²
Converted Vickers hardness	540 kgf/mm ² [22]	540 kgf/mm ² [22]

Fig. 9 shows the setup of the experiment. The top specimens were pushed onto the base specimen using the CMC method. The 350 N preload was applied to the contact surfaces with bolts. The preload was measured with a force sensor. The specification of the force sensor is shown in Table 1. After unloading the preload, the contact surface shape was measured using a laser microscope.

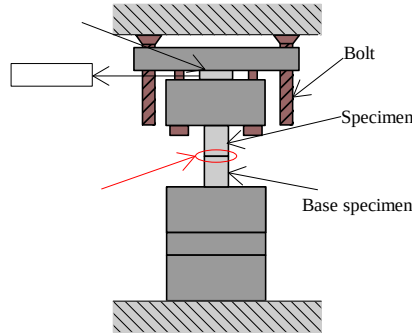


Fig. 9 Setup of the experiment

Fig. 10 shows the allowable waviness under the experimental conditions ($W = 350 \text{ N}$, $h = 10 \mu\text{m}$, $R = 0.2 \text{ mm}$ $p_m = 540 \text{ kgf/mm}^2$). The calculated allowable waviness was 2.5 μm . Therefore, the specimen 1 had a uniform distribution of the real contact areas ($w < d_c$); on the other hand, specimen 2 had a partial distribution of the real contact areas ($d_c < w$).

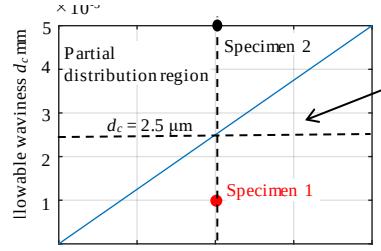


Fig. 10 Allowable waviness ($W = 350 \text{ N}$, $h = 10 \text{ μm}$, $R = 0.2 \text{ mm}$ $p_m = 540 \text{ kgf/mm}^2$)

3.2 Experimental results

Fig. 11 shows the shape of the contact surfaces of the specimens measured using a laser microscope before the experiment. It was confirmed that specimen1 had waviness of 1.2 μm amplitude and specimen 2 had a 5 μm step. Also, it was confirmed that the cusp height was 10 μm and pick feed was 0.126 mm for both specimens. Fig. 12 (a) shows the 3-D shape of the contact surface of specimen 1 after the experiment. These figures are the overall view of the nominal contact area and the enlarged views of the red square area. At all cusp crossings, plastic deformation was observed. This result shows that the real contact areas were distributed uniformly in the nominal contact area. Fig. 12 (b) shows the shape of the contact surface of specimen 2 after the experiment. In the higher area, plastic deformation was observed. On the other hand, in the lower area plastic deformation was not observed. This result shows that the real contact areas were distributed non-uniformly within the nominal contact area. These results show that the distribution of the real contact areas could be controlled by the CMC method.

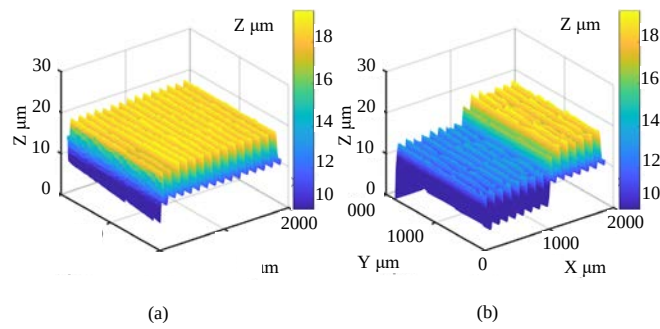
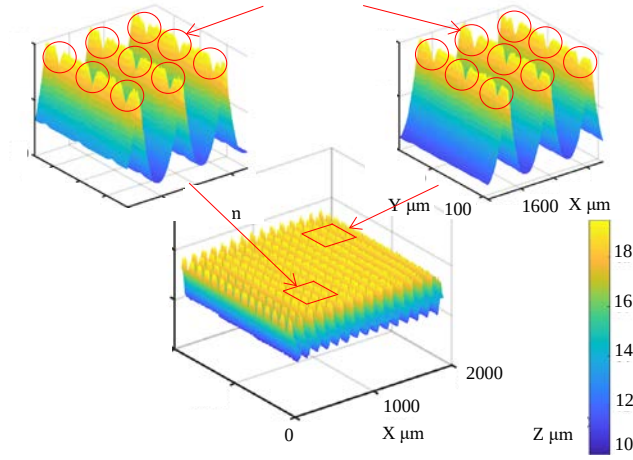
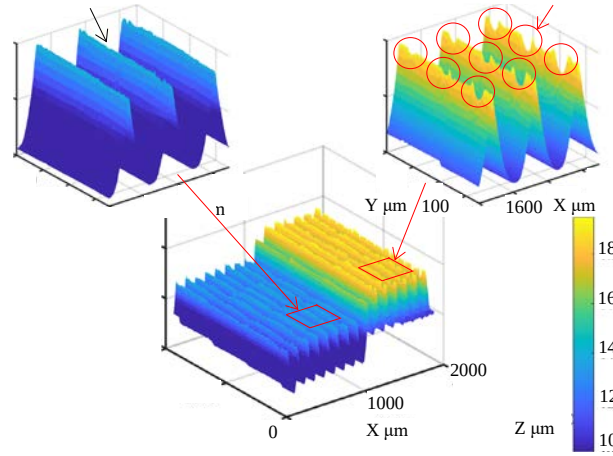


Fig. 11 Pre-experiment 3-D shape of specimen contact surfaces: (a) specimen 1, (b) specimen 2



(a)



(b)

Fig. 12 Post-experiment 3-D shape of specimen contact surface: (a) specimen 1, (b) specimen 2

3.3 Minimum real contact area

Specimen 1 had waviness amplitude of $1.2 \mu\text{m}$. The waviness margin ε is equal to 0.5 ($w = 0.5d_c$) in this case. Fig. 13 shows the relationship between x and $a(x)$ under the experimental conditions. In these conditions, the calculated minimum real contact area a_{min} was $3.0 \times 10^{-5} \text{ mm}^2$. Therefore, the minimum real contact area at the contact point should be more than $3.0 \times 10^{-5} \text{ mm}^2$ according to the analysis described in Section 2.5.

Fig. 14 shows the profile in the YZ plane of one of the smallest plastic deformation points on the contact surface measured using the laser microscope. The contact width of the contact area y is approximately $10 \mu\text{m}$. From this result, the minimum real contact area observed in the experiment was $5.0 \times 10^{-5} \text{ mm}^2$ using Eq. (8). It should be noted that the aspect ratio of the profile shown in Fig. 14 was small because its horizontal scale was almost ten times larger than its vertical scale. This result

shows that the smallest real contact area can be well controlled using the CMC method.

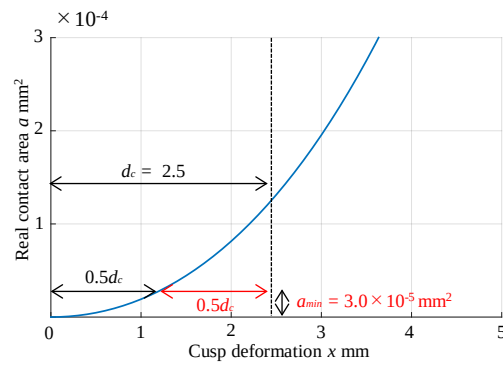


Fig. 13 Relationship x and $a(x)$ ($W = 350 \text{ N}$, $h = 10 \text{ }\mu\text{m}$, $R = 0.2 \text{ mm}$ $p_m = 540 \text{ kgf/mm}^2$)

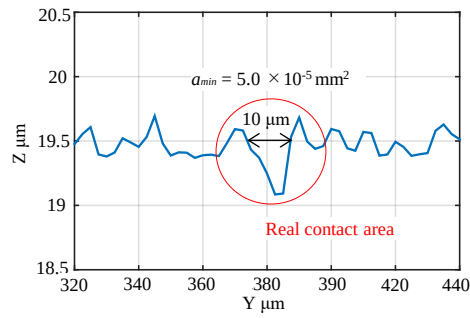


Fig. 14 Shape of one of the smallest plastic deformation points

4 Experiment to verify the effect of real contact area distribution on contact stiffness

4.1 Experimental method and condition

The distribution of the real contact areas can be controlled using the CMC method. In this section, we report a measurable effect of the distribution of the real contact areas on contact stiffness and that this was verified by experiment. An experiment was conducted to measure changes in the contact stiffness. In this experiment, contact surfaces with different distributions of the real contact areas were made using the CMC method. The contact stiffness of each contact surface was measured for comparison.

The specimens were pushed onto a base block to make a contact surface. Fig. 15 shows a schematic of the top specimens and the base block. The specimens had different distributions of the real contact areas because the specimens had different amplitudes of waviness. Fig. 16 shows the experimental setup for measuring contact stiffness. The horizontal and vertical contact stiffness was measured for each specimen. A vertical preload was applied using a bolt and measured using force sensor 1. Horizontal and vertical forces were applied to the specimen using a piezoelectric element. The vertical force was measured with a force sensor 1 and the vertical force was measured with the force sensor 2. The relative displacement between the top specimen and the base block was measured with a capacitance-type displacement sensor. The shape of contact surface is measured with a laser displacement sensor. Table 3 shows the specifications of force sensors and displacement sensors. The relationship between the relative displacement and applied force was plotted, and the stiffness was calculated from the slope.

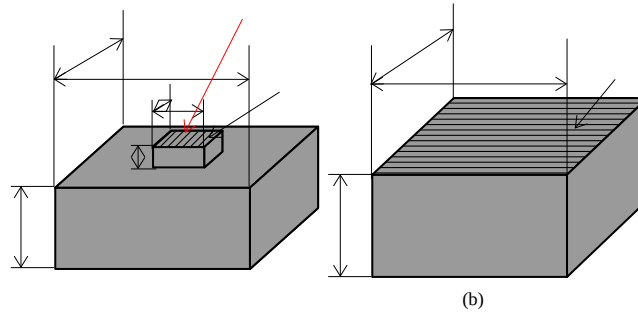


Fig. 15 Schematic of the top specimens and the base block: (a) specimen, (b) base block

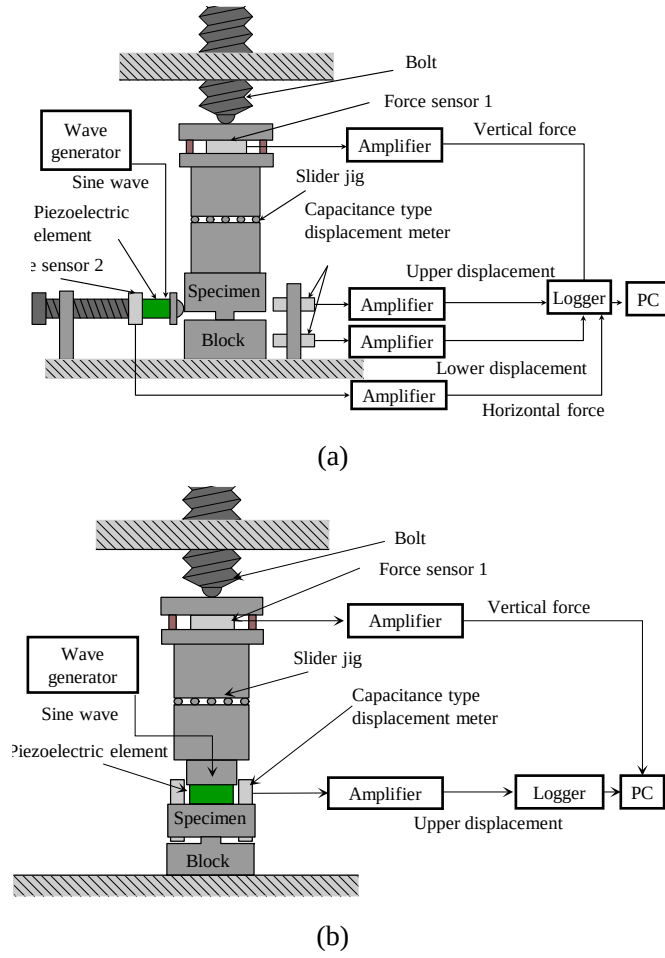


Fig. 16 Setup of the experiment for measuring contact stiffness: (a) Horizontal contact stiffness, (b) Vertical contact stiffness

Table 3 Specifications of force sensors and displacement sensor

Force sensor 1	Measurement range	26 kN
	Sensitivity	-3.8 pC/N
Force sensor 2	Measurement range	7.5 kN
	Sensitivity	-4.0 pC/N
Capacitance type displacement sensor	Measurement range	50 μm
	Resolution	1.6 nm
Laser displacement sensor	Measurement range	Lateral direction: 14 mm Vertical direction: 15.2 mm
	Accuracy	Lateral direction: 5 μm Vertical direction: 0.4 μm

Table 3 shows the experimental conditions of the experiment for measuring the horizontal and vertical contact stiffness. In these experimental conditions, the calculated minimum contact deformation d_c was 2.5 μm according to the analysis described in Section 2.4.

Four top specimens and a base block were made. The top specimens had different surface shapes and were labeled specimen 1–4. Fig. 17 shows the surface shape of the specimens and the base block measured by a laser displacement sensor. Fig. 18 shows the waviness of the specimens and the base

block obtained from Fig. 17. The waviness was obtained by extracting only waves with a wavelength of 2 mm or longer. The wavelength elements of less than 2 mm were cut in the wavelength domain. After that, the surface profile was recomposed to obtain the waviness. Table 4 shows the specifications of the specimens. Specimen 1 and specimen 2 had waviness greater than d_c and these specimens did not have uniform distributions of the real contact areas. Specimen 3 and specimen 4 had waviness less than d_c and these specimens had uniform distribution of the real contact areas. Specimen 4 was finished by grinding. Specimens 1–3 had similar roughness because the cutting tool and cutting conditions were same ($R = 0.4$ mm, $l = 0.171$ mm). The theoretical cusp height of the specimens (specimens 1–3) was $9.2\text{ }\mu\text{m}$. The waviness of specimen 1 and specimen 2 was made by pressing the specimen with a vise and a bolt, respectively. Specimen 4 had less roughness and waviness than the others. Specimen 1 had partial distribution of the real contact areas and contacts in the central part. Specimen 2 had partial distribution of the real contact areas and contacts in the outer periphery. Specimen 3 and 4 had uniform distribution of the real contact areas.

Table 4 Conditions for the experiment measuring horizontal contact stiffness

Preload	10 kN	
Input voltage to the piezo electric element	Wave form	Sinusoidal wave
	Amplitude	150 V
	Frequency	0.04 Hz
Number of tests	4 times for each specimen	

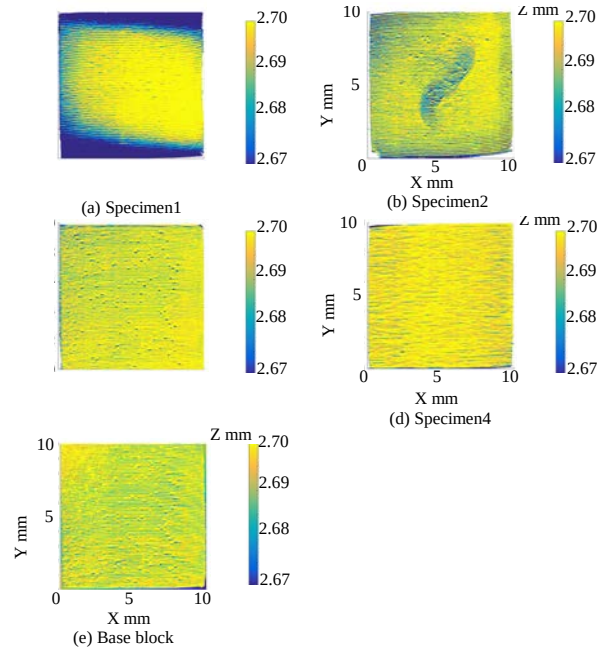


Fig. 17 Surface shape of the specimens measured using a laser displacement sensor

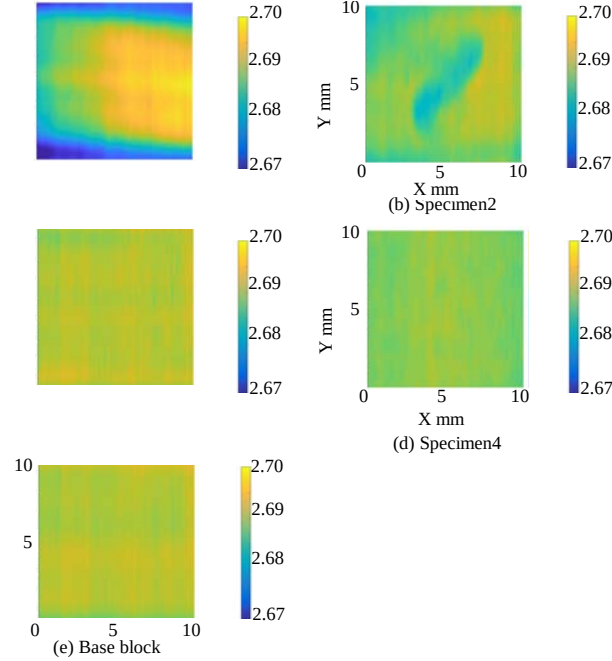


Fig.18 Waviness of the specimens

Table 5 Specifications of the top specimens and the base block

Specimen	Waviness	Cusp height	Distribution of the real contact areas
Specimen 1	40 μm	9.2 μm	Partial (center part)
Specimen 2	15 μm	9.2 μm	Partial (outer periphery)
Specimen 3	2 μm	9.2 μm	Uniform
Specimen 4	1 μm	Less than 1 μm	Uniform
Base block	2 μm	9.2 μm	

4.2 Experimental results

Fig. 19 shows the relationship between applied force and the resultant displacement. The horizontal axis shows the displacement variation excluding the displacement by the initial preload. The vertical axis shows the applied force including the preload. The cyclic force was applied to the specimens. Fig.19 shows the results after applying several cycles of force. Thus, elastic deformation was dominant, and the hysteresis loops became almost linear. The relationship was linearly approximated by the least squares method, and the stiffness was calculated from the slope.

Fig. 20 shows the obtained contact stiffness of each specimen. Fig. 20 (a) shows the horizontal contact stiffness of each specimens. Fig. 20 (b) shows the vertical contact stiffness of each specimen. The error bar shows the variation of the four tests. Specimen 1 and specimen 2 have lower horizontal and vertical stiffness than specimen 3 does. The horizontal stiffness of specimen 3 is 2.1 times greater

than that of specimen 1. The vertical stiffness of specimen 3 is 1.2 times greater than that of specimen 1. This result shows that the uniform distribution of the real contact areas has higher horizontal and vertical stiffness than do areas with irregular distribution of real contact. Specimen 3 and specimen 4 have similar horizontal and vertical stiffness. This result shows that the horizontal and vertical stiffness of a surface finished by cutting can be improved to the same level as that after grinding. Specimen 2 has greater horizontal and vertical stiffness than specimen 1 does. This result shows that the contact on the outer periphery has greater stiffness than contact in the central part.

To quantitatively discuss the stiffness change obtained in the experiment, the stiffness model considering the deformation of the cusp and the bulk near the contact surface is required. This modelling is one of our on-going projects. Thus, the deformation phenomena and model of the contact surface will be reported in our future work.

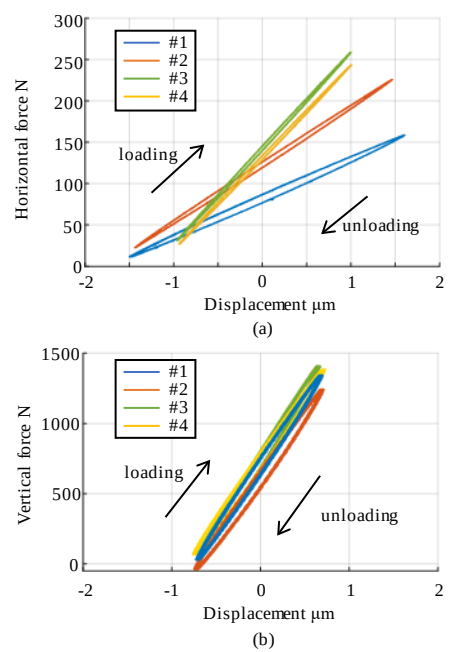


Fig. 19 Relationship between applied force and relative displacement: (a) Horizontal contact stiffness, (b) Vertical contact stiffness

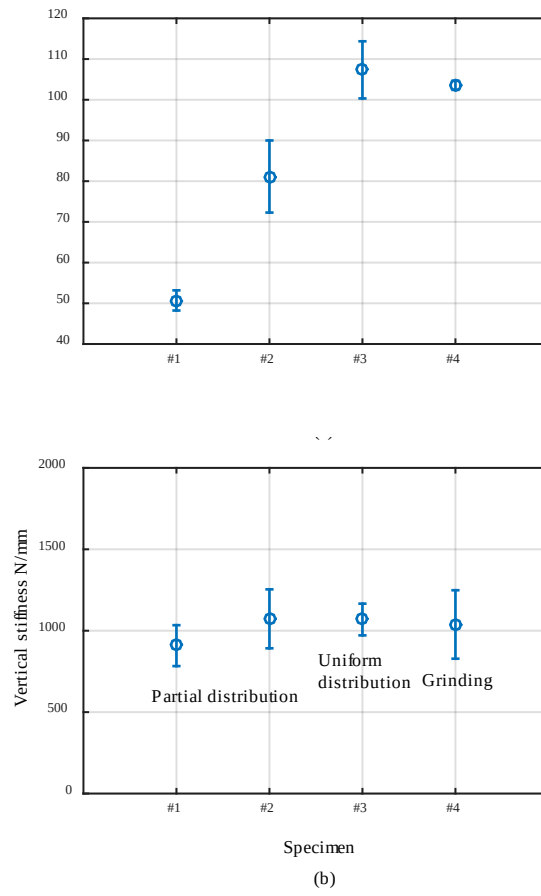


Fig. 20 Measured horizontal contact stiffness of each specimens: (a) Horizontal contact stiffness, (b) Vertical contact stiffness

5 Conclusions

Cutter mark cross (CMC) method which is a new method for improving the contact stiffness is proposed. The CMC method is a way of controlling the distribution of the real contact areas within the nominal contact area by crossing the cutter marks and making point contacts. In addition, contact conditions on the uniform distribution of the real contact areas by the CMC method were calculated from the plastic deformation of the real contact areas. Using this calculation result, the distribution of the real contact areas can be controlled. In addition, it was verified that the contact stiffness is influenced by the distribution of the real contact areas and that the CMC method can be used to improve the horizontal and vertical contact stiffness. Using CMC, the horizontal and vertical contact stiffness can be improved to match being finished by grinding. In addition, the contacts on the outer periphery have greater stiffness than those in the center.

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