Change of the Elastic Limit of an Aluminium Rod by Annealing

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Abstract

In Part I, a cold-worked aluminium rod was heated in an electric furnace, and then cooled suddenly to the room temperature. The change of the elastic limit of such a rod was measured. The elastic limit decreases with the increase of the annealing temperature and the annealing time.

In Part II, the plastic elongation of an annealed aluminium rod and its elastic limit were measured repeatedly after a lapse of certain time intervals. It is observed that the elastic property is recovered, and after the lapse of a certain time its elastic limit becomes somewhat larger than the initial one.

In Part III, a cold-worked aluminium rod was annealed, was elongated plastically beyond its elastic limit, and was annealed again for various durations of time at various temperatures. The elastic limit of the rods thus obtained was examined. When the second annealing temperature is comparatively low, the elastic limit of the rod increases at the beginning of the annealing time, and in some cases it reaches a maximum. This increase of the elastic limit by weak annealing was ascribed to the recovery of the spots of weak cohesion between atoms, which were formed by the previous plastic deformation.

Part I. Cold-worked aluminium rod

Experimental method

A commercial cold-worked aluminium wire about 3 mm. in diameter was cut off about 20 cm. in length, and the rod was made straight by hammering on a plane iron plate with a wooden hammer. Several groups of such rods, each group consisting of four, were prepared.

A small porcelain tube, inserted in the middle of a porcelain tube of an electric furnace of a resistance type, was made movable in its axial direction. One of the above-mentioned groups of rods was inserted into the inner tube of the furnace, whose temperature was raised previously to a certain point, and after being annealed for a certain time it was taken out of the tube, and then cooled to the room temperature. By the same method, every group was annealed separately for various durations of time at various annealing temperatures.

The diameter of the rod was measured at its several points with a micrometer screw guage, and from the average value the initial cross-sectional area of the rod was calculated. Next by the extensometer designed previously by the writer,[1] the elongation of the rod and the load applied to it were measured. The stress per unit initial cross sectional area was obtained by dividing the load by the initial area, and the elongation per unit length was calculated by using the constant of that extensometer. Thus a curve was drawn to show the relation existing in both quantities, and by using the contact point finder reported previously by the writer,[2] the elastic limit was determined. The values of the elastic limits of the four rods annealed under the same conditions are shown in Table I_1 as an example.

Experimental results

In the case of the annealing temperature of about 45°C, eight groups were used, one of which was heated for one week. The result

Table I_1

Annealing temperature 350°C Annealing time 4 hours

Specimen No.	Elastic limit: Stress per unit area	Elastic limit: Elongation per unit length	Young's modulus in C. G. S. unit
1	230 $\frac{kg}{cm^2}$	3.34×10^{-4}	6.75×10^{11}
2	228 ,,	3.35 ,,	6.67 ,,
3	232 ,,	3.35 ,,	6.79 ,,
4	226 ,,	3.32 ,,	6.67 ,,
Average	229 ,,	3.34 ,,	6.72 ,,

Table I_2

Annealing temperature 45°C

Specimen Group No.	Duration of annealing time	Elastic limit: Stress per unit area	Elastic limit: Elongation per unit length	Young's modulus in C. G. S. unit
1	1 hour	605 $\frac{kg}{cm^2}$	8.83×10^{-4}	6.71×10^{11}
2	4 ,,	613 ,,	8.93 ,,	6.73 ,,
3	7 ,,	608 ,,	8.85 ,,	6.73 ,,
4	13 ,,	608 ,,	8.90 ,,	6.69 ,,
5	20 ,,	600 ,,	8.79 ,,	6.69 ,,
6	30 ,,	605 ,,	8.83 ,,	6.71 ,,
7	48 ,,	608 ,,	8.86 ,,	6.73 ,,
8	1 week	608 ,,	8.88 ,,	6.71 ,,

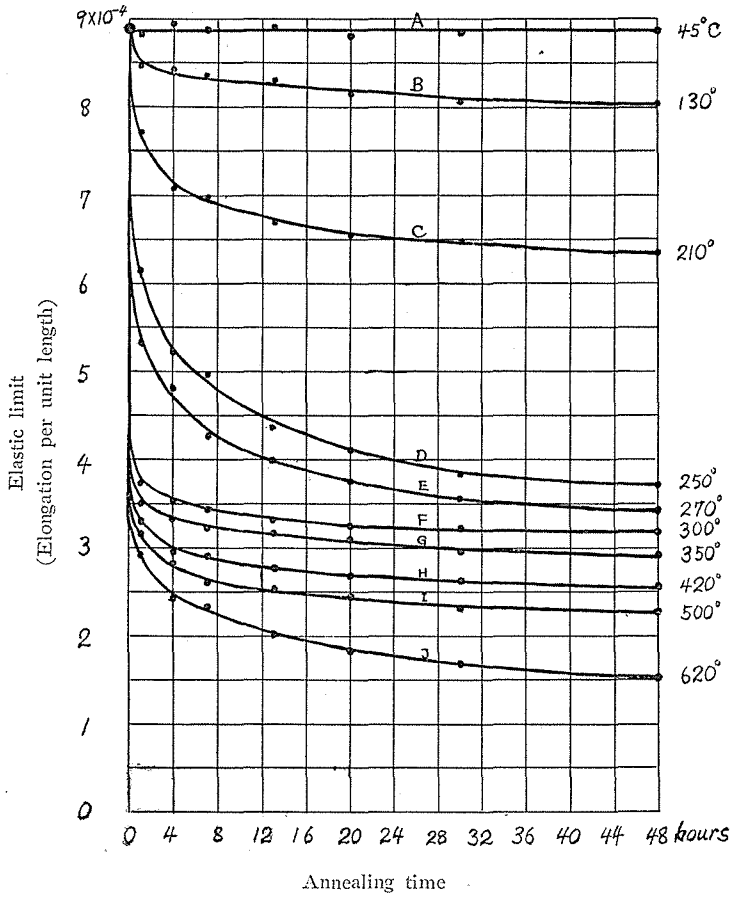
1. These Memoirs, A. **20**, 19 (1937). 2. These Memoirs, A. **20**, 27 (1937).

Table I_3

Annealing temperature 130°C

Specimen Group No.	Duration of annealing time	Elastic limit: Stress per unit area	Elastic limit: Elongation per unit length	Young's modulus in C. G. S. unit
1	1 hour	581 $\frac{kg}{cm^2}$	8.47×10^{-4}	6.72×11^{11}
2	4 ,,	577 ,,	8.43 ,,	6.71 ,,
3	7 ,,	575 ,,	8.35 ,,	6.73 ,,
4	13 ,,	568 ,,	8.31 ,,	6.70 ,,
5	20 ,,	559 ,,	8.15 ,,	6.72 ,,
6	30 ,,	555 ,,	8.07 ,,	6.74 ,,
7	48 ,,	551 ,,	8.06 ,,	6.70 ,,

Fig. I_1



is shown in Table I_2. With various annealing temperatures, the same experiment was performed. The result obtained at the annealing temperature of about 130°C is shown in Table I_3 as an example.

The results obtained at various annealing temperatures are denoted by the curves drawn in Fig. 1_1. In drawing the curves, the elongation per unit length, instead of the stress per unit cross sectional area, is accepted as the elastic limit. The stress per unit area at the elastic limit varies with the Young's modulus and with the elastic limit represented by the elongation per unit length. As the writer has shown previously, the Young's moduli of aluminium have the same value independent of the crystal size[1], and the stress per unit area increases proportionally with the elongation per unit length. But in understanding physically the elastic property of a metal the elongation per unit length indicates the elastic limit more directly and much more clearly than does the stress per unit area.

The value of 8.88×10^{-4} obtained previously[2] as the elastic limit of the commercial cold-worked aluminium rod without any heat treatment is used as the starting point in these curves, and is denoted by a large dot in the figure.

Curve A in this figure is of the annealing temperature about 45°C. It is seen from the curve, that at such a low temperature the elastic limit does not change with the annealing time. The elastic limit of the rod annealed for one week at 45°C is given in Table I_2, and no difference in its value is detected.

Curve B is of the annealing temperature about 130°C. The elastic limit is somewhat affected by the annealing temperature, and it decreases rapidly at first and then slowly with the annealing time.

As is seen from the curves C to J, whose annealing temperatures are respectively written in the figure, the elastic limit decreases rapidly at first and then slowly with the annealing time, and it decreases also with higher annealing temperature.

It is seen from the curves D and E, that the elastic limit decreases very rapidly when the annealing temperature is in the vicinity of 250°C or 270°C. This fact is considered to be due to the recrystallization which begins to occur considerably at about this annealing temperature.

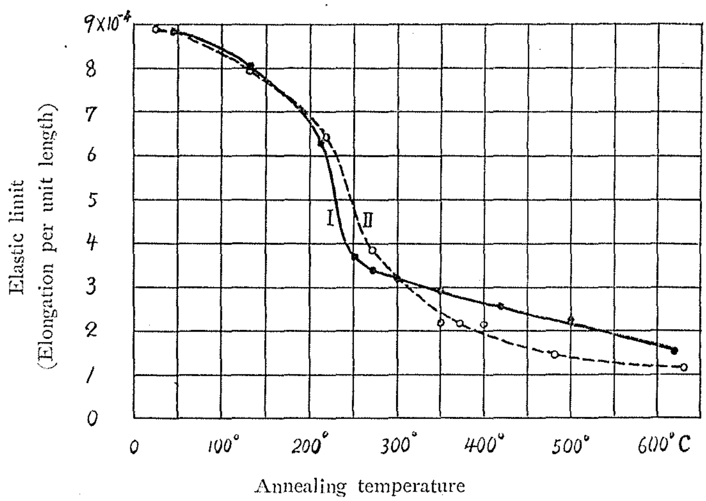
Curve F is of the annealing temperature about 300°C. The elastic limit decreases very rapidly in about one hour and after that gradually.

1. These Memoirs, A. **17**, 389 (1934).
2. „ „ A. **20**, 27 (1937).

Curves G, H, I and J whose annealing temperatures are written respectively in this figure, show the same tendency as curve F. These facts seem to indicate that, at annealing temperatures higher than 300°C, recrystallization occurs very rapidly in the beginning of the annealing time.

In the case of gradual heating and gradual cooling, the relation between the elastic limit and the annealing temperature was previously obtained for annealing time of 48 hours[1]. For the sake of comparison with the present experiment, where the heating and the cooling of the specimen were made rather suddenly, the relation between the elastic limit and the annealing temperature for the annealing time of 48 hours is represented in Fig. 12.

Fig. 12



In this figure, Curve I drawn in a continuous line, denotes the present result. It is seen from this curve, that the elastic limit decreases very slowly at first to about 200°C, and then rapidly to about 270°C, and again slowly to about 620°C.

In order to compare the present result with the previous one, Curve II in the figure which is drawn as a broken line, is replotted in the same scale as Curve I. Both curves show generally the same tendency. However entering into details, the elastic limit in the case of sudden heating and sudden cooling almost coincides with that in the

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

case of gradual heating and gradual cooling from the beginning to about 200°C, and then the former becomes somewhat smaller than the latter from about 200°C to about 300°C, and thereafter the former becomes larger than the latter. This seems to be due to the fact that the size of a crystal produced by recrystallization in sudden heating is smaller than that in gradual heating as was shown by the experiment made by Yoshida, Nagata and Mitsuki[1].

Part II. Plastic elongation and the elastic limit

Experimental method

Aluminium rods having the same size as in Part I were prepared in the same manner as before. Such a rod was inserted in an electric furnace whose temperature was previously raised to about 500°C, and after 30 hours it was taken out of the furnace and cooled suddenly to the room temperature. By the extensometer indicated in Part I, the rod was elongated plastically beyond its elastic limit, and the value of the elastic limit as well as the value of the plastic elongation was measured. The same rod was plastically elongated repeatedly at regular intervals, and at each time the maximum elongation, the elastic limit and the plastic elongation were measured. These results are shown in Table II_1. The plastic elongation above-mentioned is the quantity obtained by subtracting the elastic limit from the maximum elongation at that time.

Table II_1

Annealing temperature 500°C Annealing time 30 hours

No.	Successive interval	Elastic limit		Maximum elongation per unit length	Young's modulus in C. G. S. unit	Successive excess of elastic limit	Plastic elongation per unit length
		Stress per unit area	Elongation per unit length				
1		160 $\frac{kg}{cm^2}$	2.31×10^{-4}	4.01×10^{-4}	6.79×10^{11}		1.70×10^{-4}
2	15 minutes	196 ,,	2.84 ,,	4.03 ,,	6.76 ,,	0.53×10^{-4}	1.19 ,,
3	15 ,,	212 ,,	3.10 ,,	4.55 ,,	6.70 ,,	0.26 ,,	1.45 ,,
4	4 hours	208 ,,	3.05 ,,	5.46 ,,	6.68 ,,	−0.05 ,,	2.41 ,,
5	24 ,,	230 ,,	3.32 ,,	5.08 ,,	6.79 ,,	0.27 ,,	1.76 ,,
6	24 ,,	240 ,,	3.48 ,,	5.90 ,,	6.76 ,,	0.16 ,,	2.42 ,,
7	24 ,,	254 ,,	3.71 ,,	5.07 ,,	6.71 ,,	0.23 ,,	1.36 ,,

1. These Memoirs, A, **19**, 169 (1936).

After eight new aluminium rods were annealed at about 480°C for 30 hours as above described, their elastic limits, maximum elongations and plastic elongations were measured respectively, and the average was taken. All the rods were then classified into two sets each consisting of four rods. The elastic limits of the rods belonging to the first set were measured after one day, and the other after twelve days. The average of each set was taken. Here it must be noted that in the present experiment the maximum elongations of the rods belonging to the same set were so adjusted that they were nearly the same. Otherwise the average is meaningless.

Another group of twelve new rods was annealed for 30 hours at about 620°C. Their elastic limits, maximum elongations and their plastic elongations were measured respectively, and the average was taken. These rods were classified into three sets each consisting of four rods. The elongation-testings for three sets were made after two days, nine days and sixteen days respectively. The average of the elastic limits

Table II_2

Annealing time 30 hours

Specimen Group No.	Annealing temperature	Interval	Elastic limit: Stress per unit area	Elastic limit: Elongation per unit length	Maximum elongation per unit length	Young's modulus in C. G. S. unit	Excess of elongation per unit length	Plastic elongation per unit length
			166 $\frac{kg}{cm^2}$	2.42×10^{-4}	4.58×10^{-4}	6.72×10^{11}		2.16×10^{-4}
1	480°C	1 days	211 ,,	3.05 ,,		6.78 ,,	0.63×10^{-4}	
		12 ,,	212 ,,	3.06 ,,		6.78 ,,	0.64 ,,	
			115 ,,	1.68 ,,	4.54 ,,	6.71 ,,		2.86 ,,
2	620°C	2 days	162 ,,	2.35 ,,		6.76 ,,	0.67 ,,	
		9 ,,	160 ,,	2.33 ,,		6.73 ,,	0.65 ,,	
		16 ,,	166 ,,	2.41 ,,		6.75 ,,	0.73 ,,	

Table II_3

First annealing temperature 610°C, second annealing temperature 45°C

Specimen Group No.	Duration of annealing time	Elastic limit: Stress per unit area	Elastic limit: Elongation per unit length	Young's modulus in C. G. S. unit
1		117 $\frac{kg}{cm^2}$	1.70×10^{-4}	6.78×10^{11}
2	13 hours	120 $\frac{kg}{cm^2}$	1.75×10^{-4}	6.72×10^{11}
3	48 ,,	122 ,,	1.77 ,,	6.75 ,,
4	1 week	130 ,,	1.88 ,,	6.78 ,,

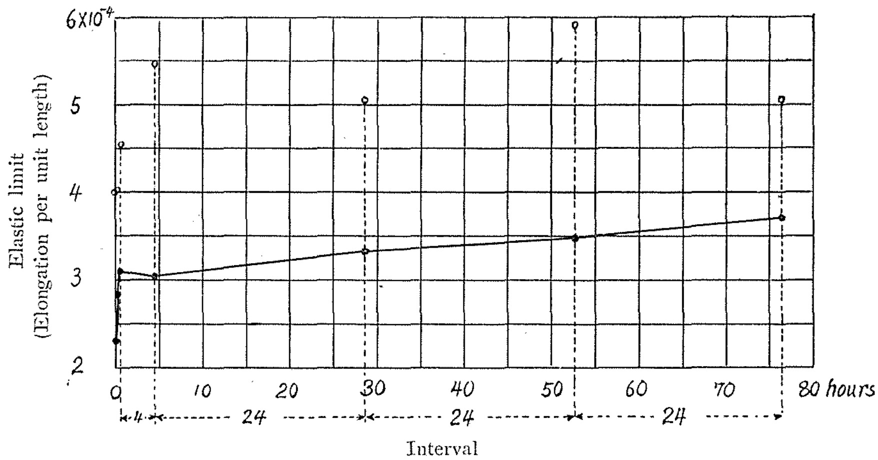
of the rods belonging to each set was taken. The results are given in Table II_2.

Next sixteen new rods were annealed for 30 hours at about 610°C as in the previous experiment. They were classified into four groups each consisting of four rods. The elastic limits of the rods belonging to the first group were measured and the average was taken. It is given in the first horizontal row of Table II_3. The three remaining groups were again annealed at about 45°C for 13 hours, 48 hours and one week respectively. After measuring the elastic limits of the rods belonging to each group, the average of the limits for each group was taken. The results are tabulated in Table II_3.

Experimental results

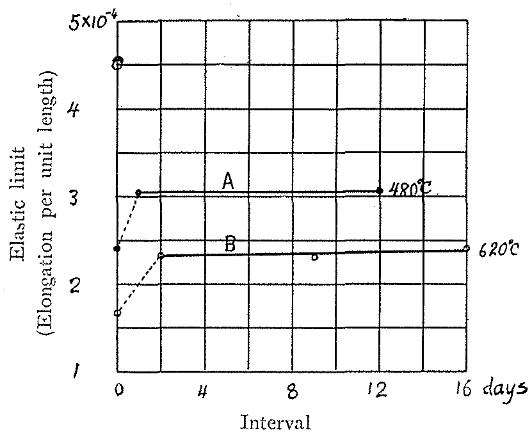
The result given in Table II_1 is represented by a graph shown in Fig. 2_1. In this figure, small dots denote the elastic limits and small circles the maximum elongations to which the specimens were subjected in measuring the elastic limits. When the elastic limit of a rod, which has been elongated previously beyond its elastic limit is measured after a lapse of a certain time, it has not returned to its initial value but remains somewhat larger.

Fig. 2_1



The residue obtained by subtracting the elastic limit from the maximum elongation per unit length to which the specimen is subjected in measuring its elastic limit, that is, the plastic elongation, is shown in the last vertical column of the table. The residue obtained by subtracting the upper elastic limit from the following one in the table, that is, the successive excess of the elastic limit is shown in the column second from the last in the table. As is shown in the table, the first plastic elongation is 1.70×10^{-4} and the excess of the elastic limit measured after the first 15 minutes is 0.53×10^{-4}. The excess of the elastic limit at the interval of 4 hours is -0.05×10^{-4}, which means that the elastic limit decreases. But as this is a very small quantity as experimental errors go, it may be stated that the elastic limit does not change in this case. In the case of an interval of 24 hours, the excesses of the elastic limits are all positive. Thus considering these facts, we may say generally that the elastic limit increases gradually by the ageing after a plastic deformation, at least for such a small plastic deformation as in the present experiment.

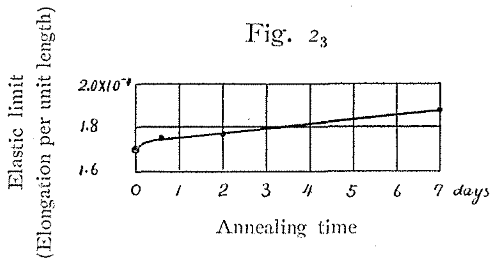
Fig. 2_2



The result given in Table II_2 is represented in Fig. 2_2. In this figure, Line A is of the annealing temperature of 480°C, and Line B is of 620°C. The small dots denote the elastic limits of the former and the small circles those of the latter. A large dot and a large circle denote the maximum elongation per unit length of the former and that of the latter respectively. It is seen from the two lines, that the elastic limit of the rod elongated once beyond its elastic limit grows somewhat larger with the lapse of time.

When the rod is elongated plastically beyond its elastic limit, a slip between the atomic planes will occur in relatively large crystal grains, and consequently such grains are broken down into smaller pieces. At the same time, spots of loose cohesion between atoms in the structure will be formed somewhere by the process of plastic deformation. The elastic limit of a metal increases by making its crystal grains smaller, and it decreases by the production of localities of loose cohesion between atoms in its structure. Thus when a metal is plastically deformed and then aged, the crystal grains get finer by the plastic deformation, and the spots of loose cohesion between atoms recover their normal state by the ageing; and consequently the elastic limit increases after ageing.

Fig. 2_3



The result given in Table II_3 is denoted by a curve in Fig. 2_3. In the present experiment, the rod recrystallized by the initial annealing at about 610°C was subjected, without rendering any elongation, to a second annealing at about 45°C which is somewhat higher than room temperature. In the figure, the elastic limit of the rod annealed only once at 610°C is denoted by a large dot. It is found from the curve, that the elastic limit of the rod which is heated again at about 45°C increases a little with the annealing time. But the elastic limit of such a rod is considerably smaller than that of the rod elongated plastically beyond its elastic limit.

Next we shall consider the reason why the elastic limit of the rod increases a little, on the second annealing, with the annealing time. When the rod annealed initially at about 610°C in the present case is suddenly cooled to the room temperature, spots of loose cohesion between atoms may appear somewhere in the structure of the rod on account of the rapid contraction. When such a rod is heated again at about 45°C, which is a little higher than the room temperature, the spots of loose cohesion between atoms will recover their normal state; and hence the elastic limit increases by ageing.

Part III. Annealed aluminium rod

Experimental method

Commercial aluminium rods which were made straight and had the same size as described in Part I were used in the present experiment. A number of rods were inserted in the electric furnace heated at about 450°C, and after 30 hours they were taken out of the furnace to be cooled suddenly to the room temperature. Such a rod was plastically elongated beyond its elastic limit, and its elastic limit and the maximum elongation of the rod were measured by the same apparatus as described before. The average value of the elastic limits and that of the maximum elongations of twenty such rods were taken respectively. The results are shown in Table III_1. The state of the rod thus elongated is taken as the initial one in the present experiment.

Table III_1

Annealing temperature 450°C

Specimen	Elastic limit		Maximum elongation per unit length	Young's modulus in C. G. S. unit
No.	Stress per unit area	Elongation per unit length		
1	176 $\frac{kg}{cm^2}$	2.53×10^{-4}	3.97×10^{-4}	6.81×10^{11}
2	184 ,,	2.66 ,,	4.07 ,,	6.78 ,,
3	182 ,,	2.65 ,,	4.16 ,,	6.73 ,,
4	172 ,,	2.50 ,,	4.07 ,,	6.71 ,,
5	176 ,,	2.55 ,,	4.07 ,,	6.76 ,,
6	174 ,,	2.53 ,,	4.13 ,,	6.74 ,,
7	180 ,,	2.63 ,,	4.06 ,,	6.71 ,,
8	174 ,,	2.50 ,,	3.90 ,,	6.80 ,,
9	168 ,,	2.42 ,,	3.95 ,,	6.80 ,,
10	170 ,,	2.50 ,,	3.96 ,,	6.66 ,,
11	170 ,,	2.49 ,,	4.02 ,,	6.69 ,,
12	174 ,,	2.53 ,,	3.95 ,,	6.74 ,,
13	168 ,,	2.44 ,,	4.02 ,,	6.75 ,,
14	170 ,,	2.45 ,,	3.97 ,,	6.80 ,,
15	176 ,,	2.55 ,,	4.11 ,,	6.76 ,,
16	176 ,,	2.54 ,,	4.22 ,,	6.79 ,,
17	170 ,,	2.47 ,,	4.21 ,,	6.75 ,,
18	170 ,,	2.46 ,,	4.16 ,,	6.77 ,,
19	172 ,,	2.47 ,,	4.03 ,,	6.82 ,,
20	174 ,,	2.50 ,,	4.02 ,,	6.82 ,,
Average	174 ,,	2.52 ,,	4.05 ,,	6.76 ,,

Several groups of the rods, each consisting of four rods in such a state, were prepared. Each group was annealed for different durations of time in the electric furnace heated at about 45°C. After the rods were taken out of the furnace suddenly, their elastic limits were measured separately with the apparatus described before. The values for the four rods belonging to the same group were averaged, and this average was taken as the value for that group.

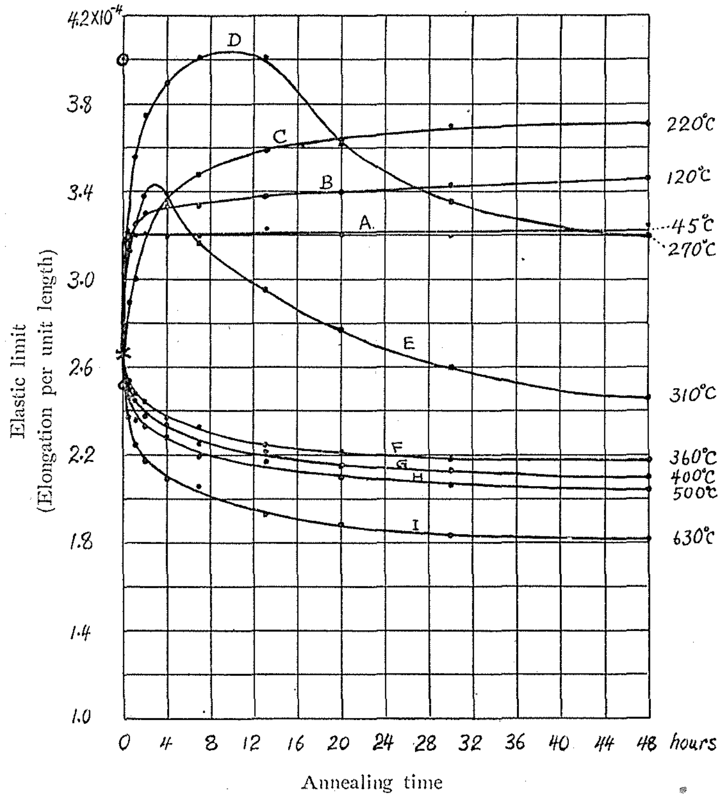
Several groups of the rods in the same initial state, each group consisting of four rods, were annealed at various different temperatures in the same manner as above stated, and their elastic limits were measured. The results thus obtained are shown in Fig. 3_1.

Further two initial states which were different from the above were employed; one was annealed initially at about 620°C and the other at about 330°C. All the rods thus annealed initially for 30 hours at these temperatures respectively were treated in the same manner as above mentioned. The results thus obtained are shown in Figs. 3_2 and 3_3 respectively.

Experimental results

In Fig. 3_1, a small circle ○ and a small circle having a centre ⊙ denote respectively the elastic limit and the maximum elongation in the initial state. Curve A is of the annealing temperature 45°C. The elastic limit becomes somewhat larger with the annealing time. Further, in this case the rod was annealed for one week, but it did not show

Fig. 3_1



any considerable increase in the elastic limit. The fact that the elastic limit in the present case is somewhat higher than that in its initial state, results from the plastic elongation, as is described in Part II.

As is stated in Part II, when the rod elongated plastically beyond its elastic limit is subjected again to a second elongation-testing after a lapse of time, the elastic limit of the rod is found to be somewhat larger than its initial one. In this figure, a cross sign × indicates the point of such increased elastic limit, and from this point all the curves are considered to start.

Curve B is of the annealing temperature 120°C, and the elastic limit increases gradually with the annealing time under the influence of the annealing temperature. Curve C is of the annealing temperature 220°C, and the elastic limit increases gradually with the annealing time like Curve B. Curve D is of the annealing temperature 270°C. The elastic limit increases considerably for about 10 hours and then decreases. Curve E is of the annealing temperature 310°C. The elastic limit increases rapidly for about 3 hours and then decreases gradually like Curve D. The elastic limit represented by this curve is always smaller at each annealing time than that represented by Curve D.

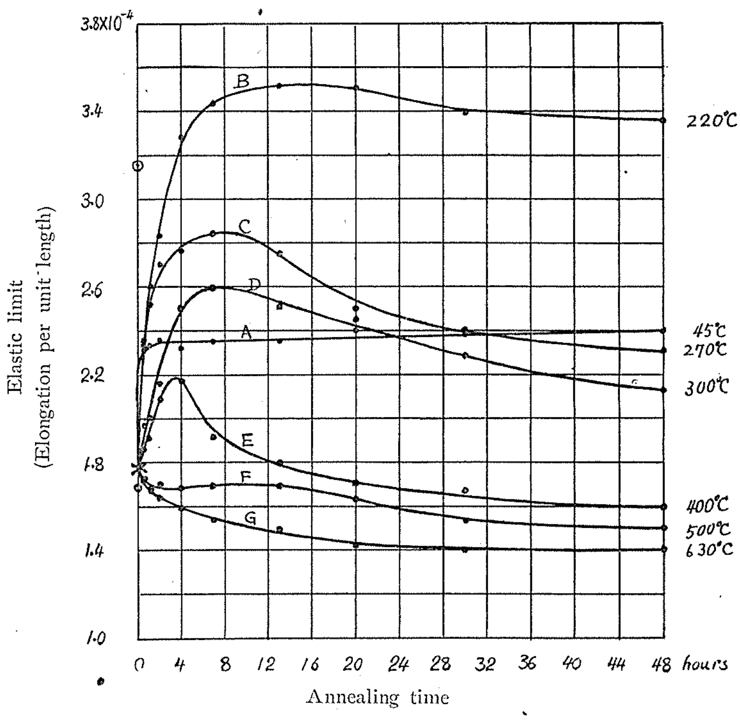
Curve F is of the annealing temperature 360°C, and the elastic limit decreases gradually with the annealing time. Curves G, H, and I are of the annealing temperatures 400°C, 500°C and 630°C respectively. In these cases the elastic limit decreases gradually with the annealing time like Curve F, and the elastic limit at a higher annealing temperature is always smaller than at a lower temperature when compared at the same annealing time.

After examining all the curves, the case can be summarized substantially as follows. The elastic limit at annealing temperatures below about 300°C increases at first with the annealing time until it reaches a maximum value. The higher the temperature, the sooner will this point of maximum value be reached. In the case of annealing temperatures higher than about 300°C, the elastic limit decreases gradually with the annealing time from the beginning.

As before stated, when a rod annealed at a high temperature is suddenly cooled, it is considered that spots of loose cohesion between atoms occur by contraction somewhere in the structure of the rod. If such a rod is elongated plastically beyond its elastic limit, the spots of such loose cohesion between atoms will be greatly increased through the breaking down of the crystal grains into smaller pieces by the plastic elongation. By annealing such a rod the spots of loose cohesion will be restored more easily by annealing even below its recrystallization temperature. Accordingly the elastic limit of the rod increases.

When the second annealing temperature is sufficiently high, the decrease of the elastic limit by the grain growth resulting from the recrystallization seems to appear more considerably than the increases due to the recovery of the spots of loose cohesion ; so that the elastic limit decreases, without showing any maximum, with the annealing time. In such a case, the higher the annealing temperature, the larger the crystal size produced by recrystallization. Hence the elastic limit decreases with higher annealing temperatures.

Fig. 3_2



The initial annealing temperature of about 620°C is illustrated in Fig. 3_2, where a small circle ○, a small circle having a centre ⊙ and a cross × have the same meaning as before. In this figure, Curve A is of the annealing temperature 45°C, and the elastic limit is only slightly influenced as in the case of the same annealing temperature in Fig. 3_1. In this case, the rod was annealed for one week, but the elastic limit of the rod increased only slightly.

Curve B is of the annealing temperature 220°C. The elastic limit increases for about 16 hours and then decreases slowly. Curve C is of the annealing temperature 270°C. The elastic limit increases rapidly for about 8 hours and then decreases slowly. The tendency of this curve is quite similar to Curve D at the same annealing temperature in Fig. 3_1.

Curve D is of the annealing temperature 300°C. The elastic limit increases rapidly for about 7 hours and then decreases gradually. Curve E is of the annealing temperature 400°C. The elastic limit increases rapidly for about 3 hours, then decreases rapidly and afterwards gradually. This curve shows a tendency similar to Curve E in Fig. 3_1, but the annealing temperatures are different in the two cases. Curve F is of the annealing temperature 500°C. The elastic limit does not change practically for the first 13 hours or so, and then it decreases very slowly. Curve G is of the annealing temperature 630°C. The elastic limit decreases slowly with the annealing time. The tendency of this curve is similar to Curves F, G, H and I in Fig. 3_1.

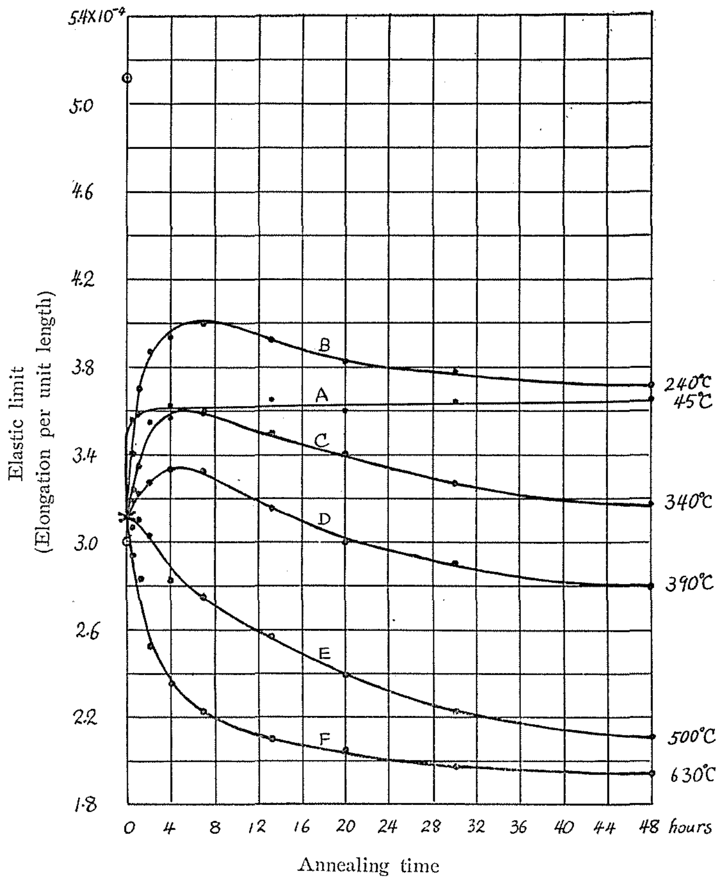
In looking over all the curves in this figure, the curve whose elastic limits increase at first like those in Fig. 3_1 was obtained at the second annealing temperature from about 220°C to about 400°C. The maximum position of the elastic limit displaces to the beginning of the annealing time according to the increase of the annealing temperature. This is a similar tendency to that shown in Fig. 3_1.

The initial elastic limit of the curves in Fig. 3_2 is smaller than that in Fig. 3_1, and the second elastic limits represented in Fig. 3_2, which are measured after the second annealing, show a much smaller tendency to decrease with annealing than those in Fig. 3_1. Moreover it can be stated in general, by comparing the above two cases, that when the initial elastic limit is small, the second elastic limit is also small. Here it must be noted that the amount of the plastic elongation beyond its elastic limit in the initial state, is 1.53×10^{-4} in the case of Fig. 3_1 and 1.47×10^{-4} in the case of Fig. 3_2. As these values are almost the same, the influence of the initial plastic elongation can be considered as almost the same in the two cases.

The results obtained at the initial annealing temperature of about 330°C are denoted by the curves in Fig. 3_3, where the marks ○, ⊙ and × have the same meanings as before.

Curve A is of the second annealing temperature 45°C. The elastic limit is influenced only slightly by the annealing temperature and

Fig. 33



increases somewhat with the annealing time like those in the above two cases. As an example, the specimen was annealed for one week. Its elastic limit did not increase greatly, but a tendency of gradual increase was observable with this annealing temperature.

Curve B is of the annealing temperature 240°C. The elastic limit increases rapidly for about 7 hours, and then decreases gradually. Curve C is of the annealing temperature 340°C. The elastic limit increases rapidly for about 5 hours and then also decreases gradually. Curve D is of the annealing temperature 390°C. It shows a similar tendency to the above two curves, and the maximum of the elastic limit appears at the annealing time of about 4 hours from the beginning. Curve E is of the annealing temperature 500°C. The elastic limit decreases gradually with the annealing time. Curve F is of the annealing temperature 630°C. The elastic limit decreases rapidly for 4 hours or so and then slowly.

In surveying in general all the curves in this figure, the elastic limit at the annealing temperature between about 240°C and about 390°C increases rapidly at first and then decreases gradually. The maximum of the elastic limit displaces to the beginning of the annealing time according as the annealing temperature becomes higher just as in the above two cases whose initial elastic limits and the initial annealing temperatnres are different from this case. The elastic limit at an annealing temperature higher than about 500°C decreases gradually with the annealing time. Within the range of the annealing temperatures employed in the present experiment, except 45°C, the elastic limit is always smaller at the higher annealing temperature when two are compared at the same annealing time.

In the above three cases having different initial elastic limits, the amount of the plastic elongation beyond the elastic limit in Figs. 3_1 and 3_2 is almost the same value: 1.5×10^{-4}; and that in Fig. 3_3 is 2.11×10^{-4}. Though the latter is somewhat larger, these may be regarded as of the same order.

If we compare the case of a smaller initial elastic limit with that of a larger one, the second elastic limit of the former increases more rapidly in the beginning of the annealing than that of the latter, when the second annealing temperature is relatively low; and when the second annealing temperature is relatively high, the second elastic limit decreases much less in the former than in the latter.

In the experiment in this Part, the rod, after being annealed at an adequate temperature, was elongated a little plastically, and then it was annealed again at various temperatures for various durations of time. Thus the plastic deformation of the crystallites is small and the recrystallization temperature is to be relatively high. Accordingly the decrease of the elastic limit due to the grain growth resulting from the recrystallization occurs when the rod is subjected to a second annealing for a relatively long time at a relatively high temperature. The increase of the elastic limit caused by heating of the specimen for a relatively short time at a relatively low temperature is considered to be due to the recovery of the spots of weak cohesion between atoms by such weak annealing. According as the second annealing temperature rises, the influence of the grain growth by recrystallization predominates step by step and at last the elastic limit decreases monotonously with the heating time.

When the first annealing temperature is sufficiently high, for example 620°C as in the case of Fig. 3_2, the crystallites grow sufficiently large by this annealing, so that the elastic limit is rather small. Even if the plastic elongation of such a small amount as 1.5×10^{-4} is applied to the specimen thus prepared, the increase of the elastic limit due to this operation is very small. Further if the specimen thus operated on is again annealed at 630°C, the size of the crystallites caused by this operation will still not be very different from those produced by the first annealing at 620°C. Accordingly the decrease of the elastic limit by the second annealing is small.

On the contrary, when the first annealing temperature is as low as 330°C (see Fig. 3_3,) the grain growth by this annealing is not sufficient. If such a specimen is elongated a little plastically and is annealed again at 630°C, the crystallites will grow considerably larger than before, so that the decrease of the elastic limit by the second annealing becomes very large.

When the second annealing temperature is so adequate as to cause a maximum in the elastic limit, the growth of the crystallites by recrystallization and the recovery of the spots of weak cohesion between atoms influence the elastic limit simultaneously. The fact that the annealing time which is necessary to cause a maximum in the elastic limit is reduced more and more according as the second annealing temperature becomes higher, seems to be explained clearly by considering that the influence of the growth of the crystallites predominates more and more with higher annealing temperature.

In Part I, commercial aluminium rods which were previously strongly cold-worked were annealed directly without any previous annealing, and the elastic limits of the rods thus obtained were measured. In this case the rods were left alone for a very long time after the cold-working ; and the spots of weak cohesion between atoms which were formed by the cold-working would be almost recovered by such long ageing. Moreover the recrystallization temperature is very much lowered by the strong cold-working, so that the decrease of the elastic limit due to grain growth by annealing even at a comparatively low-temperature predominates strongly. Actually the tendency to the increase of the elastic limit by annealing is masked entirely by such decrease of the elastic limit, and no trace of the increase is perceived.

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