539.43.01

Fatigue Damage of 6-4 Brass Specimens*

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By annealing and electro-polishing technique it was shown that the fatigue damage of 6-4 brass specimens is confined to within a thin surface layer of the specimens. The thickness of the damaged layer becomes greater when the applied stress is high and the number of stress repetitions is large. The rate of growth of the thickness of the damaged layer begins to increase rapidly, when the thickness exceeds some threshold value (in the present case, 30 to 50 microns).

The fatigue damage occurring beneath the surface layer of the specimen seems to be of strain-hardening character and it disappears by stress relief annealing. It seems from this work that the fatigue limit is the stress under which the thickness of the damaged layer remains within certain limit, even if the number of stress repetitions is infinitely large.

Introduction

About the fatigue damage of metals due to alternating stressing many investigations have been reported hither-to, by measuring, for example, changes of mechanical properties, or of fatigue lives, etc. of fatigued specimens. But these approaches seem to the author not to have been fruitful. This may be due to the fact that the fatigue damage of metals is so localized that macroscopic properties of metals do not change so much even if metals undergo alternating stressing above their fatigue limits.

In metals, subjected to stresses above their fatigue limits, plastic deformation must occur in some grains but since plastic deformation taking place on the surface or in the interior of metals will have different results concerning fracture of metals, as dislocation theory points out, the fatigue damage occurring on the surface of a specimen will be different from that in the interior of it.

Following facts will suggest some important points about the fatigue damage of metals; i) In copper specimens under alternating push-pull tests fatigue cracks start on the surface of the specimens⁽¹⁾ at a relatively early stage of the total endurance life⁽²⁾. ii) Electro-polishing of the surface of copper specimens at each interval of 25% of the estimated endurance life increased the life of the specimens by about 125% of its normal life⁽¹⁾. But by stress relief annealing fatigue damage cannot be removed

at all⁽²⁾⁽⁶⁾. iii) In the case of carbon steel under rotary bending, removal of the surface layer make the specimens survive beyond their normal lives⁽³⁾⁽¹⁰⁾. iv) The fact that fatigue strength of notched bars can be calculated from the stress distribution near the root of the notch is widely known today⁽⁴⁾. v) Extrusions and intrusions can be observed on the surface of fatigued specimens. These are literally surface phenomena. These facts suggest that the effect of alternating stress on metals will be confined mainly to the layer near the surface of the specimens.

In this paper the natures of fatigue damage of 6-4 brass due to rotary bending stress, revealed by repetitions of surface polishing followed by stress relief annealing, are reported.

Material used and method of testing

All the observations to be described in this paper have been made on two-phase commercial brass (6-4 brass; 59.05% Cu, 1.89% Pb, 0.04% Fe, bal. Zn). The micrograph of the central part of a specimen, where no stress acted, is shown in Fig.1(a), while Fig.1(b) shows that of the surface of the specimen subjected to rotary bending stress of 19 kg/mm² for 11.394×10^6 repetitions during which the specimen was annealed 7 times for 1 hour at 400°C. The black part is β -phase of the material.

All specimens were turned out from 3 segments taken from one section of a rolled bar of 40 mm dia. Before tests all specimens were heated for 1 hour at 400°C and furnace-cooled. Fatigue specimens were electro-polished so as to remove the surface layer of about 30 microns thick. The rate of stress

* Received 30th April, 1962.

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repetitions is about 2500 cycles per minute.

The mechanical properties obtained with specimens of 10.2 mm dia. are (mean value of 2 specimens): proof stress for 0.2% set = 21.3 kg/mm², tensile strength = 40.4 kg/mm², actual stress at fracture = 71.0 kg/mm², area contraction = 46.3%. Fatigue limit measured with electro-polished specimens, of which the endurance curve is shown in Fig. 2, is about 18.5 kg/mm². For detailed discussion of the fatigue life of the material itself, it will be necessary to test more specimens than shown in Fig. 2 but, as stated below, since localization of the damage is so evident that the conclusions obtained would not be misleading because of the scattering of the endurance lives, so we did not make detailed discussions about the scattering of the endurance lives of the material.

Experimental procedures are as follows; after a specimen is subjected to rotary bending stress σ for N_1 repetitions the surface of the specimen is polished off mechanically by an amount of Δr_1 with

04 emery paper followed by pot-annealing for 1 hour at 400°C avoiding oxidation of the surface. The specimen is then electro-polished to remove the surface layer of a thickness of Δr_2 . When the layer to be removed is thin, mechanical polishing was omitted and only electro-polishing was done. The thickness Δr_2 of the layer removed by electro-polishing was about 30 ± 3 microns in all cases of experiments.

In fatigue tests, for a specimen, σ , $\Delta r (= \Delta r_1 + \Delta r_2)$ and N_1 were kept constant and the fatigue life of the specimen was measured. The specimen was, therefore, subjected to repeated polishing and annealing after every N_1 cycles of stress repetitions until it failed under the applied stress σ . For another specimen σ , or Δr or N_1 was changed and its fatigue life was measured, and so forth.

Results of tests and discussions

In all Figs. the following numerals such as (1-2), (2-1).... for example, represent the specimen

a) Central part of the specimen (not stressed part)
b) Surface (about 0.03 to 0.13 mm deep from the surface)

This specimen was subjected to bending stress of 19 kg/mm² for 11.394×10^6 repetitions but did not fail. It was annealed (400°C, 1 hr) 7 times during these repetitions.

Fig. 1 Micrographs of the material (specimen No. 8-1).

Fig. 2 Endurance curve of the specimens with electro-polished surface

A: annealing (400°C, 1 hr)

P: polishing

Δr : thickness of the layer removed by polishing

Fig. 3 Results of tests under the condition of $\sigma = 19$ kg/mm², $N_1 = 2.8 \times 10^6$

number. Life of a specimen is given by the abscissa of the black point at the end of each horizontal line. Black point with an arrow shows that the specimen did not fail. At the number of stress repetitions corresponding to the abscissa of the vertical dotted lines, stress relief annealing (400°C, 1 hr) and polishing for removal of the layer to the necessary thickness Δr were carried out.

Data obtained from specimens tested under stress of 19 kg/mm² and $N_1 = 2.8 \times 10^6 (\cong 0.7N_0)$ for various values of Δr are shown in Fig. 3. In the specimen (5-1), since three fine cracks were observed on its polished surface after the third polishing was over, further test was stopped. Specimens (1-1) and (4-2) were annealed after $N_1 = 2.8 \times 10^6$ stress repetitions but not polished. Specimens (1-2), (2-1), (1-1), (4-2), (3-1) and (2-2) show no significant difference in their fatigue lives. Meanwhile the lives of the specimens (4-1), (5-1), (1-3) increased more than 100 to 200% compared with those of (1-2) and (2-1). This is due to the intermediate polishing and annealing, showing that polishing off the surface layer of about 80 to 100 microns thickness followed by stress relief annealing improved the fatigue life of the specimens. These specimens, except (5-1), however, failed eventually. This suggests that due

A : annealing (400°C, 1 hr)
P : polishing
 Δr : thickness of the layer removed by polishing,
arrow indicates a non-broken specimen

Fig. 4 Results of tests under the condition of $\sigma = 19 \text{ kg/mm}^2$, $N_1 = 1.4 \times 10^6$

A : annealing (400°C, 1 hr)
P : polishing
 Δr : thickness of the layer removed by polishing

Fig. 5 Results of tests under the condition of $\sigma = 21 \text{ kg/mm}^2$, $N_1 = 1.06 \times 10^6$

to fatigue stressing the part of specimen near its surface suffers severe damage and although its removal makes the specimen survive its normal life, some part of the damage occurred in the interior of the specimen cannot be removed by stress relief annealing.

There would be some doubts about the detrimental effects of repeated annealing on the fatigue strength of the specimens. But the specimen tested under a stress of 19 kg/mm² and subjected to repeated polishing and annealing at every interval of $N_1 \cong 0.35N_0$ stress repetitions endured more repetitions of polishing and annealing than the specimen under the conditions of $\sigma = 19 \text{ kg/mm}^2$ and $N_1 \cong 0.7N_0$. About this some more discussions will be given later.

The thickness of a severely damaged layer is a function of applied stress σ and number of stress repetitions N_1 . Fig. 4 shows the results of tests under the condition of $\sigma = 19 \text{ kg/mm}^2$ and $N_1 = 1.4 \times 10^6 (\cong 0.35N_0)$. From this Fig. it will be concluded that the severely damaged layer during 1.4×10^6 repetitions of stress reaches about 30 microns below the surface of the specimens.

Fig. 5 and Fig. 6 are the results of tests under the stress of 21 kg/mm². For the specimens in Fig. 5 polishing and annealing were repeated at every interval of $N_1 = 1.06 \times 10^6 (\cong 0.76N_0)$ and the severely damaged layer seems in this case to be thicker than 250 microns, while the thickness of the damaged layer of the specimens under the stress of 21 kg/mm² during $0.49 \times 10^6 (\cong 0.35N_0)$ repetitions of stress seems to be less than 75 microns.

Above results suggest that the main fatigue damage is initially confined to within a thin surface layer of the specimen and as the stress repetition continues the thickness of the damaged layer increases. The surface damage will include some kinds of extrusions and intrusions of the material as well as crystal disruption of grains⁽⁵⁾⁽⁹⁾. All of them cannot be removed by stress relief annealing⁽²⁾⁽⁶⁾.

A : annealing (400°C, 1 hr)
P : polishing
 Δr : thickness of the layer removed by polishing,
arrow indicates a non-broken specimen

Fig. 6 Results of tests under the condition of $\sigma = 21 \text{ kg/mm}^2$, $N_1 = 0.49 \times 10^6$

Fig. 7 shows the relations between the thickness Δr_0 of the damaged layer, as determined by the method stated above, and the magnitude of applied stress or number of stress repetitions.

In metals slip resistance, and consequently fatigue strength, will depend on the magnitude of their grain size and metals having larger grains show smaller fatigue strength. The largest grains of the 6-4 brass used in this experiment seem to be about 40 microns in their linear dimension (Fig. 1), so the fatigue damage will proceed grain by grain starting from the largest one on the surface of the specimen.

The detrimental effects of repeated stress above fatigue limit are not confined to near the surface of the specimen. The inner part of the specimen will suffer some damage also. Strain hardening will be the predominant one. On the other hand coxing effect will strengthen the inner part of the specimen. In our experiments the part at the depth $n\Delta r$ below the surface of the specimen come eventually to the surface of the specimen after n -times repetitions of polishing (and annealing), since by each polishing the surface layer of thickness Δr is removed. In

a specimen of $2a$ dia. under bending stressing, this part will undergo the stress levels $\sigma(1-n\Delta r/a)$, $\sigma\{1-(n-1)\Delta r/a\} \dots \sigma(1-\Delta r/a)$ until it comes to the surface in such way that in each stress level the stress is repeated N_1 times and so due to this coxing effect the fatigue strength of that part may change. It will be natural to conclude that if the stress relief annealing nullifies the strain hardening due to repeated stressing, the strengthening due to coxing will also be removed or becomes very small after annealing.

For this purpose we examined the distribution of the hardness over the cross section of a fatigued specimen before and after annealing. The results are shown in Fig. 8. With the specimen (5-1) which, as stated before, after the 4th annealing, developed surface cracks, further stressing was stopped. This specimen can be regarded, therefore, as being in a state of annealing. Specimen (1-3) in Fig. 9 failed after 8.295×10^6 repetitions of stress of 19 kg/mm^2 and during these stress repetitions the specimen underwent 3 times stress relief annealing and 2 times polishing, so the specimen is in a state of being fatigued but not annealed.

Fig. 8 and Fig. 9 show that the strain hardening due to stress repetitions disappears after said annealing. The effect of annealing on the grain growth seems not to occur as can be seen from the micrographs shown in Fig. 1. Even if the repeated annealings cause some grain growth, the very nature of the surface damage will not be disturbed by grain size and the fact that fatigue damage concentrates near the surface of the specimen will be still true.

The results stated above together with further experiments made with 7-3 brass, not reported here, suggest that the fatigue limit of a material is a stress level under which no or very thin (at most

Fig. 7 Relations between the thickness Δr_0 of damaged layer and applied stress or its number of repetitions

Fig. 8 Micro-hardness (Vickers) distribution over the cross section of specimen No. (5-1). dia. = 10.27 mm. The specimen was subjected to stress 19 kg/mm^2 for 8.48×10^6 repetitions but is in a state of being annealed

Fig. 9 Micro-hardness (Vickers) distribution over the cross section of specimen No. (1-3). dia. = 10.50 mm. The specimen was subjected to stress 19 kg/mm^2 for 8.295×10^6 repetitions and is in a state of not being annealed

only one grain size thick) damaged layer appears after an infinite number of stress repetitions. This view will have some close relation with the view of Watanabe⁽⁷⁾ or Wadsworth⁽⁸⁾ that fatigue limit is a stress under which fatigue crack does not propagate at all.

Conclusion

After repeated polishing and annealing procedure we reached the following conclusions about fatigue damage of 6-4 brass specimens under rotary bending stressing.

a) Fatigue damage due to stress above fatigue limit concentrates near the surface of the specimen. The damage can not be removed by stress relief annealing. It proceeds inward into the specimen when stress repetitions continue. The thickness of the damaged layer is a function of applied stress and its number of repetitions.

b) Fatigue damage seems to proceed grain by grain from the surface to the interior of the specimen.

c) Most part of the fatigue damage in the interior part of the specimen can be removed by stress relief annealing but not perfectly.

d) Fatigue limit will be the stress under which

the thickness of the damaged layer remains within some limit (perhaps 0 or one grain size thick) even if the number of stress repetitions is infinitely large.

Acknowledgments

The author would like to thank assistant T. Matake for carrying out fatigue tests and post-graduate students K. Setoguchi, M. Shibata for their aids in electro-polishing of the specimens.

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621.863.06:539.384.6

On the Strength of Hoisting Drums for Windlasses*

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Theoretical and experimental studies were conducted in order to establish a method of computing the strength of hoisting drums for windlasses. It was assumed that external pressure is the only external force applied to a hoisting drum. Further, the strength of the hoisting drum was discussed in terms of the strength of the cylindrical parts and the strength of the stiffening rings. Each of the 16 model drums failed due to the yielding of either the cylindrical parts or the stiffening rings. As a result of the research, it was made clear that the initial deflection of the hoisting drum has a considerable effect on the strength, and formulas were obtained for computing the strength of the drum. Finally, applicability of these results to actual design of hoisting drums was discussed.

1. Introduction

Methods of computing the strength of hoisting drums for windlasses have been proposed heretofore

by several research workers^{(1)~(3)}, and these methods have been in general used in designing the hoisting drums. None of these methods, however, is satisfactory for computing the strength of hoisting drums. Accordingly, it is urgently required in designing windlasses to establish a method of computing the strength of safe and economical drums.

* Received 5th June, 1962.

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