Change of the Elastic Limit of an Aluminium Rod by Cooling and by Annealing

By

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Abstract

When a commercial aluminium rod cooled by liquid air for a certain time is annealed at various temperatures for various durations of time, the elastic limit of the rod changes variously. After cooling of the rod, the annealing is started from three points: (1) a point of the increase of elastic limit by cooling, (2) the point of the maximum increase and (3) the point of the decrease giving the same value as the point of the increase. In the three above cases, the elastic limit changes in the similar manner under the same annealing temperature. Furthermore it is seen that the cases (2) and (3) show in general almost the same maximum point.

Experimental Procedure

A commercial cold worked aluminium wire about 2 mm. in diameter was cut into pieces about 20 cm. in length, and the pieces were made straight by hammering on a flat iron plate with a wooden hammer. A number of such rods were plunged into an electric furnace heated to about 420°C and were annealed for about 6 hours; then they were taken out of the furnace and cooled quickly to the room temperature. This is the initial state in the present experiment.

The diameter of the rod was measured at several different points with a micrometer screw gauge, and from the average value the initial cross-sectional area of the rod was calculated. The measurement of the elongation was performed with the extensometer designed by the writer.[1] The relation between the stress per unit initial cross-sectional area and the elongation per unit length was shown by a curve, and then the elastic limit was determined by using the contact point finder reported previously by the writer.[2] In the present experiment the following two processes were carried out.

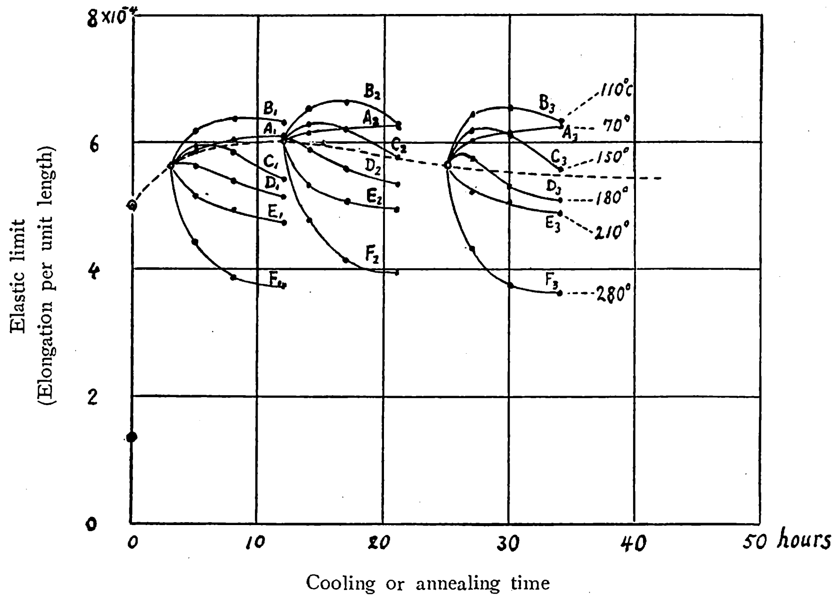
Experiment I. Many rods annealed in the furnace were elongated by about 5 % and formed the second state in the experiment. A

1. These Memoirs, A. **20**, 19 (1937).
2. These Memoirs, A. **20**, 27, (1937).

number of such rods were classified into several groups each consisting of two, and the elastic limit of one group was measured to begin with. The remaining groups were immersed in liquid air separately for various durations of time and taken out of the liquid air into the room where the elastic limits were measured. Then a curve showing the change of the elastic limit due to the cooling of various durations of time is denoted by a broken line in Fig. 1. On the curve the maximum point and two adequate points giving the same value of the elastic limit on both sides of the maximum were taken, and the cooling durations corresponding to the three points were read from the curve. The three points thus selected were made as the starting points of the following annealing process, which forms the third state in the experiment. In this way, 3, 12 and 25 hours of cooling were thus taken as these three starting points.

Many groups of the rods elongated by about 5 % were classified into three series each consisting of several groups. Then the groups belonging to each series were immersed in liquid air for the durations of time specified above, and taken out of the liquid air into the room where the elastic limit of each group was measured in order to ascertain whether they take the values obtained previously. The re-

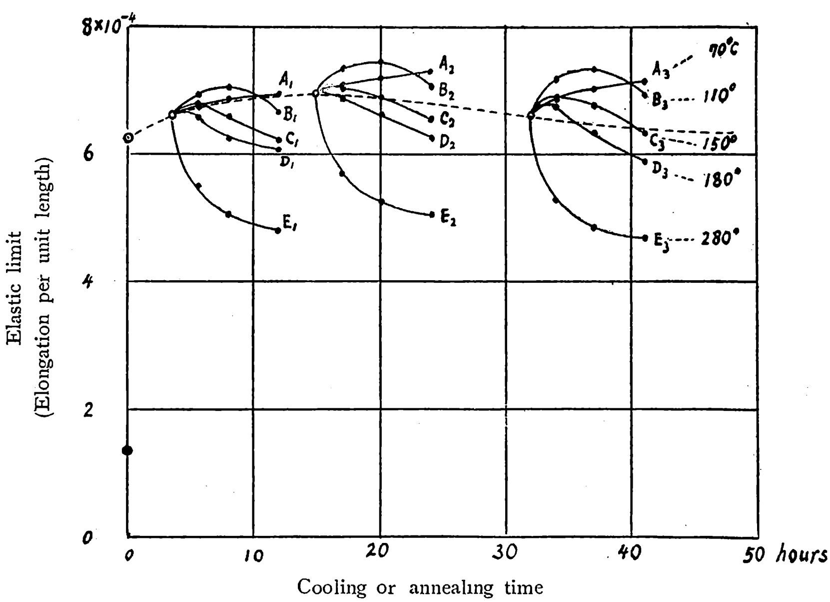
Fig. 1.



maining groups were then annealed in the furnace at various temperatures for various durations of time, and were taken out of the furnace into the room where the elastic limits were measured. The results are shown in Fig. 1.

Experiment II. The rods elongated by about 15 % instead of 5 % were used, and the same process as the above was performed. The results are given in Fig. 2.

Fig. 2.



Experimental Results

In Fig. 1 the elastic limit of the rod annealed at about 420°C for about 6 hours, in the so called initial state, is represented by a large dot, its ualue being 1.35×10^{-4}. The elastic limit at the start in the second state where the rod was next elongated by about 5 %, is represented by a circle having a central dot, its value being 5.02×10^{-4}. Further, the elastic limit attained by cooling for various durations of time is denoted by a broken line, and three small circles on it show the elastic limits selected as the starting points in the next annealing process; and the elastic limits obtained by annealing for different durations are represented by small dots. Curves A_1, A_2, A_3 etc. denote the results obtained with the same annealing temperatures.

The curves obtained with a same annealing temperature starting from three different points show the same tendency. The curves obtained with the annealing at relatively low temperatures go up rapidly at first to the maximum and then go down slowly, and the ones annealed at relatively high temperatures go down rapidly from the beginning of the annealing. Such a course is similar to the results obtained previously in the case of simple plastic elongation without cooling.[1]

In Fig. 2, a circle having a central dot represents the elastic limit of the rod elongated by about 15 % after first annealing, and the remaining marks have the same meanings as in Fig. 1. In the present case, as the cooling times for the start of the last annealig stage, which are represented by three small circles in the figure, 3.5, 15 and 32 hours are taken respectively. The form of the curves in this figure almost resembles to those in Fig. 1.

In these two figures, it is seen that the curves starting from the maximum point and from the decreasing point on the cooling curve reach almost the same maximum point in the annealing at relatively low temperatures, but the maximum point of the annealing curve starting from the point in the increasing stage of the cooling curve does not reach the above value, and is situated somewhat lower. When the annealing temperature is relatively high the curves go down from the beginning of annealing, and it is considered that, in the range of the present annealing time, the curve starting from the point in the increasing stage of the elastic limit in cooling and that starting from the point in the decreasing stage reach almost the same low value, but that the curve starting from the maximum point on the cooling curve does not reach the above value, and is situated somewhat higher.

Consideration on the Results of the Experiments

When a cold worked specimen is heated at approximately 420°C for about 6 hours, the crystallites grow considerably larger by recrystallization. In the case of aluminium the elastic limit of such a specimen decreases considerably as seen in Fig. 1, where the large dot denotes this state. If such a specimen is elongated plastically by stretching, the crystal grains are broken by slipping into smaller crystallites on the one hand; and, on the other hand, the localities of

1. These Memoirs, A. **22**, 195, (1939).

weak cohesion between crystallites and the unevenness of the internal stresses among crystallites will be formed in the structure at the same time. Of these two causes the former increases the elastic limit, and the latter decreases it; and as the former predominates in the case of aluminium at room temperature, the elastic limit increases even just after the plastic elongation. This state is shown by the mark ⊙ in Fig. 1.

When the specimen is suddenly immersed in liquid air, it contracts strongly and unevenly. Consequently the crystallites are again broken rapidly into smaller pieces, and at the same time the localities of weak cohesion between crystallites and the unevenness of the internal stresses among crystallites are again formed in the structure. These two actions exert influence upon the elastic limit in the same manner as in the case of plastic elongation, and accordingly the sudden cooling to the temperature of liquid air increases the elastic limit in the beginning of the cooling. After a certain number of crystallites have been broken during the early period of cooling, the destruction of the crystallites will be almost stopped, but the weak cohesion between crystallites at some localities and the unevenness of the internal stresses among crystallites will be enhanced gradually with cooling time, by the lack of the recovery observed at higher temperatures; so that after a certain cooling time, the elastic limit decreases gradually with the cooling time. The change of elastic limit in this way has been reported in the previous paper,[1] and now it is seen clearly again by the broken lines in Figs. 1 and 2. The maximum points of such curves are considered to represent the state in which the destruction of crystallites has almost ceased.

When the specimen whose crystallities have been destroyed by cooling is heated at a certain temperature somewhat higher than the room temperature, the localities of weak cohesion between crystallites and the unevenness of the internal stresses among crystallites formed in the structure by cooling, recover gradually to the normal state by aging, and accordingly the elastic limit increases as seen by the curves B_S and C_S in Fig. 1 and 2. The maximum point and the point in the decreasing stage of the elastic limit in cooling are considered as the states in which crystal grains are broken up almost to the same degree. Thus when the specimens in such a state is annealed at a

1. These Memoirs, A. **23**. 337 (1941).

comparatively low temperature their elastic limits will be raised approxmately to the same value. This fact is seen by Curves B_2, B_3 and C_2, C_3 in Figs. 1 and 2. But a point in the increasing stage of elastic limit in cooling represents a state in which the degree of destruction of crystallites is smaller. Hence if such a specimen is heated at the same temperature as in the case mentioned above, its elastic limit does not reach the above value, but takes a somewhat smaller value as seen by curves B_1 and C_1 in Figs. 1 and 2.

When the specimens in the three states as described above are heated at a relatively high temperature, for example 280°C in the present case, the recrystallization occurs strongly and accordingly the elastic limit decreases rapidly from the starting point. So far as the present experiment is concerned, it seems that the decreased elastic limit of the specimen starting from the maximum point in cooling remains somewhat higher than the others. Such a fact may be considered as follows : The specimen starting from the maximum point in cooling is in the state in which the destruction of crystallites is almost finished, the one starting from a point in the incerasing stage of the elastic limit in cooling is in the state in which relatively large crystal grains remain and the one starting from a point in the decreasing stage of the elastic limit in cooling is in the state in which the weak cohesions at some localities and the unevenness of the internal stresses are more pronounced than the one stating from the maximum point. These circumstances will exert influence upon the elastic limit by being superposed on the effect of recrystallization.

In looking over all the curves in two figures, the change of the elastic limit represented by the curves corresponding to the same annealing temperature in two cases behave almost similarly and the elastic limit is larger in the case of larger plastic elongation than in the other case. This is entirely similar to the results reported previously.[1]

In conclusion, the writer wishes to express his sincere thanks to Prof. U. Yoshida for his kind guidance in the present experiment.

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1. These Memoirs, A. 22, 195 (1939).