FOIL-GAUGE OF ELECTRODEPOSITED-COPPER*

HAJIMU ŌKUBO and KIKUO HOSONO

Department of Mechanical Engineering

(Received April 6, 1962)

The electroplating method of strain analysis which has been recently developed in Japan, is based on the sensitive colour change of the surface of deposited copper made by micro-flecks and also on the grain-growth occurring in deposited copper, both caused by cyclic stress. It proved useful for an accurate determination of the peak stress due to notches and also for the measurement of microscopic strain distribution in metals. By this method it is possible to locate the peak point where the initial fatigue crack will occur, prior to the appearance of any slip band.[1] Details should be referred to previous papers. Promising application of the method is the prediction of fatigue failure which may occur in structures and machines under operation.

Foil-Gauge: The remarkable forte of foil-gauges is that they can be used to measure the cyclic stress in machines and structures which are too large for copper-plating or of material which cannot be copper-plated.

A copper-foil is easily obtained by tearing off the deposited copper poorly sticked on a ground metal, such as stainless steel. A number of foil-gauges of exactly the same guality are made by dividing from a sheet of foil. Accordingly, the disarrangement of results occurring from the difference in the quality of plating solution can easily be avoided. The cyclic strees can be measured by sticking foil-gauges on an object, since there is no essential difference in the property of the plated copper either directly deposited on a ground metal or foil-gauges stickde.

Another forte of the gauge is that it is used even in an extremely limited space, since meters or lead wires are unnecessary. The necessary area to stick a gauge is very small. It can be reduced even to less than 1 mm^2.

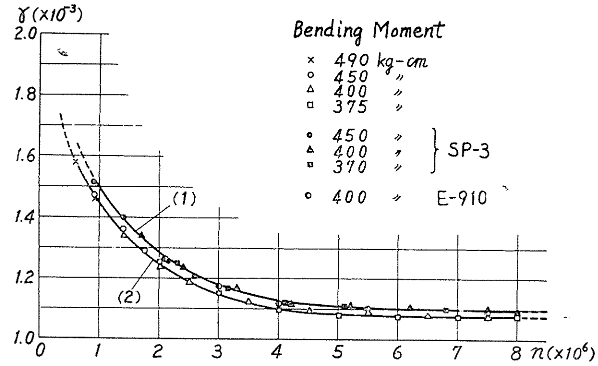

FIG. 1. (1) foil-gauge, (2)directly deposited copper

Effect of Paste: A fatigue test was made in rotary bending and torsion to find the relation between the

* A grant-in-aid of Scientific Research was given for this stduy by the Education Department of Japan. This paper was shortly reported in Technical Report of the Engineering (London), 1962.

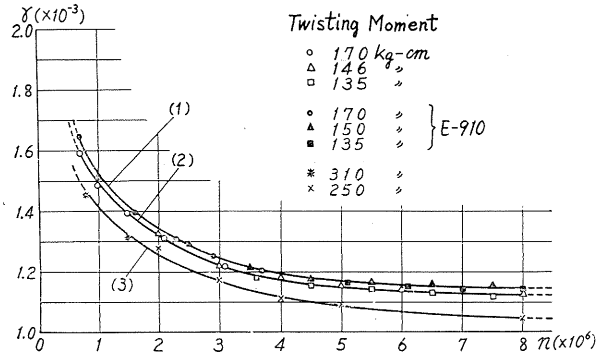

FIG. 2. (1) foil-gauge, alternating torsion, (2) directly deposited copper, alternating torsion, (3) directly deposited copper, pulsating torsion

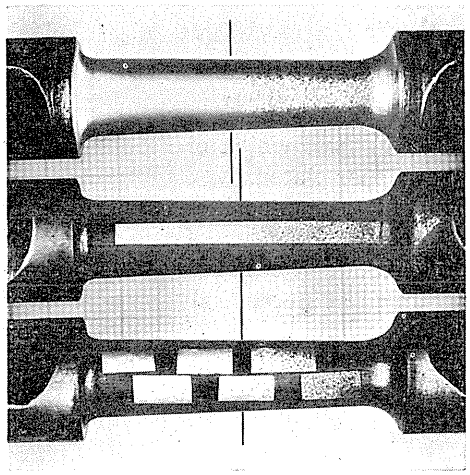

FIG. 3. Tapered rods partly changed in colour by fatigue

proper strain in shear, γ and the number of repetitions of cyclic stress, n. The results are shown in Figs. 1 and 2, where curves (1) and (2) are for foil-gauges and directly deposited copper, respectively. Little effect of the paste on the proper strain can be observed, as is shown in the figures, though the value of γ measured by foil-gauges is slightly large. Figure 3 shows tapered robs partly changed in colour by cyclic torsional stress. The twisting moment and the number of repetitions are the same for the three rods. The strain around the vertical lines is the proper strain.

Inequality of Quality, Size Effect: A number of foil-gauges of different size, varying from 1 mm to 4 mm, are cut out from one sheet of copper-foil. They are pasted on a cylindrical rod of steel. Using the rod, a fatigue test was made under a constant bending moment. The number of cyclic stress when flecking occurred on the surface of each foil-gauge was observed. The results are given in Table 1.

TABLE 1. Number of Repetitions n ($\times 10^6$)

Size→ / Gauge No. ↓	1 mm	2 mm	3 mm	4 mm
1	1.73	1.70	1.68	1.68
2	1.70	1.70	1.65	1.63
3	1.70	1.70	1.70	1.65
4	1.73	1.68	1.63	1.73
5	1.80	1.75	1.75	1.70

Referring to the curve (1) in Fig. 1, it is seen from the table that the inequality between individual gauge and the size effect on proper strain are practically negligble. In the test, the bending stress of the steel rod is $\sigma = \pm 21.5$

kg/mm², and the modulus of rigidity of the steel is $G=8.1\times10^3$ kg/mm². The shearing strain in foil-gauges is $\gamma=\sigma/2G=\pm1.33\times10^{-3}$. From the curve (1) in Fig. 1, it follows that $n=1.7\times10^6$, which definitely agrees with the values in the table.

Example of Application: As an application of foil-gauges, the cyclic stress occurring in the casing of a vibrator for moulding machines, Fig. 4, was measured. Gauges had been pasted at peak points as shown in the figure. A fatigue test was made to find the number of repetitions of cyclic stress, n, when fecking occured in each gauge. The cycle of stress in the vibrator under operation was 9,000 per minute. The result is given in the first row in Table 2.

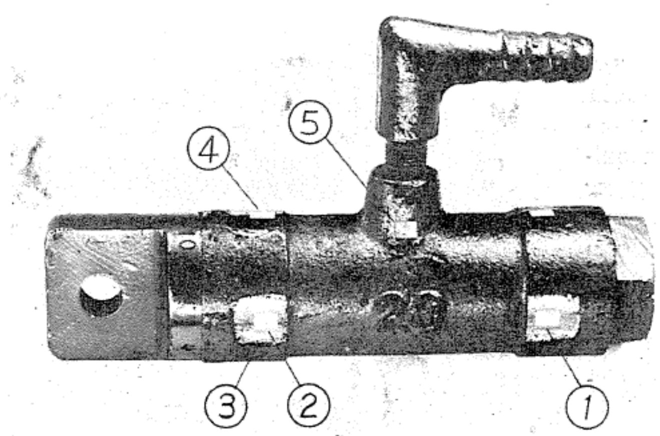

FIG. 4. Vibrator for moulding machines

TABLE 2.

Gauge No.	1	2	3	4	5	6
n ($\times10^6$)	1.1	1.3	1.4	2.0	no flecking	1.7*
γ ($\times10^{-3}$)	1.40	1.36	1.34	1.26		
σ (kg/mm²)	21.0	20.4	20.1	18.9		

* At the edge of an exhaust hole, Fig. 5(b), a small fatigue crack was suddenry produced at $n=1.7\times10^6$, but perceptible growth of the crack could not be observed till the fracture of the vibrator.

The vibrator was broken along the line connecting 2, 3 at $n=4.5\times10^6$, as is shown in Fig. 5 (a). Figure 6 is the etched surfaces of foil-gauges, 1 and 6 in Figs. 4 and 5, after the fracture of the vibrator. It shows the grain-growth occurring in the deposited copper and a fatigue crack surrounded by grown-grains.

Since the marked points in Fig. 4 is submitted to pulsating tension, the γ-n curves for alternating stress, Figs. 1 and 2, cannot be used for the evaluation of cyclic strain. In view of the lack of a suitable testing machine available at the laboratory, the γ-n curve for pulsating torsional stress was obtained. The result is shown by the curve (3) in Fig. 2. The values of γ in curves (2) and (3) in Fig. 2 are not greatly different. This shows that the statical stress produces only small effect on the proper strain. The authors consider that the γ-n curve for pulsating tension can be approximated by the one for pulsating torsion, since the difference of γ-n curves for alternating bending and torsion, Figs. 1 and 2, is not perceptible. Using the curve (3) in Fig. 2, the approximate value of proper strain in shear was estimated. It is given in the second row in Table 2.

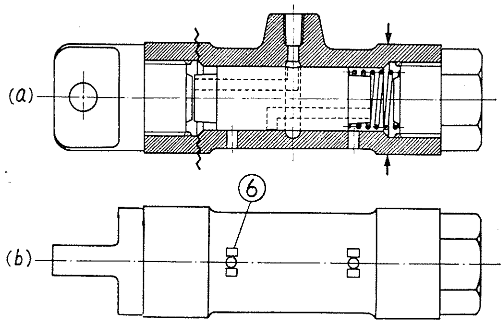

FIG. 5. Sketch of the vibrator

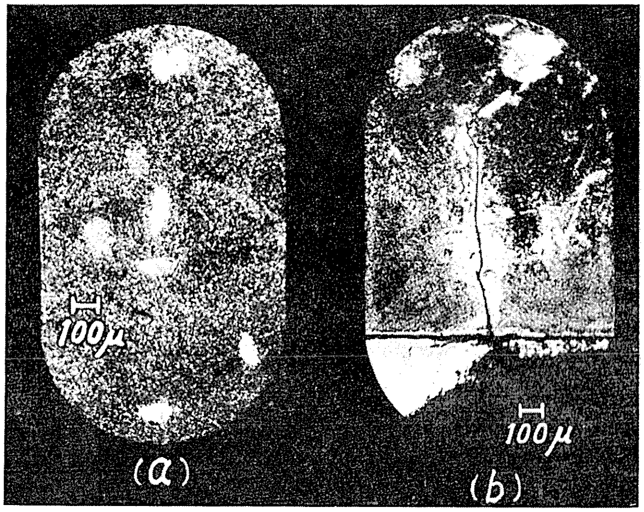

FIG. 6. Grain-growth in the deposited copper, showing strain concentration at 1, (a) and at 6, (b)

Since the tensile stress in a uniform tension field is twice the shearing stress, it follows that

$$\sigma = 2\tau = 2G\gamma \qquad (1)$$

The vibrator was of malleable cast iron and the modulus of rigidity is assumed $G = 7.5 \times 10^3$ kg/mm². The amplitude of the pulsating direct stress calculated from (1) is given in the last row of Table 2. It is seen from the table that the stress at 1, 2 and 3 is apparently larger than the endurance limit of malleable cast iron in average.

Reference

1) Read before the 10th International Congress for Theoretical and Applied Mechanics at Stresa, Italy, August 31-September 7, 1960. H. Ōkubo, S. Murakami and K. Hosono, *Journal of the Institute of Metals*, vol. 91 (1962) p. 95.