A Fundamental Study on the Copper Electroplating Method of Stress Analysis* (Occurrence of Slip Bands in Plating Foil under Variable Stresses)

by Masaro IZUMISAWA** and Yasuo NAGASE***

In this paper, fundamental experiments are carried out to examine the occurrence of slip bands (fleckes) in a copper electroplating foil under variable stresses. The following conclusions are drawn: (1) Miner's rule holds for the occurrence of slip bands under two-level single block stressing; (2) the appearance of slip bands is dominated by the amplitude of the primary stressing; (3) when different kinds of stresses act continuously on the plating foil, cumulative fatigue damage that causes the slip initiation and the grain growth in the foil is not dominated by Miner's rule; and (4) both overstressing and understressing reduce the heating duration for recrystallization of the copper plating foil and then promote the occurrence of slip bands.

Key Words : Experimental Stress Analysis, Copper Electroplating Method, Fatigue, Variable Stress, Miner's Rule

1. Introduction

The copper plating method of stress analysis⁽¹⁾ applies the phenomenon that the grain growth^{*1} in electrodeposited copper plating or the initiation of slip bands⁽²⁾ (fleckes) in grown grains depends on both the amplitude of cyclic strain acting on the copper plating and the number of strain cycles. In this method, a relation between the critical stress at which slip bands begin to appear in the copper plating, the proper stress σ_p , and the number of strain cycles N is determined first. Next, machine parts subjected to cyclic stresses are coated with the electrodeposited copper or the copper plating foil and surface stresses on them are measured. Thus, for a given number of cycles N we can obtain a corresponding value of σ_p for the copper plating used, and for a given value of σ_p we can obtain a corresponding number of cycles N . However, amplitude of stress acting on the machine part usually varies. In such a condition, it is difficult to detect each of the stress amplitudes separately by the copper plating method. Considering the fact that the slip bands in the copper plating are initiated as a consequence of cumulative cyclic strain, however, it is expected that the amount of accumulated strains is estimated by observing the slip initiation in the copper plating. Thus, the copper plating method can be applied to estimate the extent of cumulated load that induces fatigue damage in the machine parts. It is necessary for the

application of the copper plating method to variable loading to investigate fundamental properties of the slip initiation and the grain growth phenomena under variable stresses. In this respect, however, few reports have been published except those by Okubo⁽³⁾ and Shinji et al.⁽⁴⁾.

In this paper, in order to investigate the fundamental properties of the slip initiation phenomenon under variable stresses, the proper stress σ_p for the slip initiation in the copper plating foil was obtained under two-level single block loading, and some examinations were made. It was inspected whether Miner's cumulative damage rule held for the slip initiation under two-level single block loading, when bending was repeated or both bending and torsion were sequentially applied. Effects of overstressing and understressing on the slip initiation were also examined. Moreover, effects of accumulated fatigue damage on the slip initiation were briefly investigated by measuring the heating time required to cause recrystallization of the copper plating foil stressed previously.

2. Experimental Procedure

2.1 Testing machine and test specimen

An Ono-type fatigue testing machine (60Hz, 98N·m) and a Schenck type fatigue testing machine (30Hz, 78N·m) were used for rotating bending tests and cyclic torsion tests, respectively. Drawn rods of carbon

*1 When a copper-plated specimen is subjected to cyclic stress, crystal grains in the deposited copper grow and the grown grains gradually develop toward the surface with an increase in the number of cycles. A slip deformation due to cyclic stress occurs in the grown grain, and then slip bands are observed like flecks when the grown grains reach the surface.

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** Professor, Faculty of Engineering, Shizuoka University, Johoku, Hamamatsu, 432 Japan.

*** Assistant Professor, Faculty of Engineering, Shizuoka University.

steel SK-3 ($\phi 19\text{mm}$) were used as specimen material, and they were machined to tapered calibration specimens shown in Fig.1.

2.2 Copper plating foil and measurement of the proper stress

An acid copper plating of single layer was electroplated on a polished stainless steel plate in a copper sulfate bath, and then a sheet of foil was made by tearing off the plating layer from the stainless steel plate. The plating solution and condition used were similar to those in the previous paper⁽²⁾. The plating foil thus produced was cut into a number of rectangular bits ($3 \times 20\text{mm}$). Two bits were used for one specimen shown in Fig.1, and they were glued symmetrically on the tapered portion along its axis. The specimen was then subjected to rotating bending or cyclic torsion at room temperature, and the proper stress σ_p at which slip bands or grown grains begin to appear on the plating surface was measured. The plating foil was glued so that the finally deposited surface

of it was the bonding side⁽²⁾, and the proper stress was determined by a procedure similar to that in the previous paper⁽²⁾. The slip bands or grown grains were observed with an optical microscope of 100 magnifications.

3. Experimental Results and Discussion

3.1 Slip initiation due to two-level single block loading

The tapered specimen shown in Fig.1(a) was subjected to rotating bending of constant amplitude, and the relation between the proper stress σ_p and the number of cycles N , i.e. the σ_p - N curve, was obtained first. Figure 2 shows the σ_p - N curves of the plating foil used. Next, two-level single block loading tests of rotating bending, the loading modes of which are shown in Fig.3, were carried out using the tapered specimen shown in Fig.1(a). The procedure in this experiment was similar to that employed by Seika et al.⁽⁵⁾. That is, after the specimen was subjected to n_1 cycles at a primary stress and n_2 cycles at a secondary stress, slip bands appearing on the plating foil glued on the tapered portion were observed. Since appearances of the slip bands varied as the diameter of the tapered portion changed, a critical location where they begin to appear was measured. Amplitudes of the primary and the secondary stresses, σ_1 and σ_2 , applied on this location were then determined. Thus the numbers of cycles N_1 and N_2 corresponding to σ_1 and σ_2 were obtained from the σ_p - N curve shown in Fig.2, and cycle ratios, n_1/N_1 and n_2/N_2 , were calculated. Table 1(a) and (b) show the results of the cumulative cycle ratios

Fig.1 Tapered calibration specimen
(S ; distance to the location where slip bands begin to appear)

Fig.2 σ_p - N curve

(a) Loading mode I

(b) Loading mode II

Fig.3 Two-level single block loading
(rotating bending)

for high-low and low-high loading, respectively. From the table, it is known that cumulative cycle ratio is nearly equal to unity irrespective of the loading mode and Miner's rule holds for the slip initiation. Table 1 shows the test results for $n_1/N_1 = 0.06 \sim 0.76$, while Fig. 2 shows that cycle ratio of the grain growth to the slip initiation is within the range of $0.4 \sim 0.5$. From this, it follows that the results for two cases are included in the table, one of which is the case where grown grains have already appeared at the critical location under primary stressing and the other is the case where grown grains have not appeared yet. Thus it can be said that the

slip initiation under two-level single block loading is generally dominated by Miner's rule whether grown grains have appeared at the critical location under primary stressing or not.

Figure 4 shows appearances of slip bands initiated under constant amplitude loading, where the applied stress is about 10% higher than the proper stress. Figures 5(a) and (b) show appearances of slip bands initiated under two-level single block loading, where the applied stress is about 10% higher than the stress applied at the critical location. In Fig. 5(a), n_1/N_1 is larger than 0.5 for both high-low and low-high loadings. Therefore, from the above

Table 1 Cumulative cycle ratio for slip initiation under two-level single block loading

(a) High-low								(b) Low-high							
No.	σ_1	n_1	n_1/N_1	σ_2	n_2	n_2/N_2	$\Sigma(n_i/N_i)$	No.	σ_1	n_1	n_1/N_1	σ_2	n_2	n_2/N_2	$\Sigma(n_i/N_i)$
1	202	5.0×10^5	0.52	168	2.0×10^6	0.56	1.08	1	159	3.0×10^6	0.55	200	5.7×10^5	0.57	1.12
2	200	"	0.49	166	"	0.51	1.00	2	159	"	0.55	191	6.7×10^5	0.50	1.05
3	203	"	0.53	174	1.3×10^6	0.48	1.01	3	162	"	0.64	211	3.5×10^5	0.47	1.11
4	208	"	0.62	178	"	0.57	1.19	4	162	"	0.64	211	"	0.47	1.11
5	198	"	0.46	158	2.5×10^6	0.45	0.91	5	162	"	0.64	200	5.0×10^5	0.49	1.13
6	200	"	0.49	160	"	0.49	0.98	6	162	"	0.64	201	3.5×10^5	0.35	0.99
7	192	8.0×10^5	0.63	160	1.2×10^6	0.23	0.86	7	158	"	0.53	196	"	0.30	0.83
8	199	"	0.76	166	"	0.30	1.06	8	160	"	0.57	196	4.4×10^5	0.38	0.95
9	184	3.5×10^5	0.19	159	3.9×10^6	0.70	0.89	9	164	"	0.68	201	"	0.45	1.13
10	192	"	0.27	162	"	0.78	1.05	10	153	3.8×10^6	0.53	176	1.2×10^6	0.50	1.03
11	196	1.8×10^5	0.13	171	2.9×10^6	0.92	1.05	11	179	6.6×10^5	0.30	204	7.4×10^5	0.82	1.12
12	192	1.6×10^5	0.11	167	"	0.73	0.84	12	193	1.6×10^5	0.13	228	3.7×10^5	0.74	0.87
13	221	5.3×10^4	0.09	191	1.0×10^6	0.74	0.83	13	167	2.4×10^5	0.13	195	9.2×10^5	0.77	0.90
14	228	3.0×10^4	0.06	202	"	1.02	1.08	14	166	2.1×10^5	0.11	195	9.5×10^5	0.79	0.90
15	232	2.5×10^4	0.06	202	"	1.02	1.08	15	176	1.5×10^5	0.06	207	8.5×10^5	1.00	1.06
Average value							0.99	Average value							1.02

Fig. 4 Appearances of slip bands initiated under constant amplitude loading (arrow: axial direction)

Fig. 5 Appearances of slip bands initiated under two-level single block loading (arrow: axial direction)

consideration grown grains are presumed to have been already initiated at the locations shown in Fig.5(a) under primary stressing. On the other hand, in Fig.5(b) it seems that grown grains have not yet been initiated under primary stressing because n_1/N_1 is very small. In spite of such a difference, it is recognized from Figs.5(a) and (b) that each size of slip bands due to low-high loadings is larger than that due to high-low loadings, and the number of slip bands in the former is less than that in the latter. As shown in Fig.4, under a constant amplitude stressing each size of slip bands becomes larger and the number of slip bands decreases as the applied stress decreases. Comparing Fig.5 with Fig.4, it is found that slip bands are larger when the amplitude of a primary stress is smaller than that of a secondary one. Consequently, it can be said that under two-level single block loading the appearance of slip bands depends on the amplitude of a primary stress, and this is not affected by cycle ratio.

3.2 Slip initiation due to bending and torsion

It was investigated whether Miner's rule held for slip initiation when rotating bending and cyclic torsion were applied sequentially. That is, the critical location where slip bands begin to appear under this condition was measured by using the specimen shown in Fig.1(b) in a similar way to that in the previous section. Cumulative cycle ratio was then obtained using the σ_p - N curves for rotating bending and cyclic torsion. Table 2 shows the results. In the table, the cycle ratio of the primary stress n_1/N_1 is in the range of 0.33~0.88. Consequently, following the foregoing discussion, the results for two cases are probably included in the table, one of which is the case where grown grains have already

appeared at the critical location under primary stressing and the other is the case where grown grains have not appeared yet.

In order to clarify the effect of the grain growth due to primary stressing on cumulative cycle ratio, an investigation similar to that in Table 2 was carried out for the initiation of grown grains instead of slip bands. Table 3 shows the results. Cumulative cycle ratios in Tables 2 and 3 are nearly equal to each other irrespective of the loading sequence. That is, the cumulative cycle ratio for slip initiation under the sequential application of different kinds of stresses is unaffected by grain growth in primary stressing and is equal to that for grain growth. This implies that the slip bands observed in Table 2 are probably those initiated in the grown grains that appeared and grew under secondary stressing. It is found from Tables 2 and 3 that cumulative fatigue damage due to a sequential application of different kinds of stresses is not dominated by Miner's rule because of $\Sigma(n_i/N_i) > 1$ and a primary stress somewhat promotes the initiation of grown grains and slip bands due to secondary stressing because of $n_2/N_2 < 1$. This probably results from the difference in the directions and planes of maximum shear stress that causes a slip deformation between bending and torsion. It was also observed that the slip bands initiated near the critical location showed a preferred orientation along the direction of maximum shear stress at secondary stressing. This means that they are caused by the secondary stress. On the other hand, the grown grains near the critical location were so fine that the preferred orientation could not be observed.

3.3 Effects of understressing and overstressing on slip initiation

As shown in Fig.2, the slope of the

Table 2 Cumulative cycle ratio for slip initiation under two-level single block loading (different kinds of stresses)

(a) Cyclic torsion → Rotating bending							
No.	τ_1	n_1	n_1/N_1	σ_2	n_2	n_2/N_2	$\Sigma(n_i/N_i)$
1	74	1.1×10^6	0.68	172	1.0×10^6	0.56	1.24
2	79	"	0.88	182	"	0.74	1.62
3	74	1.0×10^6	0.63	185	"	0.80	1.43
4	72	"	0.53	182	1.1×10^6	0.74	1.27
5	76	"	0.67	177	"	0.65	1.32
6	71	"	0.50	190	1.0×10^6	0.91	1.41
7	70	"	0.45	187	"	0.83	1.28
Average value							1.37

(b) Rotating bending → Cyclic torsion							
No.	σ_1	n_1	n_1/N_1	τ_2	n_2	n_2/N_2	$\Sigma(n_i/N_i)$
1	183	1.0×10^6	0.76	75	1.0×10^6	0.67	1.43
2	187	"	0.83	78	"	0.77	1.60
3	157	"	0.33	78	"	0.77	1.10
4	160	"	0.36	80	"	0.83	1.19
5	186	"	0.83	82	"	0.93	1.76
6	177	"	0.63	75	"	0.67	1.30
Average value							1.40

Table 3 Cumulative cycle ratio for grain growth under two-level single block loading (different kinds of stresses)

(a) Cyclic torsion → Rotating bending							
No.	τ_1	n_1	n_1/N_1	σ_2	n_2	n_2/N_2	$\Sigma(n_i/N_i)$
1	83	5.0×10^5	0.71	191	5.0×10^5	0.68	1.39
2	82	"	0.69	188	"	0.63	1.32
3	84	"	0.74	191	"	0.68	1.42
4	85	"	0.78	185	"	0.56	1.34
5	82	"	0.69	191	"	0.68	1.37
Average value							1.37

(b) Rotating bending → Cyclic torsion							
No.	σ_1	n_1	n_1/N_1	τ_2	n_2	n_2/N_2	$\Sigma(n_i/N_i)$
1	197	5.0×10^5	0.83	85	5.0×10^5	0.78	1.61
2	191	"	0.68	84	"	0.74	1.42
3	188	"	0.63	80	"	0.63	1.26
4	194	"	0.76	87	"	0.89	1.65
5	198	"	0.85	83	"	0.71	1.56
Average value							1.50

σ_p - N curve becomes flat with an increase in N . In this paper, understress is defined as a stress that does not initiate slip bands for its application of $N=10^7$ cycles. The proper stress σ_p of a plating foil previously understressed for $N=10^7$ cycles was obtained by rotating bending tests. Here, understress σ_1 was chosen as 125 MPa, which is lower than the proper stress for grain growth at $N=10^7$ ($\sigma_{pg}=135$ MPa), so that the observed slip bands were initiated in the grown grains appearing at secondary stressing. Figure 6 shows the results. All the measured values locate on the left-hand side of a solid line, which is the σ_p - N curve shown in Fig. 2. This means that the slip initiation is promoted by an application of the understress.

Varying the value of the understress σ_1 , the lower limit of σ_1 that affects the value of σ_p at $N=10^6$ was also determined. Figure 7 shows the results. As shown in the figure, σ_p decreases considerably with an increase in σ_1 when $\sigma_1 > 100$ MPa. Accordingly, it is concluded that when the understress becomes higher than 70% of the proper stress σ_{ps} an understressing effect arises. That is, fatigue damage produced by understressing promotes the nucleation

Fig. 6 Effect of understressing on slip initiation

Fig. 7 Effect of understressing on the proper stress

and growth of grown grains, thereby promoting slip initiation.

Next, it was investigated whether fatigue damage produced by overstressing gave rise to the slip initiation during subsequent understressing or not. An over-stress $\sigma_1 \approx 197$ MPa was first repeated to $N=5 \times 10^5$, which did not cause the grain growth, and next an understress lower than σ_{pg} was repeated to $N=10^7$. Table 4 shows the value of σ_p thus obtained at $N=10^7$. Measured values in the table are lower than 147 MPa, which is the proper stress σ_p of the plating foil shown in Fig. 2. From this it is concluded that grain growth and slip initiation occur even under the understressing provided an overstress is applied previously.

3.4 Relation between fatigue damage in copper plating and heating time for recrystallization

In the previous section, it was clarified through measurement of the proper stress that both overstressing and understressing cause fatigue damage accumulation. In this section, the amount of the accumulated fatigue damage was briefly estimated by measuring the heating time required to cause recrystallization in the plating foil subjected to overstressing or understressing. The procedure was as follows⁽⁶⁾. The plating foils which were non-stressed, overstressed or understressed by rotating bending were heated in boiling water at 100°C, and occurrence of recrystallized grains was inspected with an optical microscope of 100 magnifications. Table 5 gives measured values. In the table, every applied cyclic stress is slightly lower than the proper stress for grain growth. As shown in the table, the heating time necessary for recrystallization reduces markedly when the

Table 4 Effect of primary overstressing on the proper stress

No.	σ_p MPa at $N=10^7$
1	125
2	122
3	117
4	119
5	121
6	130
Average value	
122	

Table 5 Reduction in the heating time for recrystallization due to cyclic stress (100°C)

Primary stress		Heating time for recrystallization min
Non-stressed		10 ~ 20
Over-stressed	$\sigma = 208$ MPa $N = 4.3 \times 10^5$	less than 5
	$\sigma = 146$ MPa $N = 4.0 \times 10^6$	less than 5
Under-stressed	$\sigma = 132$ MPa $N = 1.0 \times 10^7$	5 ~ 10

plating foil is previously subjected to cyclic stress. This is the effect of over-stressing and understressing on the promotion of grain growth or slip initiation as described in the previous section. Though every fatigue damage produced by cyclic pre-stressing attains just before the initiation of grown grains, reduction in the heating time for the understressed plating foil is observed to be slightly less than that for the overstressed ones.

4. Conclusions

In order to obtain knowledge of the fundamental properties of slip bands appearing in a copper plating foil under variable stresses, the proper stress σ_p for the slip initiation was measured under two-level single block loading. Some examinations were made on the applicability of Miner's rule and the effects of over-stressing and understressing on the slip initiation. The following conclusions are drawn from the results obtained.

(1) It is found that Miner's rule approximately holds for the slip initiation under two-level single block loading irrespective of the loading mode, low-high or high-low, and the cycle ratio. The appearance of slip bands initiated in this load-

ing depends mainly on the primary stress value irrespective of the loading mode.

(2) On the other hand, Miner's rule for the slip initiation and grain growth does not hold when different kinds of stresses, i.e. bending and torsion, are applied sequentially.

(3) Overstressing and understressing have an effect of promoting the slip initiation during subsequent stressing. They also reduce the heating time required to cause recrystallization of the plating foil.

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References

- (1) Ōkubo, H., *Memoirs Fac. Engng., Nagoya Univ.*, Vol.20, No.1(1968), p.1.
- (2) Seika, M., et al., *Bull. JSME*, Vol.25, No.209(1982-11), p.1653.
- (3) Ōkubo, H., *Memoirs Fac. Engng., Nagoya Univ.*, Vol.20, No.1(1968), p.27.
- (4) Shinji, Y. and Kuni, Y., *Trans. Japan Soc. Mech. Engrs. (in Japanese)*, Vol. 43, No.370(1977-6), p.2116.
- (5) Seika, M., et al., *Bull. JSME*, Vol.22, No.172(1979-10), p.1351.
- (6) Seika, M. and Kitaoka, S., *Bull. JSME*, Vol.27, No.234(1984-12), p.2664.