Change of the Elastic Limit of a Pure Aluminium Rod by Annealing

By

Miyabi Sugihara

(Received, August 27, 1942)

Abstract

A pure cold worked aluminium rod is heated at a certain temperature and elongated plastically beyond its elastic limit. When such a specimen is heated at various durations of time, the elastic limit increases in the beginning of the annealing time in the case of relatively low temperatures. Such a fact is entirely similar to that observed in the case of a commercial aluminium rod.

Experimental Method

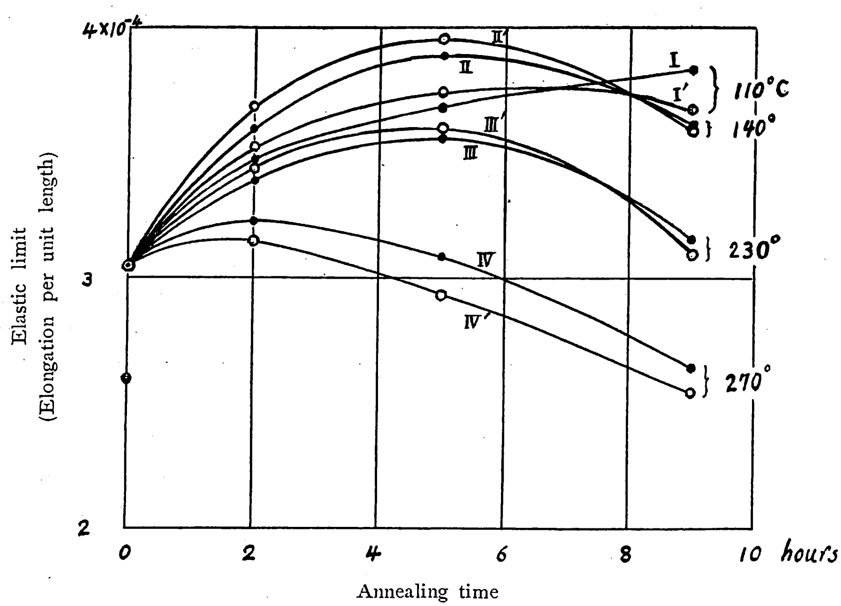
The present experiment was carried out in response to the kind suggestion of Dr. H. Hirata, who suspected the influence of some impurities contained in a commercial aluminium rod upon the elevation of elastic limit by annealing at relatively low temperatures, as was observed by a sudden cooling of the rod from a relatively high temperature to the room temperature.

The specimen of pure aluminium employed in the present experiment was of 99.996% purity. From a block of such aluminium, an adequate amount was cut off and hammered strongly into the shape af a rod from which the rod of the required size was obtained by drawing through dies: it was about 18 cm in length and about 2.6 mm in diameter. In the present experiment, the following six processes were made use of.

Experiment I. A number of such rods were put into an electric furnace heated previously to approximately 250°C and annealed for about 6 hours; then they were taken out of the furnace and cooled to the room temperature. This is the initial state in the present process. The diameter of such a rod was measured at several points with a micrometer screw gauge, and from the average value the initial cross-sectional area of the rod was calculated. The elongation testing of the rod was then performed with the extensometer designed by the writer.[1] From a curve representing the relation between the stress per unit initial cross-sectional area and the elongation per unit length, the elastic limit was determined by using the contact point finder reported by the writer previously.[2] In the present case the value 2.60×10^{-4} was obtained. When a rod in the initial state was loaded with about 21 kg, the maximum elongation of the rod became 6.32×10^{-4}, and accordingly the amount of plastic elongation was 3.72×10^{-4}. This is the second state in the present process.

A number of rods in the second state were classified into several groups each consisting of two and the elastic limit of one group was measured, its value being found to be 3.05×10^{-4}. The remaining groups were divided into two series and both series were put into an electric furnace heated previously to various temperatures and annealed for various durations of time. One series was taken suddenly out of the furnace to the room temperature, and thus suddenly cooled; and the other was cooled gradually in the furnace by cutting the electric current. The elastic limits of the rods thus prepared were measured and the results are shown in Fig. 1.

Fig. 1

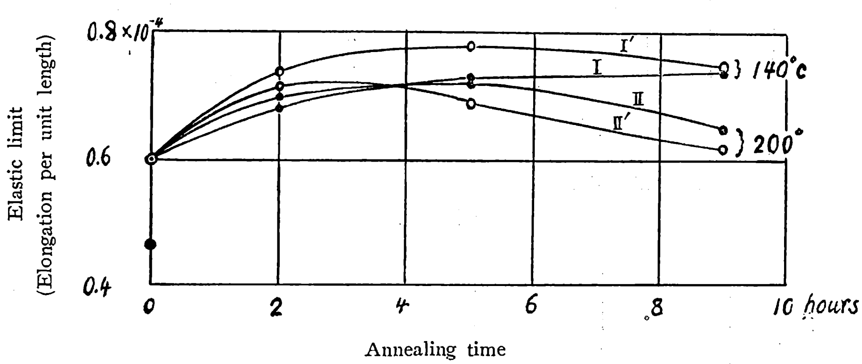


1. These Memoirs, A. **20**, 19, (1937).
2. These Memoirs, A. **20**, 27, (1937).

Experiment II. The rods employed in Process I were drawn through dies and were made somewhat smaller. A number of such rods were heated in the electric furnace at about 470°C for about 6 hours, and then they were taken out of the furnace to the room temperature. The elastic limit of the rod was measured as in Process I, its value being 0.46×10^{-4}. This is the initial state in this second process. When the rod in such a state was loaded with about 4 kg, the maximum elongation was 3.22×10^{-4}, and accordingly the amount of plastic elongation was 2.76×10^{-4}.

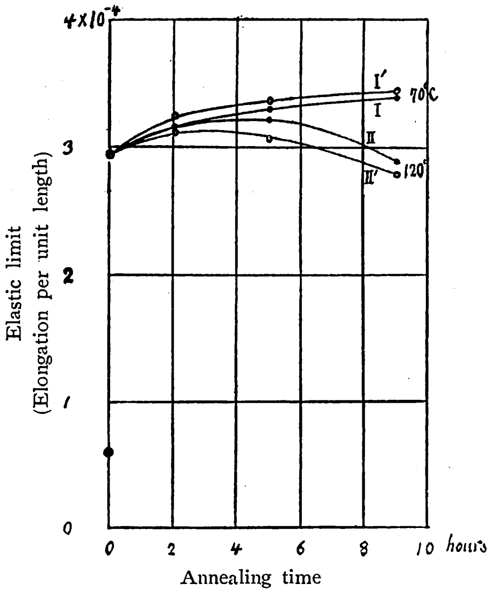
A number of such loaded rods were classified into several groups each consisting of two and the elastic limit of one group was measured and found to be 0.60×10^{-4}. The remaining groups were annealed at various temperatures for various durations of time as in the case of Process I. The results are shown in Fig. 2.

Fig. 2.



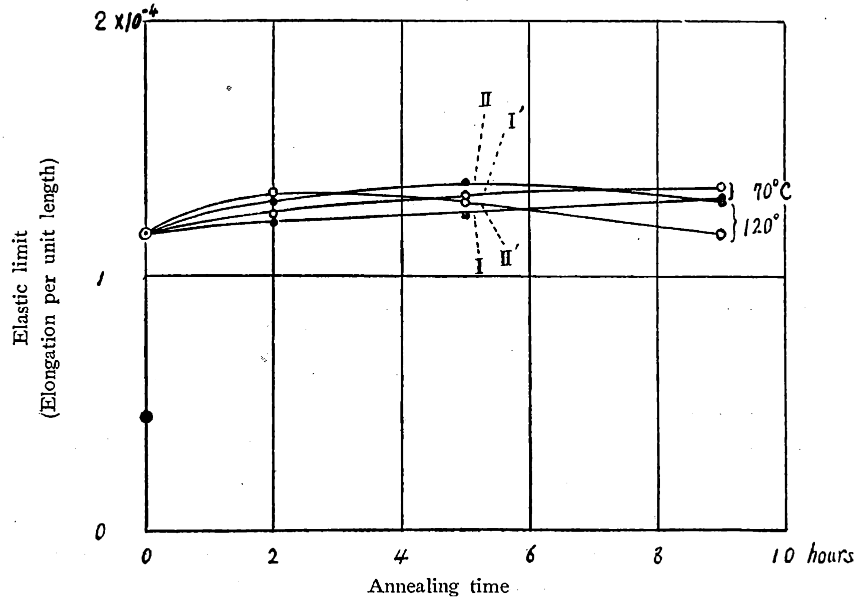
Experiment III. The rods used in Process I were drawn through dies as described in Process II. A number of such rods were heated in the furnace at about 330°C for about 6 hours, and then they were taken out of the furnace to the room temperature. The elastic limit of the rod was measured as mentioned above, its value being 0.61×10^{-4}. This is the initial state in this third process. The rod in such a state was elongated plastically by about 5 %, and the elastic limit of the rod was measured, its value being 2.95×10^{-4}. This forms the second state in the present case. A number of such rods were classified into several groups each consisting of two and annealed in the furnace at various temperatures for various durations of time. Then one half of the groups were subjected to the sudden cooling and the remaining half to the gradual cooling from the temperature of the furnace to the room temperature. The elastic limits of the rods thus prepared were measurad in the same manner as mentioned above, and the results are shown in Fig. 3.

Fig. 3.



Experiment IV. The rods used in Process II were again drawn through dies to somewhat smaller size. A number of such rods were annealed in the furnace at about 450°C for about 6 hours, and were taken out of the furnace to the room temperature. The elastic limit of such a rod was measured and the value 0.45×10^{-4} was obtained. This is the initial state in this fourth process. The rod in that state was plastically elongated by about 1 % and its elastic limit became 1.17×10^{-4}. This is

Fig. 4.



the second state in the present case. A number of such rods were annealed and then cooled in the same manner as in the case of Process III. The results are given in Fig. 4.

Experiment V. In order to compare the results obtained from pure aluminium rods in Processes I and II with those from commercial aluminium, a commercial cold worked aluminium rod of about 3 mm in diameter and about 18 cm in length was used in this fifth process. Many rods were annealed in the electric furnace at about 500°C for about 6 hours and were taken out of the furnace to the room temperature. The elastic limit of such a rod was measured, and was found to be 2.00×10^{-4}. This is the initial state in this fifth process. When the rod was loaded with about 16 kg its maximum elongation was 4.07×10^{-4}, and accordingly the amount of plastical elongation was 2.07×10^{-4}. This is the second state. A number of rods in this state were annealed and then cooled in the same manner as in the process

Fig. 5.

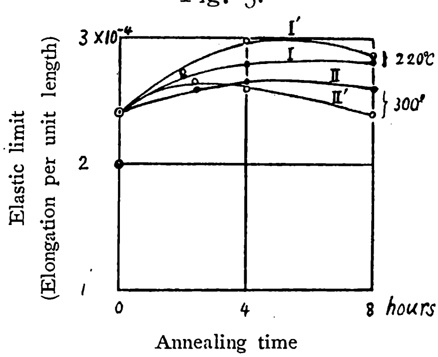
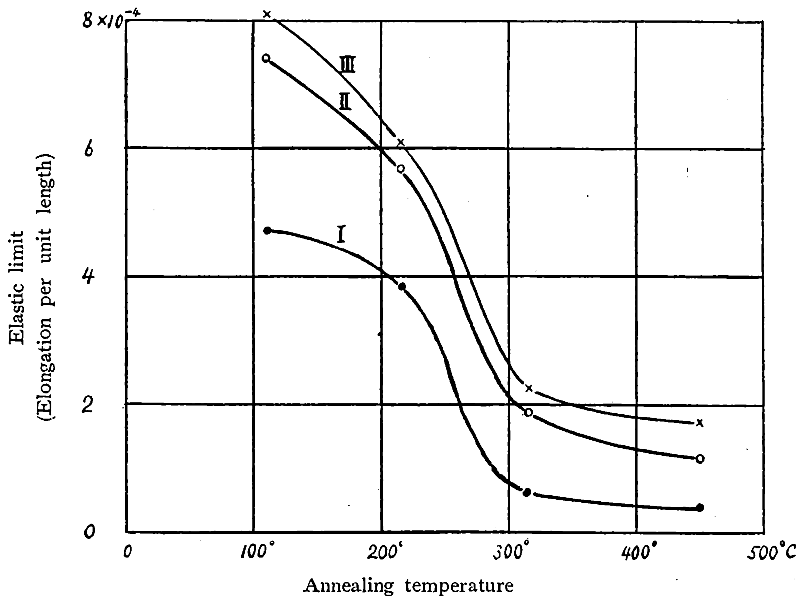


Fig. 6.

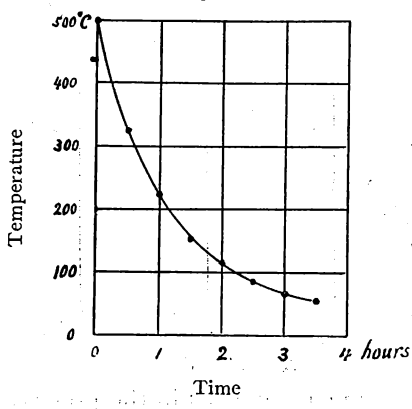


mentioned previously. The results are shown in Fig. 5.

Experiment VI. It is considered that the quality and state of an aluminium rod exert an influence more or less upon the elastic limit, so in the present process a simple experiment was made as follows: A pure aluminium rod used in the previous experiment was drawn through dies. Such a rod and other two kinds of commercial cold worked aluminium rods were used in the present case. The above three kinds of rods were annealed together in the electric furnace at various temperatures for a certain length of time, and were taken out of the furnace to the room temperature. The elastic limits of each kind of rods were measured and the results are shown in Fig. 6.

Fig. 7.

Room temperature 20°C



Further, the relation between the decrease of temperature of the furnace and the cooling time elapsing after the cutting of the electric current is given in Fig. 7.

Experimental Results

In Fig. 1 the elastic limit of the rod in the initial state is represented by a large dot and that in the second state by a circle with a central dot. The small dots and small circles represent respectively the elastic limits of the annealed rods cooled suddenly and cooled gradually. The annealing temperatures are noted at the ends of the curves.

When the annealing temperatures are relatively low as in the present case, all curves go up from the starting point, and then go down except the curve I after passing through the maximum points. In the early period of annealing time, Curves I′, II′ and III′ for gradual cooling lie somewhat higher than Curves I, II and III for sudden cooling.

In Figs. 2, 3, 4 and 5, it is seen that the tendency of the curves are similar in general to that shown in Fig. 1. In Fig. 6, Curves I, II and III represent, as is previously mentioned, the results obtained in the case of pure aluminium rods and two other kinds of commercial ones respectively. In Fig. 7, the cooling curve is plotted to show the rate of cooling in the furnace.

Consideration on the Results of the Experiment

When the specimen is annealed at about 250°C for about 6 hours, the crystal grains grow somewhat larger and the elastic limit decreases. If such a specimen is elongated plastically, the crystal grains will be broken into smaller pieces and accordingly the elastic limit of the specimen will increase. These facts are seen from the positions of the large dot and of the circle with a central dot in Fig. 1. When the specimen in such a second state is annealed at relatively low temperature, for example 140°—230°C, the localities of weak cohesion between crystallites and the unevenness of internal stresses among crystallites formed in the structure by plastical elongation, return to their normal states on the one hand; and on the other hand the crystallites grow larger by recrystallization at the same time. The former increases the elastic limit of the specimen and the latter decreases it. As the result of the superposition of such two actions, the elastic limit of the specimen increases in the beginning of annealing time, reaches the maximum value and then decreases.

It is seen from Curves II, II′ and III, III′ in Fig. 1 that the elastic limit in gradual cooling in somewhat higher than that in sudden cooling in early period of annealing time. This fact is understood by considering that the duration of recovery to the normal state is somewhat longer in the case of gradual cooling, as it takes very long time for the furnace to cool to the room temperature. On the contrary, when the annealing temperature is relatively high, for example 270°C, the elastic limit by gradual cooling becomes somewhat lower than that in sudden cooling from the beginning of annealing time. This fact is explained as follows: At such a temperature as 270°C, the effect of crystal growth by recrystallization and consequently the lowering of the elastic limit predominates over the effect of the recovery during the cooling period in the case of gradual cooling.

The specimen used in Process II is first annealed at a relatively high temperature of 470°C. When such a specimen is treated in the same manner as described above, the results, as shown in Fig. 2, are almost similar to those mentioned above in the case of Fig. 1. In Figs. 3 and 4, the results obtained by giving relatively large plastical elongations after the first annealing are represented, and they are almost similar essentially to the previous cases.

In Fig. 5, the results obtained by treating the commercial aluminium rod in the same why as Processes I and II with pure aluminium are shown, and the tendency of the curves is seen also to be almost the same as in Figs. 1 and 2.

As is seen in Fig. 6, even if the annealing temperature and annealing time are the same, the latter being about 6 hours in the present case, a pure aluminium rod and a commercial rod give different elastic limits, and the value of the former is always smaller than the latter. This effect may be ascribed partly at least to the easiness of the grystal growth by recrystallization with pure aluminium.

In the present experiment Young's modulus of pure aluminium rod was also obtained in the elongation testing, and it was found that it remained the same and had the value of 6.66×10^{11} dynes per square centimeter at room temperature irrespectively of the value of the elastic limit. This fact is entirely the same as with commercial aluminium rod. Young's modulus of commercial aluminium rod is 6.75×10^{11} dynes per square centimeter. Thus the value of pure aluminium rod is somewhat smaller than that of the commercial one.

In looking over the results obtained with present experiments, it is seen that a pure aluminium rod show approximately the same tendency in its elastic property as commmercial ones used here and previously.[1] Even if the presence of some impurities in the commercial aluminium rod may exert an influence upon its elastic limit to some degree, such an influence is considered to be relatively slight.

In conclusion, the writer wishes to express his sincere thanks to Prof. U. Yoshida for his king guidance and to Dr. H. Hirata for his kind criticisms and suggestions given throughout the present research.

1. These Memoirs, A. **21**, 154 (1938).
These Memoirs, A. **22**, 195 (1939).