Change of the Elastic Limit of an Aluminium Rod by Elongating Plastically and by Annealing

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Abstract

A cold-worked aluminium rod heated to a relatively high temperature has a small elastic limit. When such a rod is cold worked at various degrees by stretching and by drawing through dies, the elastic limit increases, at first rapidly and then slowly. When the rod thus cold worked is heated again at various temperatures for various durations of time, the elastic limit increases at a relatively low temperature and decreases at a relatively high temperature with increase of the annealing time.

Experimental method

A commercial cold-worked aluminium wire about 2 mm. in diameter was cut off about 20 cm. in length, and the rod was straightened by hammering on a plane iron plate with a wooden hammer. A number of such rods were suddenly put into and annealed for a certain duration of time in an electric furnace heated at a certain temperature, and then they were taken out of the furnace and cooled suddenly to the room temperature.

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. Next by the extensometer designed by the writer,[1] the elongation testing of the rod was performed. The relation between the stress per unit initial cross-sectional area and the elongation per unit length was shown by a curve, and then by using the contact point finder reported previously by the writer, the elastic limit was determined. In the present experiment, the following eight different processes were made use of.

Process I. A number of rods were heated at 620°C for 30 hours. This is to be considered the initial state of the rod. The elastic limit of such a rod was measured. After being plastically elongated by 1.5%, the elastic limit of the rod was measured again. Next the rod was again elongated by the same amount, 1.5%, and its elastic limit meas-

1. These Memoirs, A. **20**, 19 (1927).

ured. This process was repeated 9 times. The result is given in Table I.

Process II. Several groups each consisting of three rods in the same initial state as in Process I were prepared. Different amounts of plastic elongations were given to each group, and the elastic limits were measured soon or after four days. The average for each group was taken. The curves showing the relation between the elastic limit and the plastic elongation are shown in Fig. 2.

Process III. Several groups of the rods described before were prepared. The rods belonging to one group were drawn through dies in order that the diameter of the rods might be reduced by a certain amount. The diameter of each rod was measured by a micrometer screw gauge before and after drawing through dies, and the amount of contraction of the diameter was calculated. The amount of the contraction of the cross-section of the rod was made to be different for different groups. The same operation as above was performed upon another group of rods previously heated at 410°C for 30 hours. These two kinds of rods are to be considered as in different initial states. The results of the experiments for these two kinds are shown in Fig. 3.

Process IV. Several groups of the rods in the same initial state as in Process I were prepared. These groups were classified into two series, the one being subjected to various plastic elongations by applying tension, and the other to various plastic contractions of a cross-sectional area by drawing through dies. For the second series the elongation was calculated, for the sake of comparison, from the reduction of the diameter of the rod by assuming that the volume of the rod is constant. Two curves each showing the relation between the elastic limit and the plastic elongation are shown in Fig. 4.

Process V. The aluminium rod employed in this process had almost the same size as in the above four processes, but its initial state was a little different from the others. A number of rods were heated at 280°C for 6 hours and cooled suddenly to the room temperature. This was the initial state in the present case. The elastic limits of several such rods were measured and the value of 3.15×10^{-4} was obtained as the average.

Many other rods in the same initial state as above were drawn in the same degree through dies, and the elongation by drawing was determined from the amount of reduction of the diameter in the way described before. The amount of reduction of the diameter and the corresponding elongation were 2.1% and 4.3% respectively in the present case. With the three rods thus drawn, the elastic limits were measured, and the value of 5.74×10^{-4} was obtained as the average. The remaining rods drawn in the same degree were classified into several groups each consisting of two rods. These groups were annealed at various temperatures for various durations of time, and cooled suddenly to the room temperature. The values of the elastic limit of the rods belonging to the same group were averaged, and the results are given in Fig. 5_1.

Next many rods in the same initial state as above were elongated by 2.5% by stretching instead of drawing through dies. The elastic limit of such rods was found to be 5.14×10^{-4} as an average for three rods. The remaining rods were treated in the same manner as the drawn ones. The results of measurement are given in Fig. 5_2. Here it must be noted that the writer had intended initially to give the same elongation of 4.3% by stretching as in the case of drawing, for the sake of comparison, but the rod was broken when the elongation was about 3%, and consequently it was necessary to carry out the experiment with the stretching of 2.5%.

Process VI. Many rods prepared in the manner to obtain the initial state used in Process V were heated in the furnace at 500°C for 6 hours, and cooled suddenly to the room temperature. This was the initial state in the present case. The elastic limits of several such rods were measured, and by taking the average, the value of 0.93×10^{-4} was obtained. Many such rods were drawn in the same degree through dies, and the average value of reduction of the diameter was 2.2%. From this value the corresponding elongation was found to be 4.5%. The elastic limits of some such rods were measured soon after the drawing, and the average value 6.28×10^{-4} was obtained. The remaining rods drawn in the same degree were classified into several groups each consisting of two rods, and these groups were subjected systematically to different heat treatment. Next many rods in the same initial state as above were elongated 4.5% by stretching, which is the same as in the case of drawing through dies; and the elastic limits were measured. The average value 4.41×10^{-4} was obtained. Many such rods were classified into several groups each consisting of two rods. The above two kinds of rods prepared by drawing and by stretching were heated together in the furnace at various temperatures for various durations of time. The elastic limits of these rods were measured, and the average was taken for each group. The results are given in Figs. 6_1 and 6_2 respectively.

Process VII. A part of many rods in the same initial state as Process VI was drawn in the same degree through dies, and the average elongation by drawing was found to be 16%. The rest were elongated 16% by stretching. The elastic limits of these rods were found on the average to be 7.40×10^{-4} and 6.53×10^{-4} respectively for the drawn and stretched ones. Next these rods were subjected to the heat treatment in the same manner as in the previous process. The results are given in Figs. 7_1 and 7_2 respectively.

Process VIII. To compare with the change of elastic limit of the rod drawn through dies in Process VII, the rods annealed first in Process V were so drawn through dies as to produce an elongation of 16%. For these rods, the average elastic limit after drawing was 7.83×10^{-4}. Next, to compare with the change of elastic limit of the rod elongated in Process V, the rods annealed first in Process VI were elongated 2.5% by stretching, and soon the elastic limits of the rods were measured. The average value was 4.01×10^{-4}. These rods were treated in the same way. The results are given in Figs. 8_1 and 8_2 respectively.

Experimental results

The maximum elongation in the fifth column of Table I is the largest value when the rod is elongated plastically beyond its elastic

Table I

Annealing temperature 620°C, annealing time 30 hours

No.	Amount of elongation at each time	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	Successive excess of elastic limit	Plastic elongation per unit length
1	0%	120 $\frac{kg}{cm^2}$	1.75×10^{-4}	4.28×10^{-4}	6.72×10^{11}		2.53×10^{-4}
2	1.5	305	4.46	7.84	6.70	2.71×10^{-4}	3.38
3	1.5	470	6.90	10.03	6.68	2.44	3.13
4	1.5	510	7.50	11.90	6.66	0.60	4.40
5	1.5	540	7.90	12.61	6.70	0.40	4.71
6	1.5	580	8.52	12.86	6.67	0.62	4.34
7	1.5	590	8.63	13.19	6.70	0.11	4.56
8	1.5	610	8.90	12.59	6.72	0.27	3.69
9	1.5	630	9.21	13.60	6.70	0.31	4.39
10	1.5	640	9.28	12.89	6.76	0.07	3 61

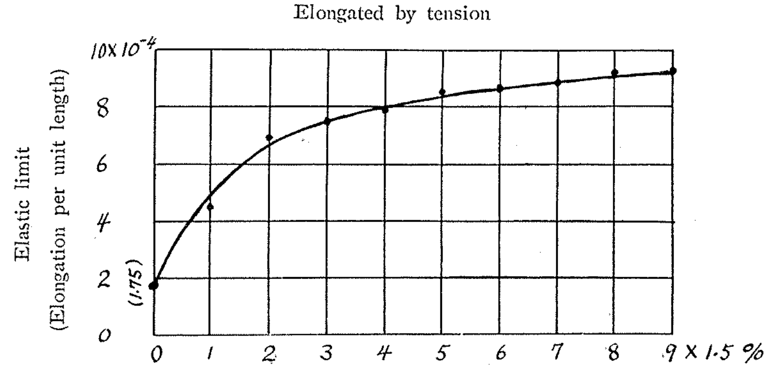
limit in measuring the elastic limit. The plastic elongation given in the last column of the table is the quantity obtained by subtracting the elastic limit from the maximum elongation at that time. The plastic elongation assumes values between 2.53×10^{-4} and 4.71×10^{-4}, which may be considered to be of the same order. These values are rather small in comparison with the permanent elongation of 1.5% applied to the rod; so that the influence of such small plastic elongation in measuring the elastic limit may be neglected in comparison with the permanent elongation applied to the rod.

The successive excess of the elastic limit in the second column from the last of the table is the residue obtained by subtracting the upper elastic limit from the following one. The values given in this column are all positive. It has previously been reported that the successive excess was positive for repeated small plastic elongation.[1] This point is confirmed clearly for the case of much larger plastic elongation.

The relation between the elastic limit of the rod and the permanent elongation applied to it successively is given in Fig. 1, where the elastic limit expressed by the elongation per unit length is taken as

Fig. 1.

Elongated by tension



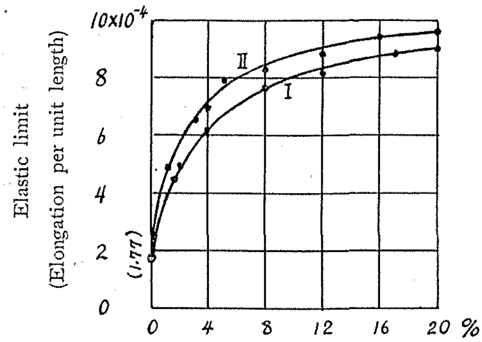
the ordinate. As is seen from the figure, when the elongation 1.5% is given to the rod repeatedly, the elastic limit increases rapidly at first and then slowly. A similar experiment was performed by applying an elongation other than 1.5%. The result shows a similar tendency.

The results obtained in Process II are given in Fig. 2. In this

1. These Memoirs, A. **21**, 153 (1938)

Fig. 2.

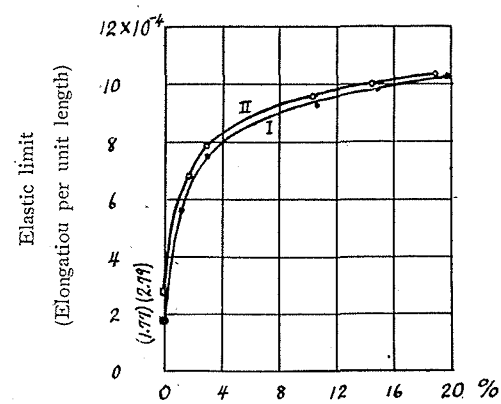
Elongated by tension



figure, Curve I is of the values measured soon after the plastic elongation, and Curve II of the value measured after leaving the specimens in the room temperature for 4 days after stretching. Both curves start from the same point 1.77×10^{-4}, which corresponds to the state annealed at 620°C for 30 hours; and show that the elastic limit increases rapidly at first and then slowly. Curve II which corresponds to the aged specimens shows an elastic limit somewhat larger than Curve I.

Fig. 3.

Drawn through dies



In Fig. 3, which corresponds to Process III, Curve I starts from the value 1.77×10^{-4} which corresponds to the state annealed at 620°C for 30 hours; and Curve II from the value 2.79×10^{-4}, which corresponds to the state annealed at 410°C for 30 hours. Both curves show that the elastic limit increases rapidly at first and then slowly. Further, Curve II occupies always a position somewhat higher than Curve I.

In Fig. 4 repesenting the result obtained in Process IV, Curve I shows the result obtained in the case of elongation by stretching, and Curve II in the case of drawing through dies. The two curves start from the same point 1.77×10^{-4}, and increase rapidly at first and then slowly with the amount of plastic elongation. Further, Curve II occupies a position a little higher than Curve I.

Figs. 5_1 and 5_2 represent the results obtained in Process V, the former showing the effect of drawing through dies and the latter that of elongation by stretching. In Fig. 5_1, the circle o denotes the initial

Fig. 4.

I Elongated by tension
II Drawn through dies

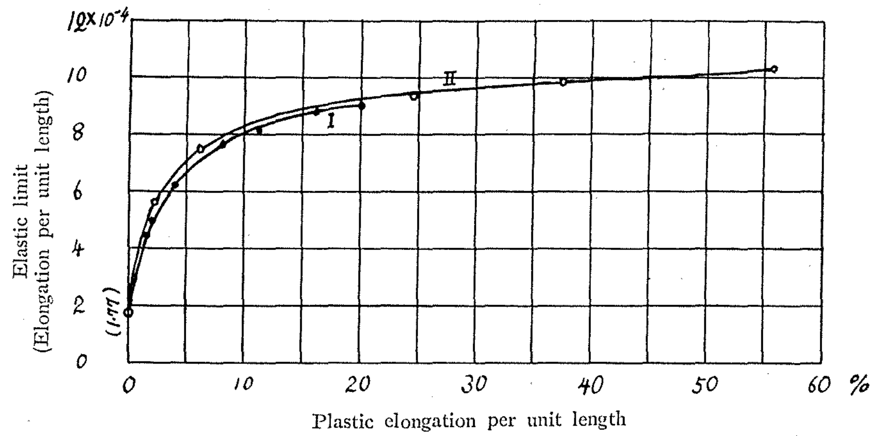


Fig. 5_1
Drawn through dies

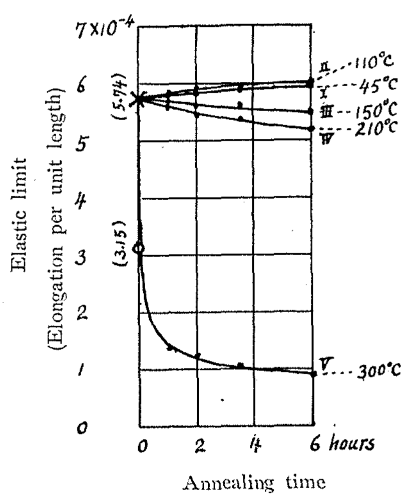
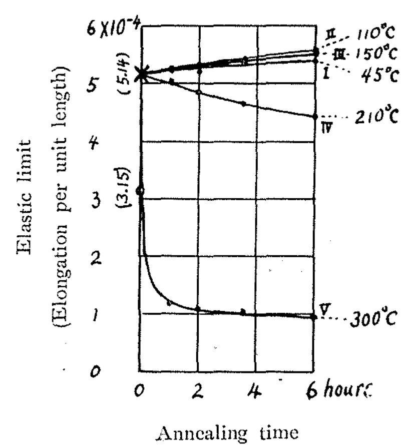


Fig. 5_2
Elongated by tension



elastic limit 3.15×10^{-4}, and the cross $\times$ the one 5.74×10^{-4} elevated by drawing through dies. In the present case, all curves start from the point marked $\times$. In the figure, Curve I is of the annealing temperature 45°C, and the elastic limit increases slightly with the annealing time. Curve II is of the annealing temperature 110°C, and the elastic limit also increases somewhat with the annealing time. Curves

III and IV are of the annealing temperatures 150°C and 210°C respectively, and the elastic limits decrease slowly. Curve V is of the annealing temperature 300°C, and the elastic limit decreases rapidly at first and then slowly.

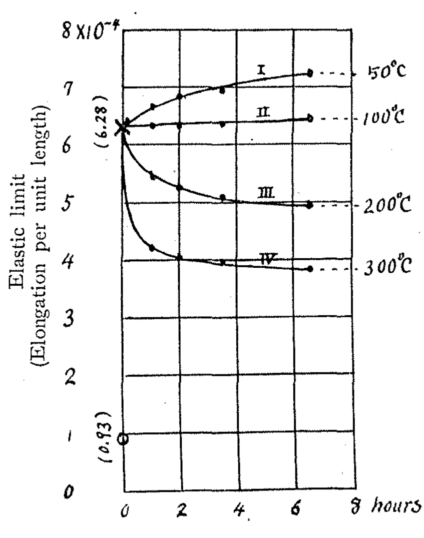
In Fig. 5_2, the circle o is the initial elastic limit, the same as is in Fig. 5_1, and the cross × from which all curves start, the one 5.14×10^{-4} elevated by elongating. In the figure, Curves I, II and III are of the annealing temperatures 45°C, 110°C and 150°C respectively, and the elastic limits increase slowly. Curve IV is of the annealing temperature 210°C, and the elastic limit decreases slowly. Curve V is of the annealing temperature 300°C, and the elastic limit decreases very rapidly at first and then slowly as in the case of Fig. 5_1.

In the present experiment, the reduction of diameter of the rod by drawing it through dies is 2.1%, and accordingly the corresponding elongation becomes 4.3%. But the elongation of the rod by being stretched is 2.5%, which is different from the above. Irrespectively of such difference, corresponding curves in Figs. 5_1 and 5_2 show almost the same tendency.

Figs. 6_1 and 6_2 represent the results obtained in Process VI. The former is in the case of drawing through dies and the latter in the case of elongation by stretching. In the figures, the marks o and ×

Fig. 6_1

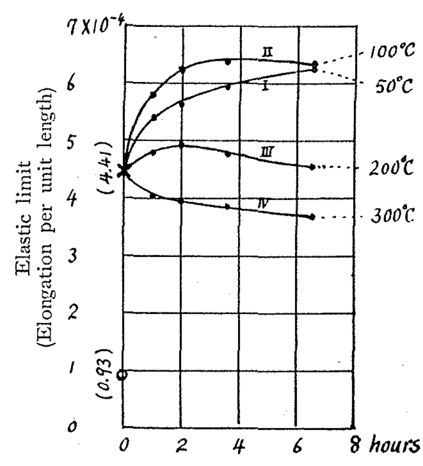
Drawn through dies



Annealing time

Fig. 6_2

Elongated by tension



Annealing time

have the same meaning as before. In the present case, the specimens employed in the two different kinds of cold working have the same initial elastic limit 0.93×10^{-4} and are elongated to the same degree, but they have different elastic limits after the cold working: that is, 6.28×10^{-4} and 4.41×10^{-4} by drawing through dies and by stretching respectively.

In each figure, the second annealing temperature is written for each curve. In Fig. 6_1, Curve I goes up with the annealing time, Curve II is almost horizontal, Curves III and IV go down. In Fig. 6_2, Curve I goes up rapidly with the annealing time. Curve II goes up more rapidly than Curve I at first and reaches a maximum point. Curve III goes up slowly, reaches a maximum point sooner than Curve II, and afterwards goes down slowly. Curve IV goes down slowly from the starting point. From these curves, it is seen that the elastic limit in the case of a higher annealing temperature, except the annealing temperature 50°C, has a value smaller than in the case of the lower temperature.

If we compare the corresponding curves in Figs. 6_1 and 6_2, it is found that the elastic limit in the case of the annealing temperature 50°C shows a similar tendency, but the rate of increase is much faster with stretched rods. The elastic limits at the annealing temperature 100°C show a different tendency: that is, the one is almost independent of the annealing time and the other increases rapidly with annealing time. The elastic limits at 200°C show a different tendency still: that is, the one decreases gradually and the other goes up slightly at first and then decreases gradually. The elastic limits at 300°C show a similar tendency, but the rate of decrease is remarkably different.

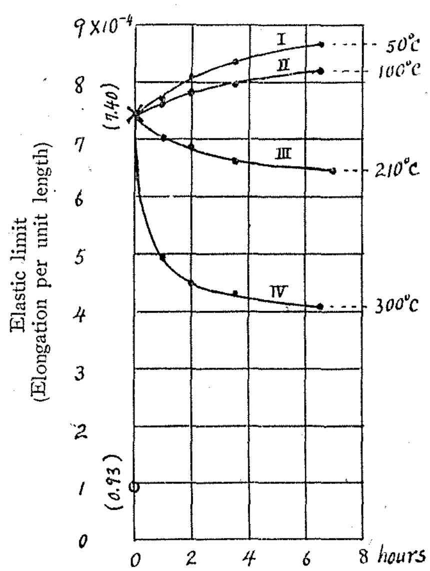
Figs. 7_1 and 7_2 represent the results obtained in Process VII. The former is in the case of drawing through dies and the latter in the case of stretching. In the present case, the plastic elongation is 16% for both kinds of specimens. In the figures, the marks o and × have the same meaning as before, and the second annealing temperatures are written separately for each curve.

In Fig. 7_1, Curves I and II go up slowly with the annealing time, Curve III goes down slowly, and Curve IV goes down rapidly at first and then slowly. In this case, the elastic limit at each annealing time becomes smaller according as the second annealing temperature becomes higher.

In Fig. 7_2, Curve I goes up rapidly with the annealing time. Curve II goes up more rapidly, reaches a maximum point and then

Fig. 7₁

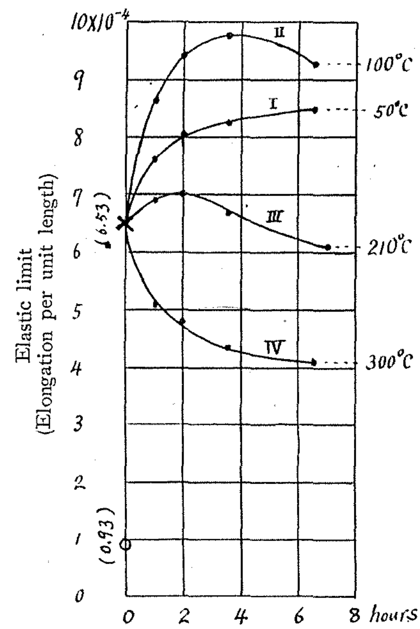
Drawn through dies



Annealing time

Fig. 7₂

Elongated by tension



Annealing time

goes down. Curve III shows a similar tendency as Curve II, but the maximum point is nearer to the starting point and lower than that of Curve II. Curve IV goes down gradually from the starting point. In this case, the elastic limit at each annealing time, except 50°C, becomes smaller according as the second annealing temperature becomes higher.

Figs. 8_1 and 8_2 represent the results obtained in Process VIII. In these figures, the marks o and × have the same significance respectively as before, and the second annealing temperatures are written separately for each curve. In Fig. 8_1, Curve I goes up slowly with the annealing time. On the contrary, the remaining three curves go down and the curve of a higher annealing temperature descends much faster than in the case of the lower. In Fig. 8_2, Curves I and II go up with the annealing time. Curves III and IV go down slowly from the beginning.

In looking over all the curves in Figs. from 1 to 4, when the specimen annealed first at a relatively high temperature is cold worked by stretching or by drawing through dies, the elastic limit of the speci-

Fig. 8_1

Drawn through dies

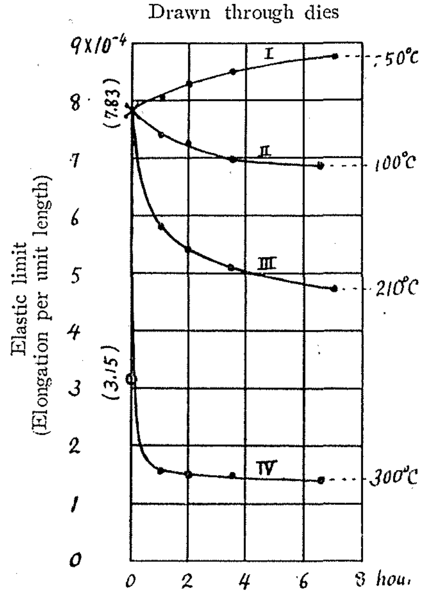
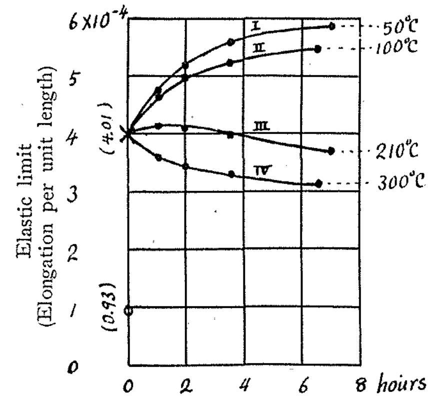


Fig. 8_2

Elongated by tension



men increases rather rapidly at first and then slowly according as the plastic elongation given to the specimen becomes larger. When the first annealing temperature is sufficiently high, for example 620°C, the crystallites grow sufficiently large, so that the elastic limit is relatively small. If a plastic elongation is applied to such a specimen, the crystal grains are broken into smaller pieces, and at the same time spots of loose cohesion between atoms form somewhere in the structure. These facts occur more remarkably in proportion to the increase of the plastic elongation. On the one hand, the fact that the crystal grains are broken into smaller pieces acts upon the specimen to make its elastic limit higher; and on the other hand, the fact that the spots of loose cohesion between atoms formed in the structure acts to make its elastic limit lower. It is considered that the former action predominates over the latter; so that, when two such actions act upon the specimen at the same time after a plastic deformation, the elastic limit ultimately becomes larger.

It is considered that the rate of destruction of crystal grains becomes smaller for higher values of the plastic elongation. Hence the rate of increase of the elastic limit becomes smaller according as the plastic elongation increases, as is seen in Figs. from 1 to 4.

When the specimen annealed at first is deformed plastically in a relatively high degree and then aged, the crystal grains become finer by the plastic deformation, and the spots of loose cohesion between atoms which are formed in the structure by the plastic deformation, recover their normal state by the aging; and consequently the elastic limit increases as seen by Curve II in Fig. 2.

The crystal grains produced at a lower temperature, for example 410°C, will be somewhat smaller than those produced at a higher temperature, for example 620°C. When two such kinds of specimens are deformed plastically in the same degree, the crystal grains which are smaller initially will be broken into somewhat smaller pieces than those which are larger initially; and accordingly the elastic limit in the case of the larger initial elastic limit becomes somewhat larger than in the case of the smaller as is seen by the Curves II and I in Fig. 3.

When the rod annealed first at a relatively high temperature, for example 620°C, is drawn through dies, the rod is compressed strongly towards its axis, and accordingly the crystal grains in the rod will be strongly cold worked and consequently severely broken into smaller pieces. It is considered that the average size of the grains thus destroyed will be somewhat smaller than that of those destroyed by stretching to the same degree of plastic elongation. Hence, as is seen by the Curve II in Fig. 4, when the rod is annealed first and then drawn through dies, its elastic limit becomes somewhat larger than that obtained by stretching to the same plastic elongation.

In looking over all the curves in Figs. 5 to 8, we find that when the rod annealed first at a relatively high temperature, for example 500°C, is cold worked strongly through dies or by stretching, and again annealed at a temperature somewhat higher than the room temperature, the elastic limit increases with the annealing time. This fact may be understood by considering that the spots of loose cohesion between atoms which have occurred somewhere in the structure by the cold working, recover their normal state by the aging. Such a consideration has been described in a previous paper.[1]

When the rod elongated by tension is heated again to an adequate temperature, for example 100°C or 200°C, the elastic limit has a maximum value. As has been illustrated in the previous paper,[2] this fact seems to be due to the two causes acting simultaneously: that

1. These Memoirs, A. **21**, 161 (1938)
2. These Memoirs, A. **21**, 162 (1938)

is, the one the recovery of the spots of loose cohesion between atoms to their normal state and the other the recrystallization of the crystallites by heating. The position of the maximum value of the elastic limit displaces to the beginning of the annealing time with increase of the annealing temperature. This is due to a more speedy recrystallization at a higher annealing temperature.

In the case of cold working through dies, so far as the present experiment is concerned, the elastic limit decreases from the beginning of the annealing time at an annealing temperature higher than about 200°C. Such a tendency is somewhat different from that in the case of cold working by stretching. This fact seems to be explained by considering that the rod is cold worked somewhat more severely in its internal structure by drawing through dies than by stretching, even though its elongation is the same; and consequently that the recrystallization temperature becomes somewhat lower with drawing than with stretching.

When the rod is annealed first at a relatively low temperature, for example 280°C, the crystal grains do not grow so large. If such a rod is cold worked strongly by drawing through dies or by stretching, the crystal grains will become still smaller by destruction, and accordingly the recrystallization temperature will become lower. This seems to be the cause of the rapid decrease of the elastic limit with the annealing temperature of 300°C in the cases of Figs. 5_1, 5_2 and 8_1.

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