CHANGES IN STRENGTH AND STRUCTURE OF METALS UNDER CYCLIC STRESS

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This study is concerned with the changes of strength and structure of certain metals and alloys subjected to cyclic loads at room and elevated temperatures. Flat specimens 0.5 ± 0.01 mm thick and 20 mm wide were tested in cyclic bending and tension. Specimens of [aluminum] alloys AD1 and D16 were annealed for 2 hrs in vacuum (10^{-4} mm Hg at 300°C) while specimens of alloys M3, L62 and Br.OF were annealed at 600°C. One set of bronze specimens was tested in the cold-worked condition.

Different groups of specimens were cyclically bent under 1, 10, 100 and 1,000 cycles. The endurance of AD1 and D16 specimens was 1200-1500 cycles and of copper and copper alloys, from 1400 and 1600 cycles.

Most specimens were tested in cyclic bending at 20°C (see paper by same author in Fizika Metallov i Metallovedenie, 1958, Vol. 6, No. 2. To obtain data for comparisons, a part of the aluminum alloy specimens was tested at 300° and of the copper alloys at 600°C. After cycling, the specimens were electropolished, tested in tension at 20°C, also for microhardness and fine structure.

The microhardness in the maximum deformation zone was determined on a PMT-3 instrument using a 10 g load for aluminum, duralumin and copper and a 20 g load for brass and bronze. Each microhardness figure is an average of 15 readings.

Studies of the fine structure were conducted on a URS-70 apparatus with a 1 KROS chamber. The X-raygrams were taken by the back reflection method onto a flat casette. Exposures of specimens of the same alloy which had sustained various numbers of cycles were made consecutively on a single film.

Flat specimens of alloy ÉI602 fatigue tested under asymmetrical tension conditions at 700, 800 and 850°C were X-rayed in the maximum stress zone and near the grips where the stresses were about half of the maximum.

Cylindrical specimens of alloy ÉI437B tested at 750°C in rotary [beam] bending (alternating stress) were cut prior to X-ray diffraction along an axial plane, the distorted layer in the plane of cut was carefully etched off and the photographs were taken from points which received different stress levels during the test, i.e. in the minimum section center and at its periphery.

The microhardness of the aluminum specimens did not change with increasing numbers of cycles; in copper and duralumin at 20°C, the microhardness first increased with progressive cycling and then gradually fell. The microhardness of the bronze and brass specimens increased under these conditions but the rate of increase tapered off later.

Testing of copper and the copper alloys did at 600°C not produce microhardness changes. Hence, work-hardening caused by cyclic straining is removed at 600°C.

Several extensometer diagrams of D16 specimens cyclically bent at 20 and 300°C are seen in Fig. 2. The strength of the specimens tested at 20°C was higher than at 300°C. Due to the reduced strength, the total failure energy of a specimen subjected to 1000 bending cycles prior to the tensile test was much less than that required to break specimens which suffered a lesser number of cycles. The same is true of copper, Fig. 2, a. The fracture work was less after 1000 cycles than after a single cycle.

A certain increase in ductility was observed in bronze specimens prepared from work-hardened sheet, Fig. 2, b. The fracture work decreased slightly with increasing cycling on account of a lower fracture load but not because of a loss of ductility.

Tension test results on aluminum and duralumin specimens which underwent various numbers of cycles at 200 and 300°C are summarized in Fig. 3. With increasing cycling at 20°C, the strength of commercial aluminum first increased and then decreased significantly. The strength of duralumin showed a substantial increase with the number of cycles increasing from 1 to 1000 cycles.

In reversed bending tests at 300°C, the strength of aluminum decreased continually while that of duralumin reached a maximum after 100 cycles whereupon it fell below its initial value.

The strength of annealed copper cycled at 20°C did not change with the number of cycles while that of brass increased. Work-hardened bronze gradually softened with increasing number of cycles. In reversed bending tests at 600°C the strength of copper and of the work-hardened bronze fell somewhat while in brass it reached a maximum after 10 cycles and then decreased.

An analysis of Figs. 3 and 4 indicates that if the cyclic deformation of the soft metals and alloys takes place at room temperatures, then they are first strengthened and then again weakened with increasing number of cycles. The cold-worked alloy softens continuously with increasing cycling.

When cyclic straining of the annealed metals is conducted at recovery temperatures, no increase of tensile strength with increasing cycling is observed. At elevated temperatures the strength of the alloys changes with cycling in the same manner as the strength of unalloyed metals at room temperature.

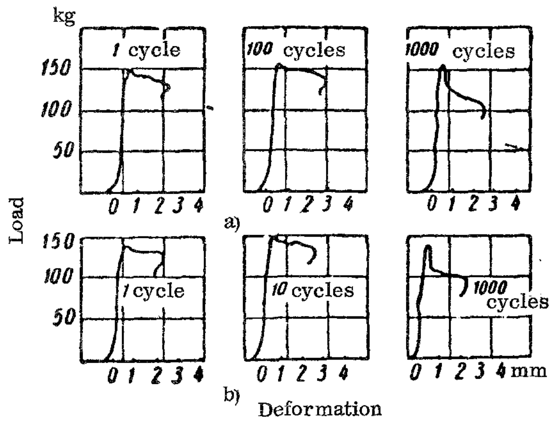

Fig. 1. Extension records of alloy D16: a - reversed bending at 20°C, b - at 300°C.

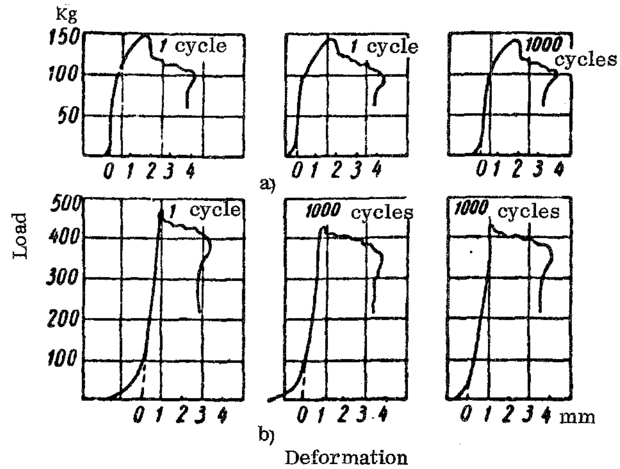

Fig. 2. Extension records of specimens subjected to plastic bending at 20°C: a - copper, b - work-hardened bronze.

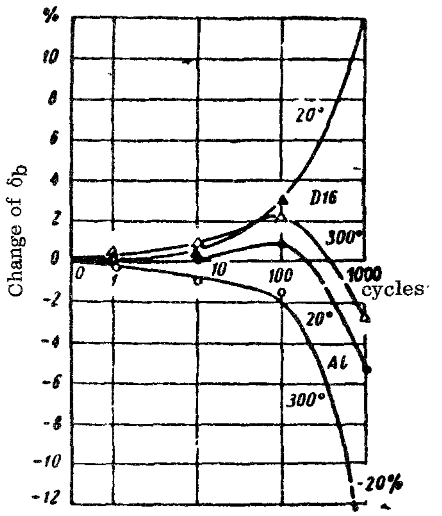

Fig. 3. Relative change of tensile strength of Al and duralumin depending on number of cycles and test temperature.

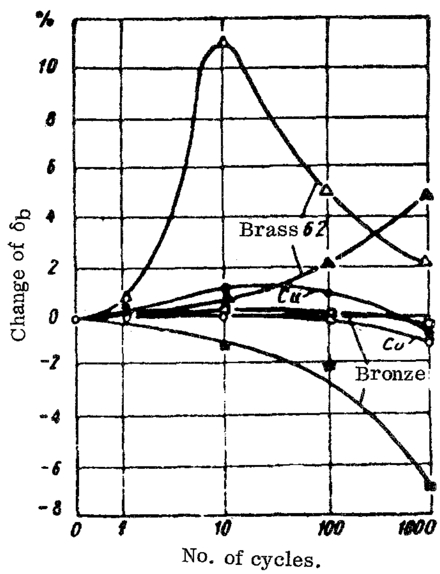

Fig. 4. Relative changes of tensile strength of copper, brass and bronze with cycling and test temperature (solid points - reversed bend tests at 20°C, open points - at 600°C).

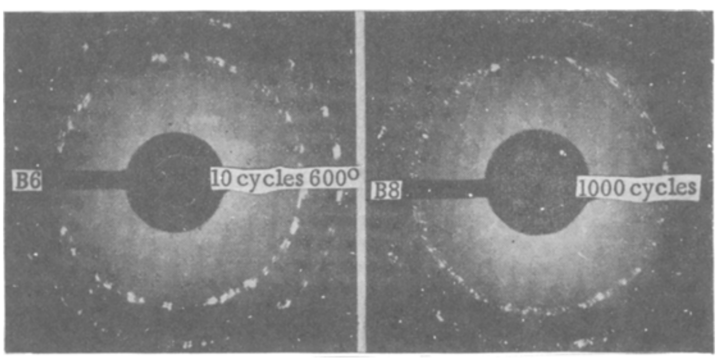

Fig. 5. X-raygrams of bronze specimens after cyclic testing at 600°C: a - 10 cycles, b - 1000 cycles.

X-raygrams taken after 1000 bending cycles on specimens at room temperature differ considerably from those after fewer cycles. After 1000 cycles the spots are diffuse mainly in the tangential direction and almost continuous Debye rings are seen. The intensity of the spots decreases. When the tests on the bronze were run at 600°C (Fig. 5) the interference spots did not become blurred with increasing cycling but the number of spots increased on account of the decreased size of each of them. The increasing number of interference spots is apparently connected with grain refinement and the absence of diffuseness indicates relief of stresses due to recovery at the test temperature which is about 0.7 T(melting).

In X-raygrams made on a rotating film the interference spots form continuous lines. The line width and intensity were evaluated on a microphotometer MF-4. Analysis of the X-raygrams showed that when the cyclic bend tests on bronze and brass are conducted at 20°C, the width of the interference line increases with number of cycles, reaches a maximum after 100 cycles and then decreases somewhat. The integral intensity of blackening of the lines decreases as cycling progresses.

Prior to taking X-ray photographs of the heat-resistant alloy ÉI602 tested in (asymmetric) cyclic tension at 700, 800 and 850°C, the oxide layer was removed by etching in a mixture of hydrochloric and sulphuric acids with addition of copper sulphide. The X-raygrams were then taken upon a flat rotating casette using a tube with a copper anode. Six X-raygrams of three specimens under a reflection angle 74° were taken on each film. Reflections from the (024) plane were photometered. Those near the fracture area were more diffuse in all cases.

At 700, 800 and especially at 850°C, the second-order stresses cannot be significant since the elastic distortions are removed by recovery and incipient recrystallization. The most probable cause of line broadening must be grain refinement and disorientation of the subgrains.

A comparison of the interference lines obtained from specimens tested at various stress amplitudes but at identical test periods showed that the higher the cycle amplitude, the more pronounced is the diffuseness. Since the degree of block disorientation depends directly on the amount of shear, the degree of line diffuseness can be related to the degree of subgrain disorientation.

The reduced intensity of the interference line in the plastic deformation zone is caused by defects appearing on the slip planes; they represent submicroscopic pores, with their number increasing with increasing plastic strain.

X-raygrams were also taken from cylindrical ÉI437B alloy specimens after rotary bending fatigue tests at 750°C. The shots were taken at the neck periphery, neck center, and the center of the specimen head. At the neck periphery, where the bending stresses were highest, the reflection lines were utterly diffuse. The diffuseness was somewhat less marked in the central zone of the neck. In the center of the specimen head which did not suffer any cyclic strains, the doublet was very well defined. Photometric evaluation showed that the blackening intensity decreased considerably in the area of maximum stresses. In the center zone of the neck, the blackening was more pronounced and the doublet was less diffuse. At the center of clamping, where the cyclic strains were nil, the doublet was perfectly well defined.

It was of interest to follow the kinetics of restoration of reflection line intensity and the decrease of diffuseness during an additional heating of the specimens without stressing. For this purpose, specimens of alloy ÉI437B were X-rayed before and after vacuum heating at 750, 800, 850, 900, 950 and 1080°C for 4-16 hrs.

Holding at 750°C for 16 hrs or at 800-950 C/4 hrs had no effect at all on the X-ray lines. Such a high stability of line blurring indicated that during cyclic straining of this alloy certain irreversible changes took place in the crystal lattice. Evidently these changes could not be removed by annealing. On the other hand, if precipitation of secondary phases were the cause of reduced intensity and line broadening, the latter should have been removed by soaking at 950 to 1080°C. This was not observed. Consequently, the cause of the reduced intensity and line broadening was the formation on the slip planes of sufficiently large defects which could not be eliminated even at the homogenizing temperature.

A study of fatigue of alloy ÉI437B at 750°C enabled defects on slip planes formed by cyclic stressing to be detected. They were very persistent and reduced the strength of the metal both at room and elevated temperatures. Actually the degree of fatigue of the alloy at recovery temperatures was higher than at room temperature, since at these temperatures there was no strain-hardening during cyclic stressing.

CONCLUSIONS

1. The strength of metals and alloys after cyclic straining does not vary consistently. Commercially pure aluminum, and copper in part, at first hardened somewhat whereupon they softened again with further cycling. Annealed duralumin and brass showed gains of strength with increasing number of cycles. Cold-worked bronze softened during cyclic stressing.

2. The strength of alloys cyclically strained at their recovery temperatures varies in the same manner as in commercially pure metals.

3. Certain irreversible processes of deterioration ("loosening") on the slip planes affect the strength changes of metals with increasing number of cycles in alternating plastic bending. The deterioration process can be retarded by initial work-hardening only at temperatures at which recovery, and especially recrystallization, are not operating.

4. Crystal structure defects which develop at a certain stage of cyclic straining cannot be removed by annealing. This is the main difference between the effects of multiple and single plastic deformation on an alloy.