Change of the Elastic Limit of an Aluminium Rod by Cooling

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Abstract

An aluminium rod previously heated, is elongated by stretching or by drawing through dies, and then immersed suddenly in liquid air for various durations of time. The elastic limit of such a rod increases rapidly in the beginning of cooling time, and then decreases slowly as the time is lengthened. Instead of being cooled in such a sudden manner, a cold worked rod is immersed in liquid air after being cooled by the cold air above the liquid. The second rod shows a similar tendency to the first in the measure of the elastic limit but gives somewhat smaller values. When the rod cooled at first by liquid air is heated at a temperature somewhat higher than the room, its elastic limit increases slightly.

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 an electric furnace heated to approximately 500°C and annealed for about 6 hours; then they were taken out of the furnace and cooled suddenly to the room temperature.

In order to calculate the initial cross-sectional area of the rod prepared in different ways, for example, annealed only, or elongated by stretching or by drawing through dies, the diameter of the rod was measured at several different points with a micrometer screw gauge, and then the average value was taken. Next elongation testing of the rod was performed by the extensometer designed by the writer.[1] A curve showing the relation between the stress per unit initial cross-sectional area and the elongation per unit length, was plotted on a section-paper, and then the elastic limit was determined by use of the contact point finder reported previously by the writer.[2] In the present experiment, the following eight different processes were used.

Process I. The rod annealed in the electric furnace was here used as the primary state, and the rod stretched to a certain plastic elonga-

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[1] These Memoirs, A. **20**, 19, (1937).

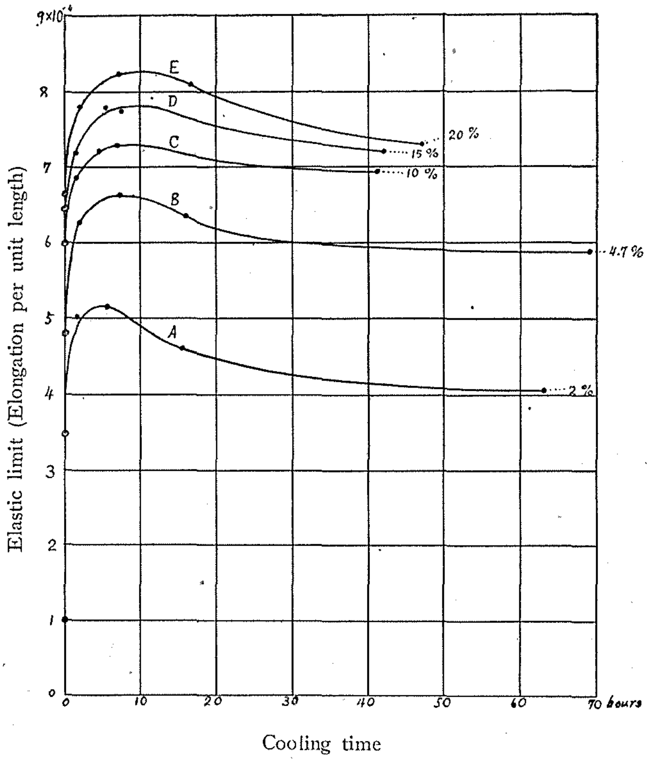
[2] These Memoirs, A. **20**, 27, (1937).

Pable I

Elastic limit of the rod in the primary state: 1.01×10^{-4}, elastic limit of the rod in the secondary state after being elongated by about 4.7%: 4.81×10^{-4}.

Specimen Group number	Duration of cooling time	Elastic limit		Young's modulus in C. G. S. unit
		Stress per unit area	Elongation per unit length	
1	2 hours	435 $\frac{\text{kg}}{\text{cm}^2}$	6.28×10^{-4}	6.79×10^{11}
2	7	453	6.61	6.72
3	16	433	6.25	6.79
4	69	405	5.88	6.75

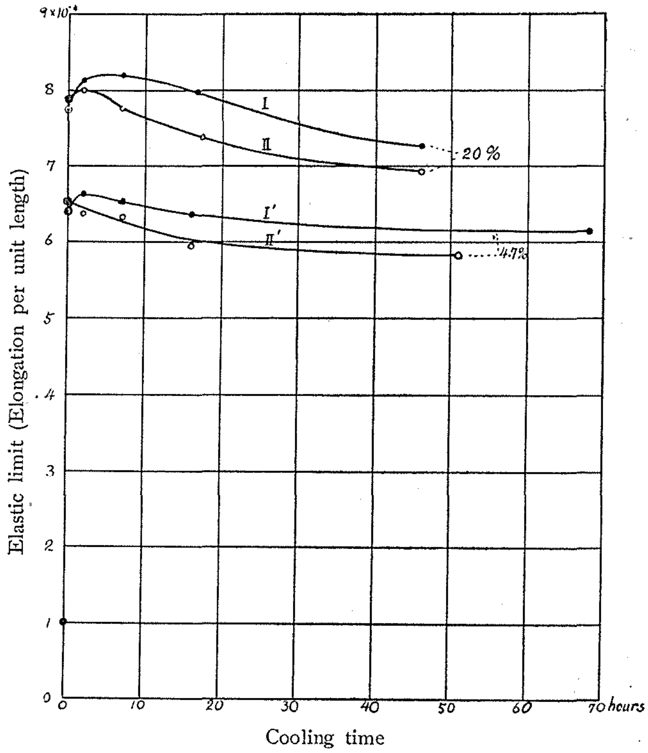
Fig. 1



tion after annealing, as the secondary. Ten rods in the same secondary state were classified into five groups of two each, and the elastic limit of one group was measured. The remaining groups were immersed in liquid air separately for various durations of time and taken out of the liquid air to the room where the elastic limits were measured. As an example the results are given in Table I. Rods stretched to several different plastic elongations were treated in the same manner as the above and the results are shown in Fig. 1.

Process II. Rods in the same primary state as in Process I were elongated, not by stretching, but by drawing through dies. This was the secondary state. Some of these rods were treated in the same way as in Process I. To compare the results in the case of gradual cooling with those obtained in the case of sudden cooling as described above, the remaining rods were classified into several groups each consisting of two in the same secondary state, and such groups were placed together for about 15 hours in the cold air (at about–40°C) above the liquid air. One group was taken out of the cold air to the room where the elastic limit was measured, while the remaining groups were immersed in liquid air for various durations of time, and then were

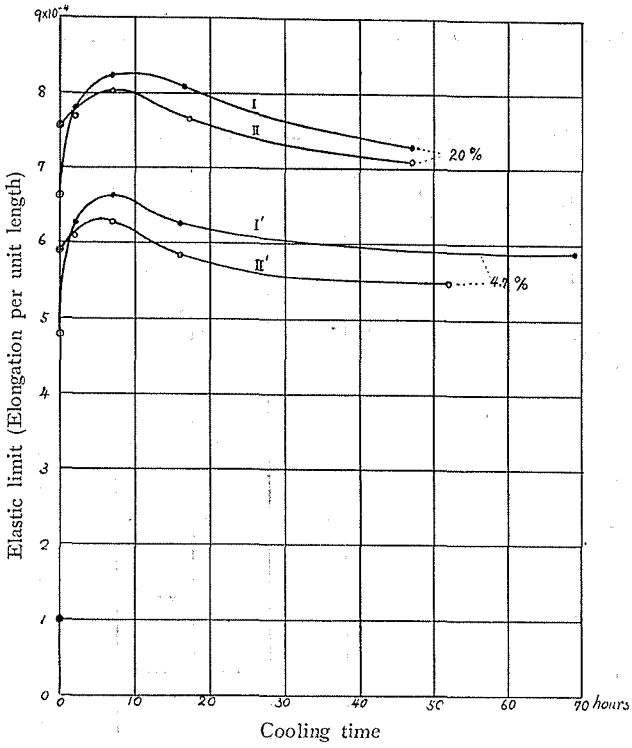
Fig. 2



taken out of the liquid air to the room where the elastic limits were measured. The results are shown in Fig. 2. The degree of elongation in this case was calulated approximately from the reduction in diameter by assuming that the volume of the rod is constant.

Process III. To compare the result in the case of elongation by tension with that in the case of elongation by drawing through dies, the rods in the same primary state as in Process I were elongated by tension to the same degree as that drawn through dies. Such elongated rods were treated in the same manner as in Process II, and the results are shown in Fig. 3.

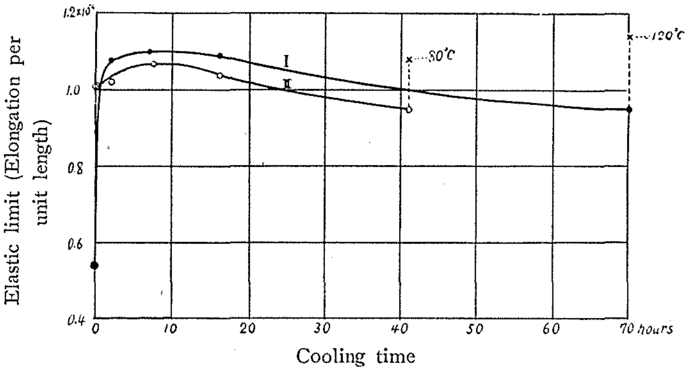
Fig. 3



Process IV. A commercial aluminium rod about 5 mm in diameter, and about 20 cm in length was heated in the furnace at approximately 300°C for two days, and then taken out of the furnace. After being elongated by about 1.5 %, the rod was heated again in the furnace at about 600°C for two days. A rod composed of large crystal grains was obtained by this treatment. This was the initial state in the present process. The elastic limits of several such rods were measured by elongation testing and the average was taken.

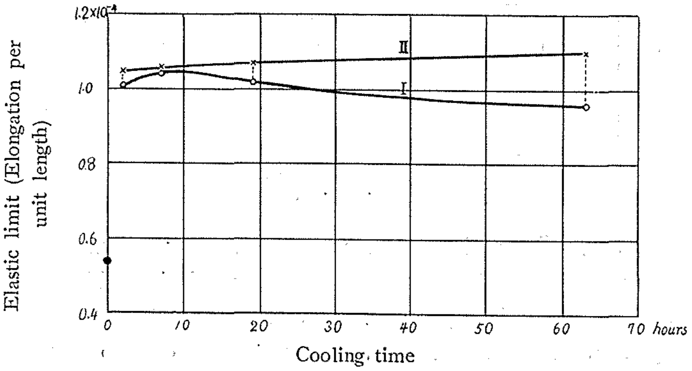
Several groups each consisting of two such rods in the initial state, were classified into two series as described in Process II, the one being subjected to the sudden cooling and the other to the gradual. One more group of each series, after being cooled, was annealed in the furnace at about 80°C and 120°C for approximately 10 bours and then the elastic limit was determined. The results obtained in the present process are given in Fig. 4.

Fig. 4



Process V. Several groups each consisting of two rods in the same initial state as in Process IV were classified into two series. Both series were subjected to gradual cooling as described above, the one being employed to measure the elastic limits after being taken out of the liquid air, and the other to do so after being annealed in the furnace

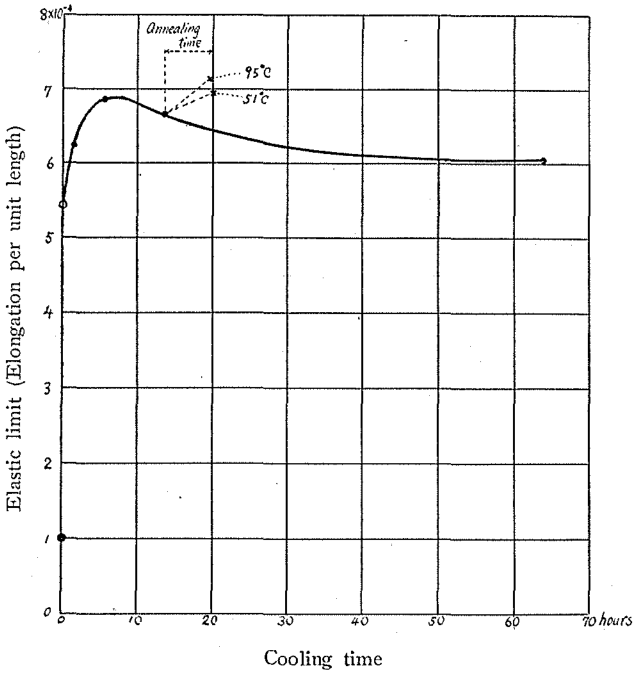
Fig. 5



at approximately 90°C for about 10 hours. The results are shown in Fig. 5.

Process VI. The rods in the same primary state as in Process I were elongated by about 6 %. This was the secondary state in the present process. By placing some such rods under elongation testing, the average elastic limit of the rods was determined. Several groups each consisting of two rods in the secondary state were cooled suddenly by liquid air and the average elastic limit of each group was determined after it had been taken out of the liquid air to the room. In the present cooling, three of the groups were cooled for 13.5 hours, one being used to dotermine the elastic limit as described above, and the remaining two for testing after they had been annealed at 51°C for 6.5 hours, and at 95°C for 6 hours respectively. The results are shown in Fig. 6.

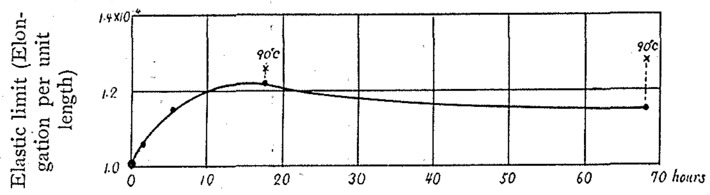
Fig. 6



Process VII. Several groups each consisting of two rods in the same primary state as in Process I were cooled suddenly, without applying any cold work, by liquid air and the average elastic limit of each group was determined after being taken out to the room air.

One more group was subjected to such sudden cooling for 16 hours, and the average elastic limit of that group was determined after being annealed at 90°C for 10 hours. In the case of sudden cooling for 68 hours, exactly the same process as before was followed and the results are given in Fig. 7.

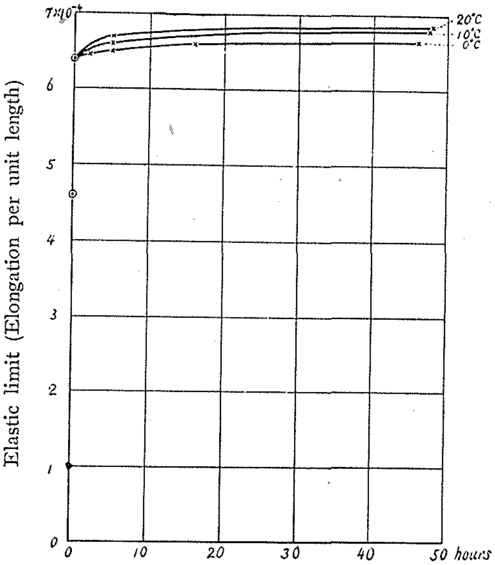
Fig. 7



Cooling time

Process VIII. In all the above experiments, the elastic testing was accomplished within 1.5 hour at room temperature, after the specimen had been taken out of liquid air. Accordingly we must expect that the elastic limit might have changed somewhat during this test. The following experiments were performed in order to estimate the degree of this change.

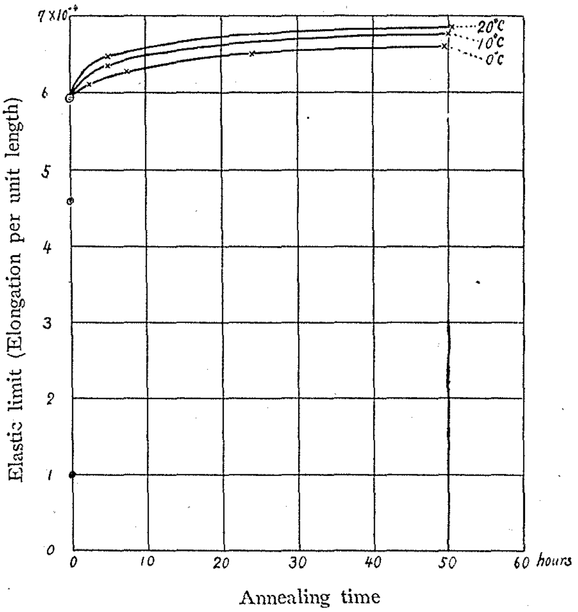
Fig. 8_1



Annealing time

Many rods in the same primary state as in Process I were elongated by 4.5 % by stretching. This was the secondary state in the case of stretching. Several groups each consisting of such rods were cooled suddenly by liquid air for 5 hours, and one group was placed under elastic testing soon after it was taken out of the liquid air, The remaining groups were classified into three series, and after each series was annealed for various

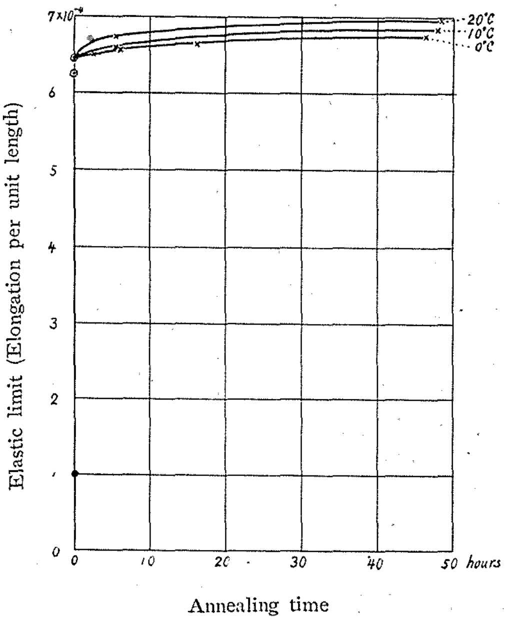
Fig. 8_2



durations of time, at temperatures respectively of 0°C, 10°C and 20°C, it was placed under elastic testing. The results are shown in Fig. 8_1. Instead of being cooled for 5 hours, the rods in the secondary state were cooled for 39 hours and then treated in the same manner as sbove. The results are shown in Fig. 8_2.

In order to compare the results in the case of stretching with those in the case of drawing through dies, rods in the same primary state as in Process I were drawn through dies to the same amount of elongation as above, that is 4.5%. This was the secodary state in the case of drawing through dies. Such rods were subjected to the elastic testing after being treated in the same manner as above. The results are shown in Figs. 8_3 and 8_4.

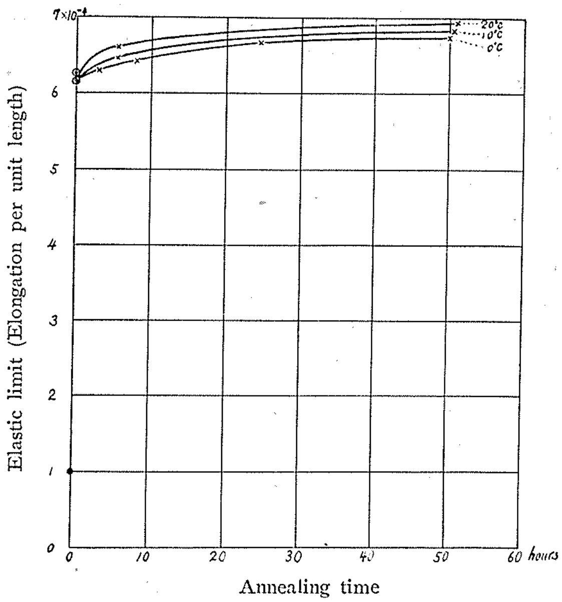
Fig. 8_3



Experimental Results

From Table I, it is found that the elastic limit changes with the duration

Fig. 8_4



of cooling time, but that Young's modulus remains almost constant. This fact is seen also everywhere through the elongation experiments carried out by the writer in room temperature.

The results obtained in Process I are shown in Fig. 1. In this figure, the elastic limit of the aluminium rod annealed at about 500°C for 6 hours, in the so called primary state, is represented by a large dot •, its value being 1.01×10^{-4}, and that of each group subjected to each different amount of elongation by a circle having a centre ⊙. Further the elastic limit of the specimen cooled by liquid air for different durations of time is represented by a small dot ·. From the marks ⊙, it is seen that the elastic limit increases according to the increase of elongation. This fact was reported in a previous paper.[1] Curves A, B, C, D and E represent the results obtained from specimens elongated by about 2, 4.7, 10, 15 and 20% respectively. From these curves, it is found that the elastic limit increases rapidly at first and then decreases slowly with the cooling time, and that the specimen elongated by a larger amount always takes a larger value for the same cooling time than one elongated to a smaller amount.

Process II used two kinds of rods drawn through dies, the amounts of elongation being about 20% and 4.7%. The results are shown in Fig. 2 where the marks •, ⊙ and · have the same meanings as before. Curves I and I′ which represent the results obtained by sudden cooling, go up at first and then go down slowly according as the cooling time increases.

The elastic limit of a rod placed in the cold air (at about -40°C)

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[1] These Memoirs, A. **22**, 199, (1939).

above the liquid air, is represented by a double circle ◎, and that of such a rod immersed then in liquid air by a small circle ○. Curves II and II′ represent the results obtained by such gradual cooling, and the former goes up at first and then goes down slowly with the cooling time, but the latter goes down slowly from the beginning. Curves I and I′ are situted higher than Curves II and II″ respectively excepting at the vicinity of the starting points. In comparing Curves I and II with Curves I′ and II′ respectively, we find that the elastic limits in the case of larger elongation are larger than those in the case of smaller.

The results obtained in Process III, the amounts of elongation by stretching being 20% and 4.7%, are shown in Fig. 3 where the marks have the same meanings as in Fig. 2. Curves I and I′ show the results obtained by sudden cooling, and Curves II and II′ those obtained by gradual cooling. The former go up rapidly at first and then go down slowly with the cooling time, while the latter go up gradually at first and then go down slowly. Curves I and I′ are situated higher than Curves II and II″ respectively excepting for about the first 2 hours of the cooling time. The curves in the case of larger elongation are situated higher than those in the case of smaller. On comparing Fig. 3 with Fig. 2, it becomes evident that in general the curves show almost the same tendency.

The results obtained with the specimen composed of large crystal grains are represented in Fig. 4 where the large dot denotes the primary state. The elastic limits obtained by sudden cooling are denoted by Curve I. The elastic limit obtained by leaving the specimen in the cold air at about–40°C for approximately 15 hours is denoted by a double circle. The elastic limits obtained by immersing such cooled specimens in liquid air for various durations of time are denoted by Curve II. The cross × above the end points of the curves denotes the elastic limits obtained when the specimens in the states corresponding to the end points of the curves were annealed for about 10 hours at 120°C and 80°C respectively. Curve I goes up rapidly at first and then goes down slowly with the cooling time, and Curve II goes up gradually at first and then goes down slowly. The latter curve is situated somewhat lower than the former excepting the small region at the starting point. The elastic limit of the specimen annealed after being taken out of the liquid air is somewhat larger.

In Fig. 5 showing the results obtained in Process V, the marks have the same meanings as described in Fig. 4. Curve I represents the result obtained by gradual cooling and Curve II that by annealing at about 90°C for about 10 hours after cooling. Curve I goes up gradually and then goes down slowly with the cooling time while Curve II goes up slowly. As seen from the curves, the elastic limits represented by Curve II are somewhat larger than those by Curve I.

In Fig. 6 showing the results obtained in Process VI, the marks have the same meanings as mentioned before, and the curve takes a form similar the curves in Fig. 1. When the specimens cooled suddenly by liquid air were annealed at 51°C for 6.5 hours and at 95°C for 6 hours respectively, their elastic limits were found to grow somewhat larger than the maximum value of the curve. Assuming that the annealing time is almost the same in each case, the value at the higher annealing temperature is somewhat larger than that at the lower.

In Fig. 7 representing the results obtained in Process VII, the marks have the same meanings as described before. The curve goes up gradually at first and then goes down slowly with the cooling time. When the specimen in the vicinity of the maximum point of the curve and that at the end point were annealed at about 90°C for about 10 hours, their elastic limits were seen to grow slightly larger in both cases.

The results obtained in Process VIII are represented in Figs. from 8_1 to 8_4 where the marks have the same meanings as before. As is seen from the curves, the elastic limit increases, to be sure, with the annealing time even with anealing temperatures as low as 0°C, 10°C and 20°C. But its amount of increase is very slight at the beginning of the annealing with those temperatures. Thus when the specimen is left at room temperature for about 1.5 hours after being taken out of the liquid air, its elastic limit is found to change only slightly; so that the specimen whose elastic limit was measured in room air in Processes from I to VII as described before, may be considered as almost identical in this respect with the same specimen immedictely after being taken out of the liquid air.

Consideration on the Results of the Experiment

In the present experiment, rods were cooled in three ways: by simply immersing the specimen in the liquid air, by placing it in the cold air (about–40°C) above the liquid air, and by placing it at first in the cold air mentioned above and then immersing it in the liquid air. The elastic testing was carried out within 1.5 hour after the rods were taken out into the room air. Thus the specimen being annealed during this period of testing at room temperature, the elastic limit measured is considered to give a slightly elevated value. But as the influence of such annealing upon the elastic limit must be considered to be very small as described above, the elastic limit measured in the room air may be expected in general to take approximately the same value it would just after being taken out of the cold place.

When the cold worked specimen is heated at approximately 500°C for about 6 hours, the crystallites grow considerably larger by recrystallization. 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 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 our case of aluminium at room temperature, the elastic limit increases 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 severely 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. This is just the same as in the case of plastic elongation, and the sudden cooling to the temperature of liquid air increases the elastic limit in the beginning of the cooling time as seen in Fig. 1. A certain quantity of crystallites breaks during the early period of cooling, but after that there is scarcely any further destruction of them; but the weak cohesion between crystallites at some localities increases and the unevenness of the internal stresses among crystallites is enhanced gradually with cooling time, by the lack of the recovery observed at temperatures higher than the room temperature. Hence after a certain cooling time, the elastic limit decreases gradually with the cooling time as is seen in Fig. 1.

When the specimen cold worked by stretching is cooled at a somewhat higher temperature, for example–40°C, by the air above the liquid air, it contracts in smaller amount than when cooled by the liquid air, and the destruction of crystallites, the weak cohesion between crystallites at some localities and the unevenness of the internal stresses among crystallites are all smaller than before; and consequently the increase of the elastic limit is smaller as shown by the starting point ◎ of Curve II or II′ in Fig. 3. In comparing the case when the specimen cooled at first by cold air and then cooled further by liquid air with the case when it is cooled directly by liquid air from the beginning, Fig. 3 shows that the elastic limit is as a whole somewhat smaller in the former case than in the latter. This seems to be due to the smaller amount of destruction of crystallites, of weak cohesion between crystallites and of the unevenness of the internal stresses among crystallites in the former case.

The fact that the starting point ⊙ of Curve I or I′ in Fig. 2 is situated higher than that in Fig. 3 is considered to be due to the severer destruction of crystallites when the specimen is drawn through dies than when it is elongated by stretching. When a specimen prepared by drawing through dies is cooled suddenly or gradually by liquid air, the amount of increase of the elastic limit is smaller than in that prepared by stretching. This fact seems to be caused by the fact that a further destruction of crystallites occurs only to a small extent in the former case. Especially, when the specimen drawn through dies is cooled at first by cold air at about–40°C and then cooled in liquid air, any further destruction of crystallites must be almost imperceptible; and only the weak cohesion between crystallites at some localities and the unevenness of the internal stresses among crystallites increase gradually as a whole on the continued cooling, Thus the elastic limit decreases from the starting point or from its neighbour with the time of cooling as shown by Curves II and II′ in Fig. 2.

When the specimen composed of large crystal grains, which are formed by recrystallization, is cooled suddenly or gradually by liquid air, the destruction of crystallites results; and at the same time localities of weak cohesion between crystallites develop and unevenness of the internal stresses among crystallites is also produced in the structure as in the former cases. As seen in Fig. 4, the influence of those changes upon the elastic limit is similar to that in the former cases. When the specimen cooled by liquid air for a certain time is heated at a relatively low temperature, for example 80°C or 120°C, the elastic limit increases slightly. This fact is due to the recovery to a normal state of the localities of weak cohesion between crystallites and of the unevenness of the internal stresses among crystallites. Such a recovery is seen more clearly in Fig. 5, where the specimen at various stages of cooling time is annealed at approximately 90°C for about 10 hours. As is seen in Fig. 7, where the specimen prepared by heating at about

500°C for about 6 hours is used, and in Fig. 6, where the specimen elongated by stretching after being heated is used, such a recovery as described above makes the elastic limit somewhat higher.

From these considerations, the following conclusions may be drawn. When the specimen composed of relatively small crystallites is cold worked by stretching or by drawing through dies, the crystallites are broken into smaller pieces on the one hand and on the other, the localities of weak cohesion between crystallites and the unevenness of the internal stresses among crystallites occur at the same time somewhere in the structure. The former makes the elastic limit higher and the latter makes it smaller. The elastic limit as measured is thus the resultant of these two effects. The fact that the elastic limit of the specimen of aluminium prepared by cold working becomes greater is due to the predominance of the former effect.

When the specimen prepared by annealing or by cold working is cooled suddenly or gradually by liquid air, the crysallites are broken into smaller pieces by the severe contraction on the one hand and on the other, localities of weak cohesion between crystallites and unevenness of the internal stresses among crystallites result in the structure at the same time. In the beginning of cooling time, the former effect predominates over the latter, so the elastic limit increases. After a certain time, the destruction of crystallites almost ceases, but gradually the weak cohesion between crystallites at some localities increases and the unevenness of the internal stresses among crystallites grows larger, and accordingly the elastic limit decreases slowly with the cooling time.

When the specimen in such a state is annealed at a relatively low temperature, for example 90°C or 120°C, the localities of weak cohesion and the unevenness of the internal stresses gradually recover to the normal state, and accordingly the elastic limit increases.

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