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Basic Study on Stress Measurement Using Slip-initiation Phenomenon in Electro-deposited Iron*

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Using slip-initiation phenomenon by fatigue in an electro-deposited iron, we propose a method of measurement of the stresses in machine elements under fluctuating service loads. In the method, both the direct iron-plating and adhesion of deposited iron-foil are utilized. Accuracy of the iron-foil method, however, is far superior to that of the direct plating method. Basic properties of the iron-plating for stress measurement, namely, applicable test temperature, and effects of test interruptions and grain size of the plating on slip-initiation are examined. When the iron-foil method is applied, the stress-concentration factors in notched specimens are obtained at various temperatures. The results are in good agreement with the theoretical and experimental values obtained previously. Consequently, it is confirmed that the present method utilizing the deposited iron-foil is effectively applicable to the measurement of cyclic stress in the range from room temperature to 250°C.

1. Introduction

The electro-plating method using deposited copper⁽¹⁾ and nickel⁽²⁾⁽⁴⁾ can measure not only concentrated stresses at notches accurately, but also cyclic stresses acting on machine parts in service. Since this method utilizes the crystal grain growth of deposited metal owing to cyclic loads, however, there is an apprehension that when test temperature approaches the recrystallization one of the deposited metal, the grain growth takes place under no load and accuracy of the measurement becomes lower. So, the applicable temperature range of the method is limited naturally.

The primary slip lines initiated by fatigue in metal are dominated by cyclic maximum shearing stress, which is similar to the occurrence of grown grains in the electro-plating method. The primary slip lines, however, do not occur under no load and are unaffected by test interruption accompanied with heating and cooling. Turning attention to these characteristics of the primary slip lines, the authors⁽⁵⁾ have proposed a method of measuring local stresses in a member subjected to a cyclic load by utilizing the slip-initiation phenomenon. It has been ascertained that the measured values are accurate enough in a wide test temperature range compared with that of the usual electro-plating method.

Since the technique mentioned in the previous paper⁽⁵⁾ is the method to observe

the slip lines which initiate directly in a measured member, it is not applicable to the material in which slip lines do not appear clearly, and it gives rise to fatigue damage in a measured member when it is applied. If the metal having lower critical stress of slip-initiation than that of a measured member is directly electro-deposited on the member or if the deposited metal foil is attached to the measuring point, the present method may become applicable easily to the member subject to a cyclic load.

In this paper, based on the above view point, for the purpose of developing a method of stress measurement using the slip-initiation phenomenon in electro-deposited metal, a basic research is carried out by using electro-deposited pure iron or its foil. Namely, effects of test temperature, intermittence of test and grain size of deposited iron upon the critical stress of slip-initiation in deposited layer are investigated and the present method is characterized as one different from the usual electro-plating method based on the grain growth of deposited metal. Furthermore, using the deposited iron-foil, the stress-concentration factors in notched specimens are obtained at several test temperatures and accuracy of the results is discussed.

2. Experimental procedure

2.1 Plating condition and operation

Deposited iron used in the present method is required to initiate slip lines at lower stress than the critical stress of slip-initiation of the object. So, using a high temperature bath of ferrous chloride which gives ductile deposited iron and taking account of hardness and grain size of the deposits, composition of plating solution and plating condition shown in Table 1 were adopted. Thickness

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Table 1 Composition of plating solution and plating condition

Ferrous chloride	$\text{FeCl}_2 \cdot n\text{H}_2\text{O}$	g	460
Calcium chloride	$\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$	g	200
Distilled water		cc	800
Bath temperature		$^{\circ}\text{C}$	95~100
Plating duration	Direct plating	min	15
	Iron-foil	min	5
Current density		A/dm^2	12
pH			1.0~1.5

Fig. 1 Wiring diagram of plating unit

of iron deposits thus obtained was about $30\text{ }\mu\text{m}$ in direct plating and about $10\text{ }\mu\text{m}$ in foil. Figure 1 shows the wiring diagram of plating unit.

Specimens of steel rods as a base metal were prepared by the following surface treatments prior to the plating: polishing with 600-emery paper and treating with acetone, calcium carbonate and dilute sulfuric acid. A plating tank made of carbon steel was used as the anode. Since the critical stress of slip-initiation of the deposited metal was considerably affected by the quality of plating solution, the same solution was used for a series of tests and a new solution was used for each specimen. Plating solution was agitated frequently during the plating operation so that hydrogen bubbles on the surface of deposits could be removed and consequently the surface with no pits could be obtained.

Figure 2 shows an appearance of the deposits observed by a scanning type electron-microscope. As shown in the figure, it is difficult to observe slip lines by an optical microscope, because of roughness of the deposited surface obtained. So, the surface of deposits was polished with 800-emery paper and finished by electro-polishing to obtain a mirror surface. Then, in order to remove residual stresses in the polished deposits, specimens were annealed in a vacuum furnace heating at 400°C for 2 hours. Figure 3 shows a microstructure of deposits after the heat treatment mentioned above.

2.2 Iron-foil and its adhesion

A round bar ($\phi 19\text{mm}$) of stainless steel was used as a base metal and it was plated over 60mm in length. After the deposited surface was finished by electro-polishing and buffing, a sheet of iron-foil was made by tearing off the deposits from the round bar. Since current density near the ends of foil did not keep constant, the foil

Fig. 2 Electron micro-photograph of deposited surface

Fig. 3 Microscopic structure of deposits

was thrown away by about 10mm in width at the ends. The remaining portion was annealed at various temperatures in a vacuum furnace, and then it was divided into a number of squares of $3 \times 3\text{mm}$ and rectangulars of $3 \times 20\text{mm}$ for the tests.

Surface of the test specimen of steel was polished with 600-emery paper prior to adhesion of the iron-foil. Two kinds of bonding cements, namely, an instant adhesive agent (Aron α) and a heat hardening type cement made of epoxy resin (XS-20) were used for the tests at room temperature and high temperatures, respectively. The heating of the latter was done in 3 stages of 20 minutes at 160°C , 10 minutes at 180°C and 10 minutes at 200°C .

2.3 Test specimens and testing machines

Drawn rods of carbon steel SK-4 ($\phi 21\text{mm}$) were used as the material of specimens for cyclic torsion tests and ones of SK-3 ($\phi 19\text{mm}$) for rotary bending tests. Figure 4 shows the tapered specimens used for the calibration tests of the deposits. Since the critical stress value of slip-initiation of the direct plating became high as mentioned later, the specimens used were oil-quenched after heating at 850°C for 1 hour and tempered after heating at 400°C for 2 hours, in order to prevent slip-occurrence in the matrix during the tests.

An Ono-type fatigue testing machine (10 kgf-m, 3600 rpm) and a Schenck type fatigue testing machine (4 kgf-m, 3600 rpm) were used for rotary bending tests and cyclic torsion tests, respectively. The tests at high temperatures were carried out in electric furnaces attached to these testing machines. The test temperatures were determined by the temperature of furnace atmosphere for rotary bending and by the tem-

S; Distance to the location where slip lines begin to grow

Fig. 4 Tapered calibration specimen

perature on the surface of specimen for cyclic torsion, and they were measured by a thermo-couple of alumel-chromel.

2.4 Items of the experiment

In order to carry out the stress measurement by utilizing the slip-initiation phenomenon in the iron deposits, the relation between the critical stress of slip-initiation and the number of cycles, namely the critical stress curve of slip-initiation in the deposited layer, must be established first. The slip-initiation phenomenon, however, depends on the test temperature. So, using the tapered specimen shown in Fig. 4(a), the critical stress curves of slip-initiation under rotary bending were obtained for both the direct plating and iron-foil at various test temperatures from room temperature to 250°C. In the foil tests, two sheets of the rectangular foil were used and they were cemented symmetrically along the specimen axis. For the purpose of preventing oxidation of these coatings at high temperatures, a constant quantity of chromium⁽⁵⁾ was vacuum evaporated on them.

Since the slip lines in the iron deposits were observed at room temperature by interrupting the tests at every appropriate number of cycles, the duration when the iron deposits were retained in high temperature atmosphere accompanied with heating-cooling cycles under no load was varied with each specimen. Thus effects of various test interruptions with such temperature changes on the critical stress of slip-initiation were examined. Namely, the calibration tests in rotary bending were carried out for the iron-foil at 250°C, and in every interruption for the observation of slip lines, the specimens were held at 250°C for either one hour or 12 hours under no load, before they were loaded in the next step of the test. In doing so, the critical stress curves were obtained for the two cases and effects of the holding time on the critical stresses were discussed.

It is likely that the critical stress

of slip-initiation is affected by the grain size of deposited metal. So, effects of the grain size on the critical stress were examined at room temperature under cyclic torsion by using the rectangular foil attached to the specimen shown in Fig. 4(b), after grain sizes of the foil were varied by vacuum annealing at various temperatures.

Next, as an example of the stress measurement in the case of iron-foil, the stress-concentration factors in circular shafts with a flat part under torsion and those in circular shafts with a circumferential groove under bending were obtained at various test temperatures from room temperature to 240°C. The results were compared with those obtained previously to examine accuracy of the present method.

3. Experimental results and discussions

3.1 The critical stress of slip-initiation in direct plating and iron-foil

When the tapered specimens (Fig. 4), which are plated directly or to which the iron-foil is attached, are loaded by rotary bending or cyclic torsion, slip lines in the iron deposits begin to grow in a slender part of the tapered portion at 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 slip lines begin to grow and the diameter d of the location are measured, the critical stresses of slip-initiation σ_p under bending and τ_p under torsion are calculated by the following formulas, respectively.

$$\sigma_p = 32M/\pi d^3, \quad \tau_p = 16T/\pi d^3 \quad (1)$$

where M is bending moment and T is torsional moment applied. If S is measured successively with the interruptions of test at every fixed number of cycles, the relation between σ_p or τ_p and N , namely the critical stress curve of slip-initiation in the iron deposits, can be obtained. The occurrence of slip-initiation was judged by using an optical microscope of 200 magnifications. The distance S was determined as an average of values measured at four locations dividing equally the periphery of specimen in the direct plating and at two locations in the iron-foil attached symmetrically. In the case of iron-foil, the deviation of each measured value of S from the average one was within 1mm and it gave only 2~3% difference in the critical stress. On the other hand, in the case of direct plating, the deviation was about 4mm at maximum. The reason will be given later.

Figure 5 (a), (b) show the critical stress curves under rotary bending for both the direct plating and the iron-foil which is annealed after heating at 700°C for one hour in a vacuum furnace, respectively. Here, the measured values at each temperature were obtained by using 1~2 specimens for the direct plating and 2

Fig. 5 Critical stress curve of slip-initiation

specimens for the iron-foil. It was confirmed that the critical stress of slip-initiation in material of specimen was much higher than that in the iron deposits at each value of N . Figure 6 and 7 show examples of the appearance of slip lines in the direct plating and in the iron-foil, respectively. Figure 8 shows a sectional view of the iron-foil attached using the heat-hardening type adhesive.

It is clear from Figs. 6 and 7 that crystal grain size in the direct plating is much smaller than that in the iron-foil recrystallized. Accordingly, as shown in Fig. 5(a), (b), the critical stress in the direct plating is much higher than that in the iron-foil at the same temperature. Since the plating solution adopted is very easy to oxidize and especially ferric ions in the solution increase rapidly during the plating operation, it is difficult to hold the same quality of deposited layer on each specimen. Consequently, it seems that difference among the measured values S at each temperature becomes relatively large in the case of direct plating and the accuracy of σ_p - N curves lowers as shown in Fig. 5(a). On the other hand, it seems that the iron-foil has the same quality because it is made of a sheet of foil by

(a) 120°C
 $\sigma = 25.0 \text{ kgf/mm}^2$, $N = 4.3 \times 10^6$

(b) 150°C
 $\sigma = 24.0 \text{ kgf/mm}^2$, $N = 0.6 \times 10^6$

Fig. 6 Appearance of slip lines in direct plating (Arrow: Axial direction)

(a) 30°C
 $\sigma = 17.0 \text{ kgf/mm}^2$, $N = 4.4 \times 10^6$

(b) 200°C
 $\sigma = 5.0 \text{ kgf/mm}^2$, $N = 3.1 \times 10^6$

Fig. 7 Appearance of slip lines in iron-foil (Arrow: Axial direction)

dividing. Consequently, the scattering of measured values at each temperature becomes small and the σ_p - N curve is accurate enough as shown in Fig. 5(b). In view of the results obtained above, it is necessary for practical use of the direct plating method to examine further the composition of plating solution, plating conditions, plating operations, etc. Then, the results

Fig. 8 Sectional view of iron-foil attached

obtained by using the iron-foil will be described in this paper.

It is clear from Fig. 5(b) that the critical stress of slip-initiation becomes lower quickly with a rise of temperature and a knee point where the σ_p - N curve becomes horizontal appears at lower number of cycles gradually. A marked temperature dependence of σ_p , however, appears up to 100°C, and σ_p becomes almost constant over 150°C. The tendency mentioned above is found also in characteristic features of mild steel, namely yield point, tensile strength and fatigue limit⁽⁶⁾⁻⁽⁹⁾, the factors of which have been interpreted based on the theory of dislocation⁽¹⁰⁾⁻⁽¹²⁾. Consequently, it may be considered that there are a few dissolved atoms like carbon and so on in the iron deposits used in this experiment.

Figure 9 shows an example of the relation between the proper stress and the number of cycles, namely the σ_p - N curve, obtained by observing the flecks of the surface of nickel-foil⁽¹³⁾ in the electroplating method. Comparing Fig. 9 with Fig. 5(b), it is clear that the value of critical stress in the iron-foil is only one-third of the value of proper stress in the nickel-foil and that the critical stress in Fig. 5(b) little depends on the test temperature in the range of 150~240°C. So, the present method can be effectively used without correction of the critical stress for the temperature change within the above range and can be applied under much lower stress amplitudes than those required for the nickel plating method. Though the upper limit of test temperature is restricted to 250°C by property of the adhesive used, it is considered that the present method can be applied up to higher temperature range using an appropriate adhesive.

Fig. 9 σ_p - N curve of the nickel-foil⁽¹³⁾

3.2 Effects of test interruptions on the slip-initiation

It was confirmed in the previous paper⁽⁵⁾ that the critical stresses of slip-initiation in the specimen of pure iron at both 150°C and 300°C were unaffected by test interruptions with heating and cooling. Then, in order to study whether the similar result could be obtained in the iron-foil or not, the σ_p - N curves under the rotary bending test with interruptions were investigated at 250°C by using the specimens shown in Fig. 4(a). Here, slip lines were observed at room temperature by interrupting the test at every appropriate number of cycles, and in every interruption of the test, the next step was started after the specimen was held at 250°C for either one hour or 12 hours under no load. Such test interruptions accompanied with heating-cooling cycles for observation of slip lines were repeated 1~4 times for each specimen. The results obtained are shown in Fig. 10. It is clear that the measured values on the relation between σ_p and N almost lie on a curve regardless of both the holding time and the repeated number of heating-cooling cycles. Consequently, it is concluded that the slip-

Fig. 10 Effect of test interruption on slip-initiation

initiation in the iron-foil is unaffected by the test interruptions with temperature change for observation of the slip lines. When the material damaged by fatigue is left under no load in a high temperature atmosphere, strain aging in the material develops with the lapse of time and work hardening caused by cyclic stresses also vanishes. In the iron-foil examined, however, it seems that effects of the adopted temperatures and holding time on the development of strain aging and disappearance of work hardening are markedly insufficient near the critical location of slip-initiation, because these phenomena cannot progress before a certain amount of slip deformation happens in the material.

3.3 Effects of the heat treatment of iron-foil on the critical stress of slip-initiation

In order to investigate effects of the grain size of iron-foil on the critical stress of slip-initiation, cyclic torsion tests were carried out at room temperature using the specimens shown in Fig. 4(b). The rectangular iron-foils used were annealed at various temperatures in the range of 650~950°C in vacuum in order to have various grain sizes. Figure 11 shows the relation between the critical stress τ_p at

$N=3 \times 10^5$ and the mean grain size d of the foil. As an example, Figs. 12 and 13 show microscopic structures of the foil and appearances of slip lines, respectively. It is clear from Fig. 11 that the relation between τ_p and $1/\sqrt{d}$ is linear and it is expressed by the following formula

$$\tau_p = \tau_n + k d^{-1/2} \quad (2)$$

which is the same form as Petch's formula¹⁴⁾ for the lower yield point of polycrystalline substance. Here, τ_n and k are specific values of the iron-foils used. Consequently, if the grain size of iron-foil is controlled by means of recrystallization, the present method may be applied to the measurement of stresses with various magnitudes at smaller numbers of cycles than those required for the electro-plat-

Fig. 11 Relation between the critical stress τ_p and the mean grain size d (Test at room temperature)

(a) Annealing temperature 750°C

(b) Annealing temperature 950°C

Fig. 12 Microscopic structure of the iron-foil annealed in vacuum

(a) Annealing temperature 750°C
 $\tau = 9.0 \text{ kgf/mm}^2$, $N = 5.3 \times 10^6$

(b) Annealing temperature 950°C
 $\tau = 6.5 \text{ kgf/mm}^2$, $N = 5.1 \times 10^6$

Fig. 13 Appearance of slip lines in the iron-foil annealed at various temperatures (Arrow: Axial direction)

ing method.

Furthermore, from the results of investigation with the iron-foils of various thicknesses, it is confirmed that the critical stress is unaffected when the thickness is within the range of 8~15 μm .

3.4 Measurement of the stress-concentration factors at various temperatures

In an application of the present method, the stress-concentration factor in a circular shaft with a flat part under torsion, the cross section of which is shown in Fig. 14, was obtained at room temperature and 240°C. The experimental procedures were as follows: At first, a sheet of the rectangular iron-foil (3×20mm) is cemented along the center line of the flat part and cyclic torsion tests are performed under a constant torsional moment T . By increasing the number of cycles N successively, it is observed by an optical microscope of 200 magnifications whether slip

Fig. 14 Cross section of the circular shaft with a flat part

lines begin to occur near the point a (Fig. 14) or not. Then, both the number of cycles N at which slip lines are about to appear and that at which they begin to occur thinly are obtained. Next, using the critical stress curve of slip-initiation obtained for the iron-foil in advance, the critical stress values, τ_s , corresponding to each N mentioned above are determined. Consequently, by taking the average value of τ_s , the critical stress τ_p at the point a is obtained. Then, the stress-concen-

tration factor k based on the surface stress τ_0 of the circular shaft with diameter d is given by

$$k = \tau_p / \tau_0, \text{ where } \tau_0 = 16T / \pi d^3 \quad (3)$$

Table 2 (a), (b) show the test results at room temperature and 240°C, respectively. For comparison, the values calculated for $\theta=30^\circ$, 60° using the theoretical solution by Ōkubo⁽¹⁵⁾ and the exact solution⁽¹⁶⁾ for $\theta=90^\circ$ are also shown in the table. Figure 15 (a), (b) show an appearance of slip lines

(a) Room temp., $\theta=60^\circ$
 $\tau_0=4.40\text{kgf/mm}^2$, $N=3.2\times 10^5$

(b) 240°C, $\theta=60^\circ$
 $\tau_0=1.42\text{kgf/mm}^2$, $N=7.0\times 10^4$

Fig. 15 Appearance of slip lines produced near the point a (Arrow: Axial direction)

Table 2 Measured values and calculated values of stress-concentration factor (Cyclic torsion)

(a) Results at room temp.

Dimension	Nominal stress τ_o kgf/mm ²	N	Occurrence of slip lines	Critical stress τ_s kgf/mm ²	τ_p kgf/mm ²	k	Calculated value
$d=10\text{mm}$ $\theta=30^\circ$ $h/d=0.93$	5.96	60×10^4	none	7.75	7.60	1.27	$1.28^{(15)}$
		100	thin	7.45			
	6.47	38	none	8.25	8.14	1.26	
		50	very thin	8.03			
		40	none	8.22			
6.20	55	very thin	7.95	8.09	1.30		
	$d=12\text{mm}$ $\theta=60^\circ$ $h/d=0.75$	4.40	27	none	8.55	8.48	1.93
32			thin	8.40			
4.34		31	none	8.45	8.34	1.92	
		40	very thin	8.23			
		20	none	8.80			8.71
25	thin	8.62					
$d=16\text{mm}$ $\theta=90^\circ$ $h/d=0.5$	1.90	40	none	8.22	8.05	4.24	$4.48^{(16)}$
		60	thin	7.88			
	2.07	16	none	9.00	8.88	4.29	
		21	very thin	8.76			
		2.05	13	none			
	18	thin	8.90				

(b) Results at 240°C

Dimension	Nominal stress τ_0 kgf/mm ²	N	Occurrence of slip lines	Critical stress τ_s kgf/mm ²	τ_p kgf/mm ²	k	Calculated value
$d=14.5\text{mm}$ $\theta=30^\circ$ $h/d=0.93$	2.28	7×10^4	none	2.85	2.80	1.23	$1.28^{(15)}$
		20	very thin	2.75			
	2.18	3	none	3.05	2.95	1.35	
		7	very thin	2.85			
	2.07	7	none	2.85	2.80	1.35	
		20	thin	2.75			
$d=17\text{mm}$ $\theta=60^\circ$ $h/d=0.75$	1.43	3	none	3.05	2.93	2.05	$1.91^{(15)}$
		8	very thin	2.80			
	1.42	3	none	3.05	2.95	2.08	
		7	thin	2.85			

produced thinly near the point a at room temperature and 240°C, respectively.

Next, the stress-concentration factor in a shaft with a circumferential groove (Fig.16) under bending was obtained at 90°C and 240°C. Six sheets of the square iron-foil (3×3mm) were cemented along the periphery of the bottom of groove. Rotary bending tests were performed under a constant bending moment M and the critical stress σ_p at which slip lines just began to occur in the iron-foils was obtained in a similar way to the method mentioned in the preceding example. Then, the stress-con-

Fig. 16 Circular shaft with a circumferential groove

Table 3 Measured values and calculated values of stress-concentration factor (Rotary bending)

(a) Results at 90°C

Dimension mm	Nominal stress σ_0 kgf/mm ²	N	Occurrence of slip lines	Critical stress σ_s kgf/mm ²	σ_p kgf/mm ²	k	Previous results
$r=3.0$ $t=0.82$ $d=12.0$ $D=13.6$	4.53	30×10^4	none	6.67	6.60	1.49	1.47 ^(1) 8) 1.47 ^(1) 9) 1.44 ^(1) 7)
		42	thin	6.53			
	4.46	50	none	6.49	6.43	1.44	
		310	very thin	6.37			
$r=3.0$ $t=0.45$ $d=12.0$ $D=12.9$	4.49	72	none	6.45	6.41	1.43	1.40 ^(1) 8) 1.44 ^(1) 9) 1.41 ^(1) 7)
		400	thin	6.36			
	4.57	60	none	6.47	6.45	1.41	
		90	thin	6.42			
$r=3.0$ $t=1.55$ $d=12.0$ $D=15.1$	4.17	40	none	6.55	6.52	1.56	1.50 ^(1) 8) 1.50 ^(1) 9) 1.46 ^(1) 7)
		50	thin	6.49			
	4.35	20	none	6.92	6.80	1.56	
		30	thin	6.67			
$r=6.0$ $t=0.46$ $d=12.0$ $D=12.9$	5.11	72	none	6.45	6.41	1.25	1.26 ^(1) 8) 1.24 ^(1) 9) 1.24 ^(1) 7)
		302	very thin	6.37			
	5.25	80	none	6.43	6.40	1.22	
		380	thin	6.37			
$r=6.0$ $t=0.80$ $d=12.0$ $D=13.6$	5.06	40	none	6.56	6.51	1.29	1.28 ^(1) 8) 1.26 ^(1) 9) 1.25 ^(1) 7)
		60	very thin	6.47			
	5.06	100	none	6.40	6.39	1.26	
		200	very thin	6.38			
	5.06	200	none	6.38	6.37	1.26	
		400	very thin	6.36			

(b) Results at 240°C

Dimension mm	Nominal stress σ_0 kgf/mm ²	N	Occurrence of slip lines	Critical stress σ_s kgf/mm ²	σ_p kgf/mm ²	k	Previous results
$r=8.0$ $t=0.60$ $d=16.0$ $D=17.2$	2.04	7×10^4	none	2.55	2.51	1.23	1.26 ^(1) 8) 1.24 ^(1) 9) 1.24 ^(1) 7)
		13	very thin	2.46			
	1.89	47	none	2.22	2.20	1.18	
		187	thin	2.18			
$r=8.0$ $t=1.10$ $d=16.0$ $D=18.2$	1.97	12	none	2.44	2.39	1.21	1.28 ^(1) 8) 1.26 ^(1) 9) 1.25 ^(1) 7)
		20	very thin	2.34			
	1.96	7	none	2.55	2.48	1.27	
		15	slightly thick	2.40			
$r=4.0$ $t=1.05$ $d=16.0$ $D=18.1$	1.67	15	none	2.40	2.35	1.41	1.47 ^(1) 8) 1.47 ^(1) 9) 1.44 ^(1) 7)
		25	thin	2.30			
	1.69	10	none	2.48	2.40	1.42	
		22	thin	2.31			
$r=4.0$ $t=0.61$ $d=16.0$ $D=17.2$	1.69	8	none	2.55	2.49	1.47	1.40 ^(1) 8) 1.44 ^(1) 9) 1.41 ^(1) 7)
		14	very thin	2.42			
	1.84	7	none	2.55	2.49	1.35	
		13	very thin	2.43			
	1.84	7	none	2.55	2.50	1.36	
		12	very thin	2.45			
	1.84	8	none	2.53	2.48	1.35	
		14	thin	2.42			

centration factor k based on the bending stress σ_0 at the minimum section of the specimen is given by

$$k = \sigma_f / \sigma_0, \text{ where } \sigma_0 = 32 M / \pi d^3 \quad (4)$$

Table 3 (a), (b) show the test results at 90°C and 240°C, respectively. For comparison, the calculated values by Neuber's formula⁽¹⁷⁾, the experimental results at room temperature by Kikukawa et al.⁽¹⁸⁾ using resistance strain gauges and the values in the diagram compiled by Peterson⁽¹⁹⁾ are also shown in the table. Figure 17 (a), (b) show

(a) 90°C, $r=3.0\text{mm}$ (b) 240°C, $r=4.0\text{mm}$
 $D=12.9\text{mm}$, $t=0.45\text{mm}$, $\sigma_0=4.57\text{kgf/mm}^2$, $N=9.0 \times 10^5$
 $D=18.1\text{mm}$, $t=1.05\text{mm}$, $\sigma_0=1.69\text{kgf/mm}^2$, $N=2.2 \times 10^5$

Fig. 17 Appearance of slip lines produced at the bottom of groove (Arrow: Axial direction)

an appearance of the slip lines produced thinly at the bottom of groove.

It is clear from Table 2 and 3 that the results obtained by the present method are in good agreement with the values obtained previously, though accuracy of the results at 240°C is slightly lower than that of the results at room temperature and 90°C.

From the above results, it is found that an application of the slip-initiation phenomenon in the iron-foil to the stress measurement has sufficient reliability. Accordingly, it can be considered that the present method is useful for the measurements of cyclic stresses in machine parts at various temperatures within the range from room temperature to 250°C.

4. Conclusions

Using the slip-initiation phenomenon in deposited iron, a fundamental study for developing the method of measurement of cyclic stresses in the elastic range is carried out. The following conclusions are drawn from the results obtained.

(1) It is difficult to use the direct plating method in practice, because the quality of deposited iron is not uniform in each plating and the accuracy of the critical stress of slip-initiation is insufficient.

(2) On the other hand, the method in which iron-foils are used can be applied

to measure accurately cyclic stresses at every temperature in the range from room temperature to 250°C.

(3) In the temperature range from 150°C to 250°C, the critical stress of slip-initiation in the iron-foil becomes about one-third of the value at room temperature and it is little affected by the temperatures. So, when the test temperature fluctuates in the range mentioned above, the present method can be utilized under low cyclic stresses without any temperature compensation. This is very advantageous as compared with the copper and nickel electro-plating methods.

(4) It is confirmed that the slip-initiation phenomenon in the deposited layer is unaffected by test interruptions even at high temperatures below 250°C.

(5) When the grain size of iron-foil is controlled by using recrystallization, the critical stress value of slip-initiation can be altered in a wide range. This shows the applicability of the present method to the measurement of cyclic stresses in members at various stress levels, by controlling the grain size of iron-foil reasonably.

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