A New Surface Tester with a Stylus Driven by an On-Off Servomechanism*

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This paper purports to describe the construction and experimental results of a new surface tester with a stylus. The trial device consists of a sensor, a work table, a gear train, a servomotor, a binary code drum, electric digital circuits, a code panel, and a recorder. Measured value of surface roughness is held on the code panel and after converted to voltage, it is given as a curve recorded on a chart paper.

The sensor touching periodically the surface of a test piece is an electric contact switch with a stylus driven by an on-off servomechanism.

The sensor has a sensitivity of 0.1 micron of roughness height and a low measuring force of about 4 milligrams. It is also shown that this tester gives an accuracy of ± 0.2 micron.

1. Introduction

Recently, soft materials such as aluminum and plastics are often being used for industry. When these soft materials are used for sliding surfaces or machine parts which fit into each other, the surface roughness has a great influence on some mechano-engineering functions like static and kinetic frictions, fluid tightness, wear resistance, resistance against fatigue, friction against fluid flow, wringing, and adhesion⁽¹⁾.

For measuring the roughness of soft surface, we recall first of all, the no touch method by an optical interference microscope which does not damage the surface and gives accurate and sensitive results. The microscopic photographs obtained by this method show contour lines of surface roughness based on a reference plane, and the topological representation clearly shows distribution of roughness. On the other hand, the photographs obtained by the no touch method are unsuitable for the determination of the peak-to-peak value, the root mean squared value, the loading curve, and the autocorrelation function of a roughness curve. For this purpose, the roughness profile curve gained by the stylus method is better than a photograph. But, by the stylus method, a tip touches the surface to be examined and makes a trace resulting in errors of measurement. Generally, the touching force of a stylus is about 100 milligrams. When the roughness of a spattered aluminum surface was measured with a stylus force of 30 milligrams,

the trace of the tip with a radius of 3 microns was hardly visible with a microscope at a magnification of $600\times$. Although the trace was almost invisible, it is possible that a finer trace existed. If the width of the trace was 0.2 micron, the depth of the trace was less than $17\text{\AA}$. A roughness of this extent may be present even on a gage surface, so existence of such a trace on the surface of machine parts may be tolerated in practical use. Therefore, the stylus method can be applied for measurement of aluminum surface provided that the touching force of a stylus is less than 30 milligrams.

In the present study, the touching force of a stylus was reduced by fixing the stylus to a contact piece of an electric switch to form a break switch. The stylus head was driven by a servomechanism. The accuracy of the tester was improved by the use of a suitable servomechanism.

2. General construction and motion of the tester

Figure 1 shows a block diagram of the tester. In the figure the summing point is the stylus head. A test piece is fed into the system automatically as an input. The stylus head, consisting of a stylus, an electric contact switch, and an electric magnet, is driven as one body by a servomotor with a reduction gear train. When it approaches the test surface and the stylus tip touches the surface, the switch is opened and it generates an "off" signal. Then the rotation of the servomotor is reversed and, at the same time, the pull coil current increases. So the stylus is pulled downwards immediately. Meanwhile the stylus head is also pulled downwards. When it reaches enough

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depth, the hold circuit (2) releases itself and decreases the pull coil current. The stylus returns to the set position. The hold circuit (1) releases itself and the rotation of the servomotor returns to its normal state. Thereafter the operation is repeated.

The values are read off from the code drum mounted on the servomotor. The reading is made at the instant when the tip touches the surface and the switch is opened. The numerical value is retained in the memory device until the next value is read.

Figure 2 shows the construction of the tester. The reduction gear train is built up with a 1/1 000 mm dial gage and a 20× gear train connected to the pointer shaft of the dial gage. The stylus head is mounted on the measuring spindle of the dial gage, and the pointer shaft is driven by the 20× gear train.

3. Measuring force

Figure 3 shows the stylus head. The measuring

Fig. 1 The block diagram of the tester

Fig. 2 The construction of the tester

force is just large enough to open the electric contact switch. When the stylus tip touches the surface, the switch mounted on the spring base is opened by the reaction of the surface. Therefore the measuring force diminishes as the closing force of the switch drops.

To minimize the force, the position of the opposite switch piece is finely adjusted by the mechanical method to close the switch as lightly as possible. Moreover, a steady current, slightly insufficient to open the switch, is given to the magnetic coil. Also, the prescribed pull current supplied by the hold circuit (2) in Fig. 1 is superimposed to the above current.

Now the force is calculated when the contact switch is ready to open by the force applied to the stylus tip. It is assumed that the pull current by the hold circuit (2) is not supplied yet. When the switch is opened, the stylus weight balances with the force exerted by the spring deflection.

Therefore,

$$W_s = F_k,$$

where

W_s : stylus weight

F_k : spring reaction for W_s

Now, it is assumed that the plate with the stylus is a reduction lever with a lever ratio, n , and the fulcrum is the middle point of the spring.

$n = (\text{distance between the fulcrum and the base of the stylus}) / (\text{distance between the fulcrum and the electric switch})$ The experimental value of n was about 4.9.

Now,

$$F_R = [(F_c + F_a) / n] + F_b,$$

where

F_R : the reaction of the test surface at the stylus tip

F_a : adhesion force caused by the contact force, F_c , of the switch, namely, (mechanical contact force)-(pull force of

Fig. 3 The stylus head

coil). Both of the contact pieces were made of platinum alloy, 90%Pt10%Ir⁽²⁾.

F_b : the force that forms gap b by pressing the spring at the stylus tip. The spring constant is $10 \text{ mg}/\mu$ and $nb=0.05\mu$ hence $F_b=0.5 \text{ mg}$. b is the minimum gap of the contact that can generate an "off" signal. The experimental value was 0.01μ .

4. Experiments to determine the optimum contact force F_c

Here is to be described the reason why an electric contact switch was used as a sensor. When a closed switch begins to open, the electric resistance of the switch changes very rapidly. Subsequently, a break contact switch, which is opened from a closed state, acts more reliably than a make switch. Since the tester is a kind of a servomechanism which adopts the null method for measuring, the operation is sufficient if the switch merely indicates the time when the stylus tip touches the surface. In order to maintain the stability of the amplifier, the current was set at a value of 0.5 mA when the contact was closed and the voltage, at 10 mV when the contact was opened.

Figure 4 shows the relation between the electric contact resistance and the normal distance between the contact pieces. To assure fine adjustment, reduction levers of $1/10$ were constructed in three stages. The long levers were 100 mm in length and the short lever 10 mm in length. The levers were supported at the center holes by two conical pointed ends set against each other. Displacements were given by a thread micrometer equipped with a $1/1000 \text{ mm}$ dial gage at long lever end of the initial stage. Displacements given at one time were more than 2μ at the

Fig. 4 The relation between the electric contact resistance and the normal distance between the contact pieces of the switch

above point of the initial stage and more than 2μ at the short lever end of the last stage⁽³⁾.

Figure 5 shows the relation between the electric contact resistance and the contact force. The experimental device is of a balance type, as shown in Fig. 6. A switch was fixed to the end of a lever, and a steel wire was fixed to the other end perpendicularly to the lever. The lower end of the steel wire sank in a mercury pool, and the buoyancy of the steel wire balanced the lever.

The contact pieces used in the above two experiments were made of the same metal, 90%Pt10%Ir. They were of the same shape consisting of a combination of a plane and a cone which was rounded at its top with a radius of $3/100 \text{ mm}$. Most of the above two experiments were made in the elastic range. In Fig. 4, the point of zero contact force and zero air gap could not be determined exactly. However, by superposition of Figs. 4 and 5, it was found that the tendencies of Figs. 4 and 5 were the same. Then for particular resistance, the contact force and the normal distance correspond to each other. Figure 7 shows the relation between the contact force and the normal distance.

Fig. 5 The relation between the electric contact resistance and the contact force

Fig. 6 The balance device for giving various contact forces

5. Accuracy of the gear train in the feedback loop

Figure 8 shows the structure of the gear train. Since the magnification of the displacement of the stylus head is the reciprocal of the ratio of the reduction gear, the accuracy of this tester depends mostly on the gear train. The errors of the gear train consist of static shape errors, and dynamic errors under loads. Static errors have been discussed in the past but the dynamic errors are peculiar to this tester. Therefore, discussions will be made on the latter. Now, 1 revolution of a code drum corresponds to 10μ of straight motion of the stylus head. The circumferential length of the code drum is about 100 mm, so the ratio of peripheral linear displacement of the drum to the stylus head displacement is nearly 10 000. Now, the load on a servomotor consists of the force from the tension spring which pulls down the stylus head and the friction force among all of the

Fig. 7 The contact force versus normal distance for the electric contact pieces

moving parts. When these forces act on each gear, deformations arise and cause some decrease in the transmitting angle of the gear train. This decrease of the angle near the stylus head comes out almost directly as an error but those near the driving end are reduced by a factor of about $1/10\,000$. So the latter can be neglected. On the other hand, data are read off during an approaching stroke of the stylus head. Therefore, the errors that appear in the steady state of running must be examined. The deformation which appears on a pair of gears is due to elastic deformation at a contact point on the flank, the bending of teeth, the elongation of the distance between the centers, and the twist deformation of the shafts.

Now, consideration is made on the case when a dynamic friction torque ΔT arises only on the pointer shaft 3 and the whole system is driven by the servomotor. The torque of the servomotor which is transmitted through the shafts 9, 8, ..., and 4 overcomes the friction torque ΔT on shaft 3 and drives the system. The deflection angle of shaft 3 caused by torque ΔT is written as $\Delta\theta_3$ rad. Then $\Delta T/\Delta\theta_3 = C_3$ is the spring constant of the shaft. The torque ΔT is transmitted to shaft 4 and becomes equal to $\Delta T/U_{34}$. The speed ratio U_{34} is given by $U_{34} = (\text{number of gear teeth on shaft 3})/(\text{number of gear teeth on shaft 4})$. The deflection angle $\Delta\theta_4$ on the shaft 4 is given by $\Delta\theta_4 = (\Delta T/U_{34})/C_4$. The torque $(\Delta T/U_{34})$ on shaft 4 is transmitted to shaft 5 and becomes equal to $\Delta T/(U_{34} \cdot U_{45})$. Then a deflection angle $\Delta\theta_5$ arises on shaft 5. The same occurs with the following gears. $\Delta\theta_3$ on shaft 3 is amplified and appears on the indicating shaft 9. The value is given by $\Delta\theta_3 \cdot U_{34} \cdot U_{45} \cdots U_{89}$. Similarly, $\Delta\theta_4$ arises on shaft 9 as an angle of $\Delta\theta_4 \cdot U_{45} \cdots U_{89}$. Assuming that the spring constant of each shaft is equal to C , the total deflection angle on shaft 9 is calculated as $1\,434.125 \times (\Delta T/C)$ using the number of gear teeth written in Fig. 9. When the above gear train having a friction torque ΔT on shaft 3 is driven from the stylus head, the deflection angle arising on shaft 9 is calculated as $495\,000 \times (\Delta T/C)$. The latter value is about 345 times that of the former value.

Fig. 8 The gear train in the feedback loop

6. Reading of the experimental values

Figure 9 shows the device for reading the minimum figure. The other six units are read in the same way. To avoid misreading by the brushes present on the border-line of a code, one more minimum figure disk was added on the right end of the drum, its angle position being shifted by a half-pitch of the code. Read off pulses generated by the border line of this code disk trigger the memory circuit after going through the and-gate (1) and (2) or (3). Then, misreadings are reduced for read off positions which are in the middle of the minimum code.

7. Experimental results

Figure 10 shows the approaching motion of the stylus head to a test piece. It was detected by an

Fig. 9 Reading device of the experimental value

Fig. 10 The approaching motion of the stylus head

Fig. 11 The experimental results obtained by this tester for an optical prism surface

electric capacity transducer of Inoue's circuit and was indicated on an oscilloscope. The amplitude and the mean velocity of the cycling motion were 4.4μ and $2.4 \mu/\text{sec}$, respectively. The deviation of the motion line from the straight line was about $\pm 0.1 \mu$. Figure 11 shows the experimental results obtained by this tester for an optical prism surface inclined on a table at an angle of $(1/25)$. Figure 12 shows the measured record of a cylindrical gage. The maximum error was $+4 \mu$ referring to the calculated value given in the figure. Figures 13 and 14 show the interference fringes of a sample surface and the experimental result obtained by this tester, respectively. The sample surface, which was an aluminum spattered glass plate marked by a felt-tipped pen, was traced by the stylus from the middle of the left side in a straight line to the

Fig. 12 The measured circumference of a cylindrical gage

Fig. 13 The interference fringes of a sample surface, which was an aluminum spattered glass plate marked by a felt-tipped pen

Fig. 14 The experimental results obtained by this tester for the sample shown in Fig. 13

right side, across the ink figure. The maximum thickness of the ink corresponded to 29 interference fringes of a sodium vapor lamp or was 8.6μ thick and the value of that thickness coincided with the measured value.

8. Summary

This method is a null method using a servomechanism.

(1) Resolving power: the tester could detect a stylus displacement of 0.05μ .

(2) Accuracy: it is estimated that the error of the gear train is $\pm 0.1\mu$ and the overall error is $\pm 0.2\mu$ in a short range including the reading error $\pm 0.1\mu$ on the code drum. In the long range of more than 10μ , error is $\pm 0.4\mu$.

(3) The measuring force: it is estimated to be 4 mg. By the equation $F_R = [(F_c + F_a)/n] + F_b$, [section 3], put $F_c = 15$ mg, and $F_R = 4$ mg is gained.

Further,

(4) The stylus tip touches a surface for an instant every cycle and does not scratch the surface.

(5) The measured values were gained even as a digital value.

(6) It does not have a skid and can also measure the shape of a test piece.

(7) The measuring range is as broad as 2 mm.

(8) Recorded values do not scale out.

(9) The measuring force is indicated.

Weak points of the tester:

(1) Test pieces must be of a small size. When a somewhat hard replica can be made, a part of a big piece may be measured.

(2) The accuracy is reduced by a fluctuation of room temperature.

(3) The stylus speed for measuring is slow, being similar to that of the "Talystep" made by Rank Taylor Hobson Co⁽⁴⁾.

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Discussion

J. NARA (National Research Laboratory of Metrology):

(1) The assumed profile curve is gained when the surface is traced by a stylus having a finite curvature at the tip. The curve is similar to the profile curve obtained by a rolling sphere. The curve may be different from the real profile curve that contains very fine roughness. Accordingly, it is likely that very fine roughness is not the object of the stylus method. How does the author consider from this point of view?

(2) According to the conclusion of this paper, the magnification of this tester can not be made so large as that of "Talystep" on account of the large error brought about by the gear train which makes use of dial gage. What does the author think about the method to reduce the disturbance?

(3) Explain the durability of the tester, especially those of the electric contact points and the gear train.

A. TOYAMA (Tokyo Institute of Technology):

(4) It is likely that the accuracy of the tester largely depends upon that of the dial gage. According to the specification of JIS B7509, the allowable errors of this dial gage are 1.5μ for the stroke

of 0.2 mm and 5μ for the whole stroke of 2 mm. So the overall accuracy assumed in this conclusion seems to be too high. Explain the basis of the assumption for the accuracy.

The overall accuracy can be gained immediately by measuring the surface of an optical flat or a block gage by this tester with zero setting angle. Were such tests made already?

(5) The reduction lever used in the experiment of Fig. 4 is supported at the center holes by two conical pointed ends. It will be impossible for the axis of the rotation to stay at a constant position during the operation. Accordingly, it is doubtful that a displacement of $2/1000\mu$ always arise at the output end, when the displacement of 2μ is given at the input end. For this reason reproducibility of this experiment may be low. What is the author's opinion?

Y. FUKUTA (Tokyo Institute of Technology):

(6) How did the author examine the reproducibility of the graph of the electric resistance versus normal distance shown in Fig. 4 and overall accuracy of the tester?

(7) $1434.125(\angle T/C)$ means an angle, by which

the code drum rotates, when it is so twisted that a torque of ΔT acts on the fixed pointer shaft. Rotation angle of which shaft does an angle of 495 000 ($\Delta T/C$) mean in this sense?

Y. NAKANO (Nagoya Municipal Industrial Research Institute):

(8) The specifications of JIS B7509-1964 of dial gage say as follows: indicating stability of a pointer is allowed up to 0.3 scale unit when a pointer is driven slowly or rapidly at definite position. Allowable indicating error of the return stroke is 1.5μ in a narrow measuring range within 0.2 mm. Moreover, the difference of the measuring force between go and return strokes must not exceed 80 g. In this experiment, the dial gage was driven inversely by a servomotor, and a strong reciprocating motion was given to the spindle though the stroke was very small. Show the experimental proof that the dynamic error is always less than the specified values.

Author's closure

(1) The statements agree with the author's opinion. Waviness and form errors of machine parts are also important. This tester, which has a broad measuring range and no skid, can measure the waviness and form errors if the servomotor and the reduction gear train are remodeled to slide.

(2) A reduction lever will be suitable, but the measuring range becomes short.

(3) The electric contact switch was renewed 5 times. It was found by microscopic observation that the contact points of all the pieces were pressed and deformed. However, under a very small contact force with the electric contact resistance of 10Ω shown in Fig. 4, it is supposed that a fine tip of the roughness touches the opposite side tip.

The gear had been used for 9 years. The dial gage was dismantled and observed for inner details. The lubricating oil was oxidized, but the gears were worn only a little. It is supposed that this tester had been driven for 2 000 hours in total and the number of huntings was about 3 600 000 times. The pinion on the code drum shaft was almost worn out. It was made of brass and driven at 20 rpm. The module, width, and rotating angle per hunting were 0.25 mm, 1.5 mm, and about 90° , respectively. In spite of the small torque load, it was worn rapidly. The wear of the gear decreased a little as the revolution decreased. So, the gear on the pointer shaft of the dial gage was almost free of wear. The same tendency was observed also with the bearings. The brushes of the code drum were worn badly so all of these were replaced with new ones, recently.

(4) The approaching motion of the stylus head is shown by the curve in Fig. 10. If the curve is

linear, the motion of the stylus head is proportional to the angle rotation of the code drum because the code drum rotation is oscillatory with constant angular velocity except near the dead points. Therefore, the two parallel lines were drawn so as to just include the bends of the motion line. The vertical distance of the two parallel lines was equal to 0.2μ . Hence, the error was considered $\pm 0.1\mu$. The quantitized error of binary code was $\pm 0.1\mu$. Accordingly, the overall errors were $\pm 0.2\mu$. The measuring values were read during the steady state motion of the stylus head. When the displacement of the stylus head is observed while the code drum is at rest after 1/100 rotation and this operation is repeated, such an accuracy can not be obtained. Now an optical prism was measured by this tester with zero setting angle. It was confirmed that the error was $\pm 0.1\mu$ but in this case, only the same parts of the gear train were used without testing the accuracy of the other parts. Therefore, the prism surface was then measured by this tester with setting angle of $\angle\theta = \tan^{-1}(1/25)$. In this case, many different parts of the gear train were used, and their accuracy was tested. For the form measuring test, one of the 3 wire gages was measured by this tester shown in Fig. 12. In the figure, vertically enlarged parts of a circle were recorded and the calculated values were plotted on the paper, then the maximum error observed was $+0.4\mu$.

[Similar questions were presented by Dr. Y. NAKANO and Dr. Y. FUKUTA]

(5) When a displacement is given at "A" in the Append.-Fig. 1, a fluctuation of the axis of rotation of the lever arises by the shape errors of the center holes and conically pointed end. Then, for example, when the X axis is pushed to the left in a horizontal plane at front side and at the same time pushed in the opposite direction at backside, the lever is rotated clockwise around the Z axis as viewed from above. When the lever is pushed in the same direction at both the back and front sides, the lever is shifted to the left along the Y axis. Next, when a fluctuation arises in the vertical plane by the errors of holes and conical ends, the lever is rotated around the Y axis or shifted along the Z axis. Due to these errors, the

Append.-Fig. 1 Rotating axis of the lever

Append.-Fig. 2 Last stage of the three stage reducing lever

Interference fringes, Slide glass with partly spattered aluminum on the surface. The shift was 3 pitches. Thickness of film was calculated as 0.885μ . By sodium vapor lamp $\lambda = 5890\text{\AA}$

Append.-Fig. 3 Measurement by interference microscope

lever supporting becomes loose or tight. The normal distance between the contact points is changed directly by the shifted distance along the Z axis. Further, friction torque changes as the supporting becomes loose or tight. As described later, the friction errors become relatively small in the reduction lever. When a displacement is given at point "A", the driving source receives a fluctuation of the friction torque. However, the spring constant of the driving source is very large and the reaction of the driven lever is small because the lever is long. Consequently, when the cantilever between X axis and point "A" is deflected slightly, the error caused by the fluctuation of friction decreases. Once again, the shifted distance along the Z axis wholly results in errors. Experimental results will be explained in the next answer.

(6) The Append.-Fig. 2 shows the last stage of the reduction lever mechanism. In the accuracy test, the lever inclination was measured by a level fixed to the last lever driven by the initial stage. The sensitivity of the level was 0.728 mm in a displacement of a bubble per 10^{-3} rad . The displacement was measured by a micrometer microscope up to 1μ . Since the distance between the electric

Append.-Fig. 4 Measured record of aluminum film

contact point and the lever center was 10 mm , the displacement of $13.7\text{ m}\mu$ was hardly recognized. Accordingly, it was not possible to follow the displacement which took place at intervals of $2\text{ m}\mu$. But the relation of Fig. 4 was always obtained during the experiments for two months.

The overall reproducibility was ascertained by measuring the flat surface of an optical prism and one of the wires of a 3 wire gage repeatedly as shown in Fig. 12, for example.

(7) When a torque ΔT was given to the pointer shaft from the measuring point (from the stylus head), $495\,000 \times (\Delta T/C)$ is the displacement of the measuring point reduced to the angle of rotation of the code drum.

(8) The basic experimental results are shown in Figs. 10 and 11. Moreover, complementary results are shown in Append.-Figs. 3 and 4. A test sample was made of a slide glass used for microscopes by partly spattering aluminum on the surface. The thickness of the aluminum film measured by this tester was compared with that obtained by an interference microscope. In the Append.-Fig. 4, the end of the spattered aluminum film was measured. The measurement was made from the glass base side to the aluminum film side, and then repeated in the reverse direction. The difference of the values obtained by the two methods was less than 0.2μ .