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Fundamental Study on a Foil Strain Gauge of Electrodeposited Nickel*

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The properties of foil strain gauges made of a sheet of nickel foil electrodeposited in a sulphamate bath are studied by rotary bending tests at high temperatures. A nickel foil of 5 μm in thickness is obtained by tearing off the deposited nickel from a ground metal plate of stainless steel. A number of foil gauges of the same quality are made by dividing the nickel foil and they are stuck on the surface of the specimen with an adhesive of epoxy resin. Little effect of the adhesive layer on the proper stress of foil gauge is recognized, though the applicable test temperature is confined to the range of 180~250 $^{\circ}\text{C}$. If the size of foil gauge is more than 1 mm^2 , the size effect of gauge on the proper stress is negligible. Using the foil gauges at 250 $^{\circ}\text{C}$, the peak stresses in grooved shafts under bending are measured and it is confirmed that the results are accurate enough.

Key Words: Experimental Stress Analysis, Electroplating Method, Nickel Plating Foil, Foil Strain Gauge

1. Introduction

In the nickel electroplating method of stress analysis^{(1)~(3)}, the elastic surface stress or strain of a specimen is measured by observing fine black flecks on the surface of deposited nickel, resulting from growing grains in the deposited layer, when the specimen coated with the deposits is subjected to repeated loads at high temperatures up to about 250 $^{\circ}\text{C}$. Grain growth in the deposits is dominated by the magnitude of repeated shearing strain on the surface of ground metal, and the relation between the proper strain at which the growing grains begin to occur at an assigned temperature and the number of repetitions is peculiar to the plating used. Accordingly, the above relation established in advance is usually adopted as the calibration value of the plating in the actual measurement, and it has been ascertained that the stress concentrations at notches can be measured with high accuracy.

It is often found that if only the local stress at a specific place in machine parts can be measured accurately, the test will answer the purpose, and furthermore there are many parts made of materials difficult to plate. It may be favourable for stress measurement in such cases that a foil of the deposited nickel is stuck at the place in question with an adhesive and it is adopted as a strain gauge. The strain gauge made of a plating foil is characterized in the fact that many divided gauges with uniform quality can be produced from a sheet of the foil deposited under an assigned plating condition.

In the present paper, a foil of nickel plating deposited in a sulphamate bath⁽³⁾ is adopted and a basic study on the foil strain gauge is performed by rotary bending tests at high temperatures. The calibration test on the foil gauge is conducted for inspecting the range of applicable test temperatures, appearances of flecks and grown grains, and effects of both adhesive layer and size of gauge on the proper stress. Using the foil gauges at 250 $^{\circ}\text{C}$, the stress-concentration factors in grooved shafts are obtained and the results are compared with those^{(3)~(6)} published previously. A foil strain gauge of deposited copper was developed by Ōkubo and Hosono⁽⁷⁾ for the purpose of stress measurement at room temperature. In the present study, a similar technique is used to develop a foil strain gauge of deposited nickel serving at high temperatures.

2. Experimental procedure

2.1 Nickel foil and its adhesion

The plating used consists of two layers, namely, a basic alkaline copper and an upper sulphamate nickel. The composition of plating solution and plating conditions are shown in Table 1.

In the case of direct plating on a specimen of carbon steel, the surface of the specimen was finished with No.800 paper file first and coated with the basic copper plating. The surface of copper plating was lightly polished with calcium carbonate to remove attached copper powder and then coated with sulphamate nickel plating. Hereupon, the basic copper plating serves to ensure good adhesion between the steel specimen and the nickel plating. In this case, thicknesses of the copper and nickel platings are less than 1 μm and about 5 μm ⁽³⁾, respectively. Accordingly, it may be considered that the strains in the deposited layer coincide with those on the surface of ground metal.

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In the case of deposited nickel foil, a stainless steel plate (100×50 mm) was used as the ground metal, which is inferior in holding the basic copper deposits. The surface of stainless steel plate was finished with No.1000 paper file and then plated under the conditions shown in Table 1. However, it took 10 minutes for the basic copper deposits, which was one half the time adopted in the direct plating, in order to repress the copper powder being segregated on the surface. The deposited layer was torn off from the stainless steel plate to obtain a thin foil of nickel plating with the basic copper deposits. Since the current density near the edges of stainless steel plate became uneven throughout the electrodeposition, the deposited foil torn off was thrown away by about 10 mm in width along the edges. Finally, the remainder of the foil was cut into a number of small pieces of square types (1×1, 2×2, 3×3 mm) and a rectangular type (3×20 mm) for foil gauges. It may be considered that the gauges thus produced have a uniform quality and no directional properties.

The surface of test specimen made of carbon steel was finished with No.800 paper file prior to sticking the foil gauge. A thermosetting type cement made of epoxy resin (XS-20) was used as an adhesive agent of the foil gauge. The heating of the cement was done in 3 stages of 20 minutes at 160 °C, 10 minutes at 180 °C and 10 minutes at 200 °C, giving a pressure to the cemented foil. Thickness of the adhesive layer was measured by observing microscopically a sectional view of the rectangular foil attached to a steel rod.

2.2 Testing machine and test specimen

An Ono-type fatigue testing machine (10 kgf·m, 2800 rpm) with an electric furnace was used for rotary bending tests. The test temperatures were determined by the temperature of furnace atmosphere and they were measured by a thermo-couple of

Table 1 Composition of plating solution and plating conditions

Alkaline copper plating (Base)	
Copper cyanide CuCN g	23
Sodium carbonate Na ₂ CO ₃ g	10
Sodium cyanide NaCN g	30
Distilled water H ₂ O cc	1000
Bath temperature °C	30
Plating time min	Direct plating 20
	Plating foil 10
Current density mA/mm ²	0.006
Bath Voltage V	0.4~0.6
Nickel plating	
Nickel sulphamate Ni(NH ₂ SO ₃) ₂ ·4H ₂ O g/l	300
Nickel chloride NiCl ₂ ·6H ₂ O g/l	30
Boracic acid H ₃ BO ₃ g/l	30
pH	4.8
Bath temperature °C	50
Plating time min	10
Current density mA/mm ²	0.25
Bath voltage V	1.4~1.6

alumel-chromel.

Drawn rods of carbon steel SK-3 (φ19 mm) were used as the material of specimens and they were annealed after heating at 850 °C for 1 hour prior to machining. Figure 1 shows a tapered specimen used for the calibration test on the plating. Figure 2 shows the shape of a circular shaft with a circumferential groove and Table 2 shows dimensions of the groove tested.

2.3 Measurement of the proper stress

The tapered specimen shown in Fig.1 is plated with nickel directly or is coated partially with the rectangular foils of deposited nickel attached along the axis of it, and is put to rotary bending test at an assigned temperature. Flecks or grown grains in the nickel deposits begin to occur at a slender part of the specimen first and then progress into a thicker part with an increase in the number of cycles *N*. If the distance *S* from one end of the tapered portion to the location where flecks or grown grains begin to occur is measured under a bending moment *M* and then the diameter *d* of the location is determined, the proper stress σ_p in tension-compression of the deposits is calculated by the following formula.

$$\sigma_p = 32M/\pi d^3$$

Four sheets of the rectangular foil were used per one specimen and each of them was cemented along the axis and at a location quartering the periphery of cross section. Flecks or grown grains were observed by an optical microscope of 100 magnifications. However, the grown grains can be observed after the plating surface discoloured by the flecks is put to electrolytic

S: Distance to the location where flecks or grown grains begin to occur

Fig.1 Tapered calibration specimen

Fig.2 Specimen with a circumferential groove

Table 2 Dimensions of shafts with a circumferential groove

Specimen	<i>D</i> mm	<i>d</i> mm	<i>t</i> mm	ρ mm	<i>D/d</i>	ρ/d	<i>t/p</i>
(a)	12	8	2	8	1.5	1.0	0.25
(b)	12	8	2	4	1.5	0.5	0.5
(c)	12	8	2	2	1.5	0.25	1.0

polishing and then etching with Grard's reagent⁽³⁾.

The distance S was determined as an average of the values measured at four locations quartering the periphery of cross section. In the case of direct plating, the deviation of each measured value of S from the average one was within 0.5 mm and it was less than 0.2 kgf/mm² in the stress value σ . On the other hand, the deviation of S in the case of foil was about 1 mm at maximum and it was less than 0.3 kgf/mm². So, it may be said that the accuracy of

Fig.3 Sectional view of the nickel foil and direct plating

230 °C, $N = 2 \times 10^6$, $\sigma = \pm 18$ kgf/mm²
Fig.4 Flecks and grown grains produced in the nickel foil and direct plating

foil is somewhat lower than that of direct plating.

3. Experimental results and discussions

3.1 Effects of adhesive layer on the proper stress

When the calibration test of the nickel foil attached to the tapered specimen is performed at a constant temperature and under an assigned loading condition, the proper stress of foil is affected by both the heating for adhesion of the foil and the adhesive layer. In order to eliminate the effect of the heating of foil on the proper stress, the direct plating was done first on the tapered specimen and then the rectangular foils were stuck on the direct plating, namely, the direct plating and attached foils were heated together during the cementing operation of foil. Accordingly, by comparing the proper stress of the direct plating with that of the attached foil, the effect of the adhesive layer on the proper stress could be examined separately.

Figure 3 shows a sectional view of the direct plating and the foil attached on it. As shown in the figure, thickness of the adhesive layer is about 1 μm. Figure 4 shows (a) flecks and (b) grown grains which appear in the foil and the direct plating, respectively, at 230 °C, $N = 2 \times 10^6$, and $\sigma = \pm 18$ kgf/mm². As shown in the figures, the flecks and grown grains in the foil are smaller in size and decrease in number in the same field of observation as compared with those in the direct plating. Figure 5

Fig.5 σ_p - N curves of the nickel foil and direct plating (230 °C)

Fig.6 σ_p - N curves of the nickel foil

shows the calibration curves (the σ_p - N curves) at 230 °C, which are obtained by observing the flecks in the foil and direct plating. The σ_p -values (• marks) of the foil are larger by about 4% than those (o marks) of the direct plating preheated together with the foil, resulting from a lowering of strain sensitivity of the foil owing to the adhesive layer. The σ_p -values

of the usual direct plating without preheating lie on a broken curve in the figure and they are somewhat larger than those of the preheated plating. This indicates that the preheating of plating affects the proper stress sensitively.

At a small number of cycles, $N \leq 0.5 \times 10^6$, some errors are contained in the proper stress because the flecks become extremely

Fig.7 Relation between the distribution of flecks and the applied stress (230 °C, $N = 2 \times 10^6$)

Fig.8 Relation between the distribution of grown grains and the applied stress (230 °C, $N = 2 \times 10^6$)

fine owing to a large repeated strain.

As mentioned above, the proper stress of the foil is somewhat larger owing to the adhesive layer than that of the direct plating. On the other hand, it is found from the foregoing results that the proper stress becomes lower when the plating is preheated. This may be due to the following facts. When the plating is preheated at a certain temperature slightly lower than the recrystallization one of it, nuclei of grain growth are formed in the deposited layer and so the occurrence of grown grains due to repeated strain is promoted.

The recrystallization temperature of the nickel deposits under no load was about 280 °C for heating time of 2 hours, which was measured with a similar technique to that in the previous paper⁽³⁾. So, using the foil preheated at 260 °C for 2 hours, the σ_p - N curve at 230 °C was obtained as shown by a chain curve in Fig.5. Namely, a marked decrease in the σ_p -values is caused by the above preheating and this means that strain sensitivity of the foil gauge is raised by about 10 %. It is favourable that the proper stress becomes as low as possible at each number of cycles because the present method is a nondestructive one of stress measurement. Accordingly, it may be said that the technique of preheating the foil is an effective one for practical application of the present method.

3.2 The σ_p - N curve of the foil

Figure 6 shows an example of the σ_p - N curves at various test temperatures and it is obtained by observing the flecks. As shown in the figure, the σ_p -value at a constant temperature diminishes gradually with an increase in N , but it becomes almost constant when $N > 2 \times 10^6$. On the other hand, with a lowering of temperature, the σ_p -value at a constant number of cycles increases and moreover the rate of increasing in σ_p becomes remarkable. So, when the temperature is lower than 180 °C, fine cracks occur in the foil discoloured by flecks regardless of the number of cycles, and a similar phenomenon occurs at 180 °C as well when $N < 2 \times 10^6$. In such cases, accuracy of the method becomes lower necessarily.

When the temperature was higher than 250 °C, the stress measurement with the foil became impossible because the adhesive layer was degenerated owing to the high temperature. In the calibration test for the direct plating at 270 °C, however, the σ_p - N curve could be obtained easily by observing the flecks though initial recrystallizations were found together with the grown grains in the deposited layer. This is due to the facts that the recrystallizations initiated in the deposits are extremely fine and the growth of them is far slower than that of the grown grains owing to repeated strains. Accordingly, if a pertinent adhesive agent is used, the foil tested may be adopted up to about 300 °C because the recrystallizations at an early stage have little effect on the occurrence of flecks.

The flecks and grown grains in the

rectangular foil attached to the tapered specimen were observed under various test conditions. As an example, Fig.7 shows the relation between the distribution of flecks and the magnitude of applied stress at 230 °C when $N = 2 \times 10^6$. Figure 8 shows an example of the relation between the distribution of grown grains and the magnitude of applied stress as well. Arrows in these figures indicate the axial direction of the specimen. As shown in the figures, the distributions of flecks and grown grains become thicker gradually with an increase in the stress amplitude. The flecks in Fig.7(a) are those produced by the cyclic stress somewhat larger than the proper stress at 230 °C when $N = 2 \times 10^6$, which is shown in Fig. 6. In Figs.7(d), (e) and 8(d), (e), fine cracks owing to higher stress amplitudes are found partially in the flecks and grown grains.

If we make such a series of photographs as Figs.7 and 8 by using a calibration specimen made of the same material as an object and adopt the photographs as the standard ones for stress measurement, we can presume the stress value in the object by comparing the distributions of flecks or grown grains in the attached foil with those in the photographs.

3.3 Size effect of the foil on the proper stress

The foils with various sizes were attached to the tapered specimen as shown in Fig.9 and the size effect of foil on the proper stress was examined. As an example, Table 3 shows the results obtained by ob-

Fig.9 Foils of various sizes attached to the calibration specimen

Table 3 Relation between the size of foil and the proper stress (250 °C, $N = 1 \times 10^6$)

Size of foil mm	Specimen	Measured value of proper stress σ kgf/mm ²	Average value of proper stress σ_p kgf/mm ²
1×1	A-1	14.4	14.6
	A-2	14.7	
	A-3	14.8	
2×2	B-1	14.4	14.6
	B-2	14.7	
	B-3	14.7	
3×3	C-1	14.7	14.6
	C-2	14.8	
	C-3	14.6	
	C-4	14.3	
3×20	D-1	14.4	14.6
	D-2	14.6	
	D-3	14.6	
	D-4	14.6	

serving the flecks at 250 °C when $N=1 \times 10^6$. As shown in the table, the size of foil has little effect on the proper stress provided that the dimension of foil is more than 1 mm^2 . However, the σ_p -values in the table are somewhat smaller than the proper stress at 250 °C when $N=1 \times 10^6$, which is shown in Fig.6. This may be based on the use of a newly-compounded solution of the nickel plating. Namely, it is considered that the proper stress is affected sensitively by a minute amount of impurity contained in the plating solution, even if the solution of the same composition as that in Table 1 is adopted under the same plating conditions. Accordingly, it is essential to use the same plating solution throughout a series of experiments and besides perform a calibration test for the new plating whenever a different solution is adopted.

3.4 Stress-concentration factors in grooved shafts

Using the nickel foil discussed in 3.3, the stress-concentration factors in the grooved shafts (Fig.2 and Table 2) subjected to bending were obtained under the conditions of 250 °C and $N=1 \times 10^6$. Eight sheets of the square type foil were attached at regular intervals along the bottom of groove. Using several specimens with a kind of geometrical form of the groove, the tests were carried out by decreasing the bending moment M successively and the nominal stress $\sigma_d = 32M/\pi d^3$ for each M was obtained by observing flecks produced in the attached foils with an optical microscope of 100 magnifications. Here, judgement of the occurrence of flecks was made as follows: When flecks appeared in the greater part of eight foils, it was judged "thick", and when they appeared in less than the half, it was judged "thin". Thus, the standard stress σ_o was determined by the average value of the nominal stresses corresponding to "thin" and "none". In this case, the flecks observed within the range of microscope in the "thick" and "thin" were 3~5 and 1~3 in number, respectively.

As the stress at the bottom of groove attains the proper stress σ_p when the spec-

250 °C, $N=1 \times 10^6$, $\sigma_d = \pm 12.9 \text{ kgf/mm}^2$

Fig.10 Flecks produced at the bottom of groove

imen is subjected to the standard stress σ_o , which is based on the consideration in the previous paper⁽³⁾, the stress-concentration factor is given by $k = \sigma_p / \sigma_o$. The results obtained are shown in Table 4. Figure 10 shows an appearance of the flecks produced thinly in the foil attached to the specimen (a), where an arrow indicates the axial direction of the specimen. For comparison, the calculated values by Neuber's formula⁽⁴⁾, those using the finite element method⁽⁵⁾, the experimental values at 180 °C using the method of direct nickel plating⁽³⁾ and those at room temperature using resistance strain gauges⁽⁶⁾ are also shown in the table. The present results are in good agreement with those values.

4. Conclusions

The plating foils of sulphamate nickel attached to objects are applied for measurement of cyclic stresses acting upon the objects at high temperatures. The following conclusions are drawn from the results obtained.

- (1) The plating foil is produced by

Table 4 Measured values of the stress-concentration factor ($N=1 \times 10^6$)

Specimen	Temperature °C	Proper stress $\sigma_p \text{ kgf/mm}^2$	Nominal stress $\sigma_d \text{ kgf/mm}^2$	Occurrence of flecks	Standard stress $\sigma_o \text{ kgf/mm}^2$	Stress- concentration factor $k = \sigma_p / \sigma_o$	Previous results
(a)	250	14.6	13.5 12.9 12.7 12.5	Thick Thin None None	12.8	1.14	1.10 ⁽³⁾ 1.14 ⁽⁴⁾ 1.14 ⁽⁶⁾
(b)	250	14.6	11.7 11.5 11.3 11.1	Thick Thin None None	11.4	1.28	1.22 ⁽³⁾ 1.25 ⁽⁴⁾ 1.27 ⁽⁶⁾
(c)	250	14.6	9.39 9.33 9.27 9.10	Thin Very thin None None	9.30	1.57	1.55 ⁽³⁾ 1.56 ⁽³⁾ 1.47 ⁽⁴⁾ 1.50 ⁽⁶⁾ 1.53 ⁽⁵⁾

tearing off the nickel deposits from the ground metal plate of stainless steel. It consists of two layers in which one is a basic alkaline copper (thickness: less than $1\mu\text{m}$) and the other is an upper sulphamate nickel (thickness: about $5\mu\text{m}$).

(2) The thermosetting type cement made of epoxy resin (XS-20) is used as an adhesive agent of the foil and the adhesive layer is about $1\mu\text{m}$ in thickness.

(3) The flecks and grown grains in the foil are much smaller in size and decrease in number in the same field of observation as compared with those in the direct plating.

(4) The proper stress of the foil is larger by about 4% than that of the direct plating, so the effect of the adhesive layer on the proper stress is not remarkable.

(5) When the plating foil is preheated at a certain temperature slightly lower than the recrystallization one of it for a short time, the proper stress of the foil diminishes by about 10%. So, the above method of preheating the foil is an effective technique for the improvement of strain sensitivity of the foil gauge.

(6) The applicable test temperature of the foil gauge is within the range of $180\sim 250^\circ\text{C}$ provided that the adhesive agent XS-20 is adopted.

(7) If the dimension of foil is more than 1 mm^2 , the size of foil has little effect on the proper stress.

(8) Using the foil gauge at 250°C , the peak stresses in grooved shafts under bending are measured and it is confirmed that the present method has sufficient accuracy.

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