

## Sub-Zero Treatment of Quenched Steel. I : On the Stabilization of Retained Austenite

著者	IMAI Yunoshin, IZUMIYAMA Masao
journal or publication title	Science reports of the Research Institutes, Tohoku University. Ser. A, Physics, chemistry and metallurgy
volume	10
page range	414-425
year	1958
URL	<a href="http://hdl.handle.net/10097/26893">http://hdl.handle.net/10097/26893</a>

# Sub-Zero Treatment of Quenched Steel. I On the Stabilization of Retained Austenite\*

Yûnoshin IMAI and Masao IZUMIYAMA

*The Research Institute for Iron, Steel and Other Metals*

(Received October 15, 1958)

## Synopsis

As a fundamental study of sub-zero treatment of steel, the effects of quenching temperature, room temperature aging and tempering on the stabilization of retained austenite were examined. The stabilization of retained austenite was promoted by aging, because the martensite transformation rate due to subsequent sub-zero cooling was increased by the increase in aging, and moreover, when aging increased, the martensite transformation rate passed through a maximum. The martensite transformation due to subsequent sub-zero cooling gave rise to the burst transformation when aging increased to a certain degree. The remarkable increase in the stabilization was caused by the increase in the amount of prior martensite, though the stabilization occurred without prior martensite. It was suggested that the stabilization of austenite was caused by a mechanism similar to age-hardening.

## I. Introduction

When quenched steel is further cooled at low temperature, retained austenite is, as well known, transformed into martensite, and physical and mechanical properties of steel can be improved by this treatment<sup>(1)~(15)</sup>. There have been many investigations, in which the hardness<sup>(11)(12)</sup>, dimensional stability<sup>(13)(14)</sup> and wear resistance<sup>(15)</sup> of quenched steel are increased by sub-zero treatment.

To make sub-zero treatment effective, the stabilization of retained austenite is the most important problem to be solved. If quenched steel is held at room temperature, retained austenite will become stable, and the transformation of retained austenite into martensite will be hard to occur during subsequent sub-zero

---

\* The 921st report of the Research Institute for Iron, Steel and Other Metals.

- (1) J. A. Mathews, *Trans. Amer. Soc. Steel Treat.*, **8** (1925), 565.
- (2) W. P. Sykes and Z. Jeffries, *ibid.*, **12** (1927), 871.
- (3) E. Harder and R. L. Dowdell, *ibid.*, **9** (1927), 391.
- (4) K. Honda and K. Iwase, *ibid.*, **9** (1927), 399.
- (5) E. C. Bain and W. E. Griffiths, *Trans. Amer. Inst. Min. Met. Eng.*, **75** (1927), 166.
- (6) V. N. Krivobok and M. A. Grossman, *Trans. Amer. Soc. Steel Treat.*, **18** (1930), 808.
- (7) O. E. Brown, *Materials & Method*, **24** (1946), 1445.
- (8) P. Gordon and M. Cohen, *Trans. Amer. Soc. Metals*, **30** (1942), 569.
- (9) S. G. Fletcher and M. Cohen, *ibid.*, **34** (1945), 216.
- (10) S. G. Fletcher, M. Cohen and B. L. Averbach, *ibid.*, **40** (1948), 703.
- (11) H. E. Boyer, *Iron Age*, **161** (1948), No. 7, 69; No. 8, 78; No. 9, 85.
- (12) M. Kondo and T. Hachisuka, *Nippon Kinzoku Gakkai-Si*, **21** (1957), 227.
- (13) B. L. Averbach, M. Cohen and S. G. Fletcher, *Trans. Amer. Soc. Metals*, **40** (1948), 728.
- (14) B. S. Lement, B. L. Averbach and M. Cohen, *ibid.*, **41** (1949), 1061.
- (15) M. Kondo, *Nippon Kinzoku Gakkai-Si*, **19** (1955), 62.

cooling. Consequently,  $M_s$ ' point, at which retained austenite transforms into martensite, will become lower, and the amount of martensite transformed by subsequent sub-zero cooling will be decreased due to stabilization.

Such being the case, the present investigation was carried out on the stabilization of austenite to give light on the fundamentals of sub-zero treatment of quenched steel.

## II. Experiment

Four kinds of steels were used, the respective compositions being shown in Table 1. Steel SUJ-2 is the commercial bearing steel. Steels 1C, 1C3R and 1C5Ni

Table 1. Chemical analysis (weight per cent)

Steel	C%	Si%	Mn%	P%	S%	Ti%	Cr%	Ni%
1C	1.14	0.23	0.33	0.003	0.019	—	—	—
SUJ-2	1.02	0.18	0.38	0.027	0.019	—	1.35	—
1C3R	1.14	0.084	0.024	0.003	0.020	0.040	3.28	—
1C5Ni	1.12	0.27	0.33	0.003	0.017	—	—	4.98

were melted in a high frequency induction furnace. After casting into a chill mould of 40 mm diameter and then forging to 7 mm diameter, specimens were annealed at 1100°C for 24 hours. The specimen for dilatometric measurement was of 5 mm diameter and 100 mm length, and that for magnetic measurement was of 5 mm diameter and 70 mm length. For hardness measurement, the specimen, 10 mm in diameter and 10 mm in length, was used. Steel SUJ-2 was used mainly for the experiment, while the other steels were used for an additional experiment. The apparatus for the dilatometric measurement is shown in Fig. 1, temperature range of which was from room temperature to  $-196^\circ\text{C}$ . For the homogeneous distribution of temperature of the dilatometer, copper pipe, 8 mm in outside diameter, was wound on 20 mm thick copper block, and this was wrapt with asbestos and

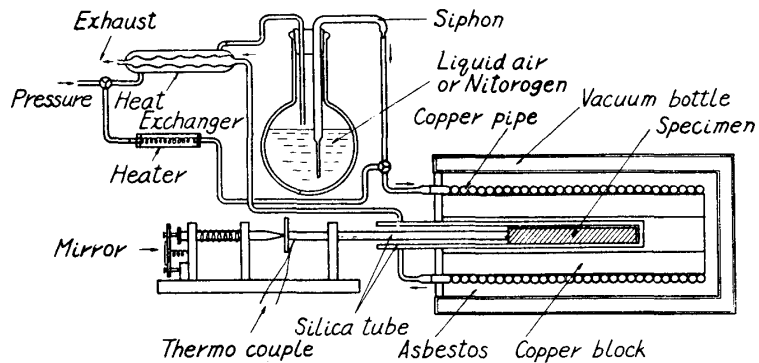


Fig. 1. Schematic diagram of cryostat used for cooling and heating the dilatometer at controlled rates below room temperature.

put into the steel Dewar flask. Liquid air or liquid nitrogen was used for cooling and put into copper pipe, 8 mm in diameter, which was wound in spiral. For heating, the heater was set in the by-path and the heated air in it was sent into copper pipe. As the moisture in air would be frozen in path at cooling, the heat exchanger equipment was set on the way to path. The cooling rate was  $1^\circ\text{C}/\text{min}$ .

The ballistic method was used for the magnetic measurement.  $M_s$  point was determined with Sato's rapid action dilatometer or microscope. Specimens were all heated in vacuum of  $10^{-5}$  mm Hg.

### III. Result

#### 1. Estimation of $M_s$ point and retained austenite

The carbides in steel SUJ-2 can not perfectly dissolve below  $950^\circ\text{C}$ . Therefore, the increase in concentration of austenite is caused by the rise in austenitizing temperature. When quenching temperature was raised,  $M_s$  point fell remarkably as shown in Fig. 2.

Retained austenite was estimated by magnetic analysis. For the standard specimen the same kind of steel heated at  $1000^\circ\text{C}$  for 1.5 hours and cooled in the furnace was used. As the magnetic saturation value of the standard specimen

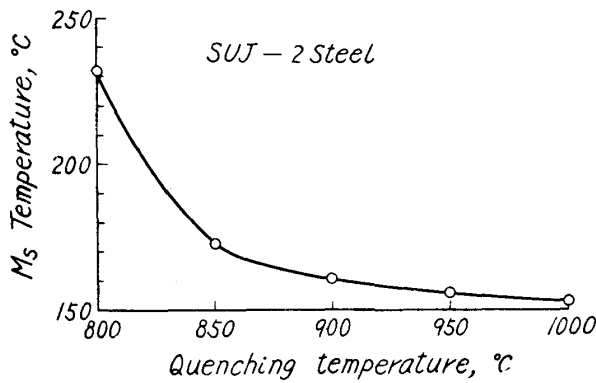


Fig. 2. Change of  $M_s$  points when quenched in oil at each quenching temperature.

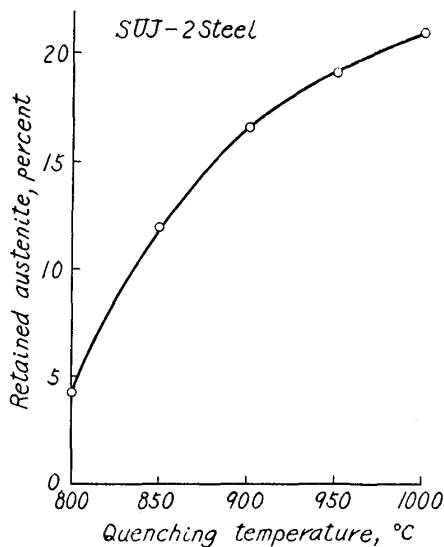


Fig. 3. Effect of quenching temperature on amount of retained austenite in the ball-bearing steel.

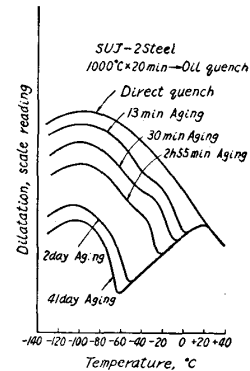


Fig. 4. Dilatometric changes of the ball-bearing steel by sub-zero cooling after quenching and aging at room temperature.

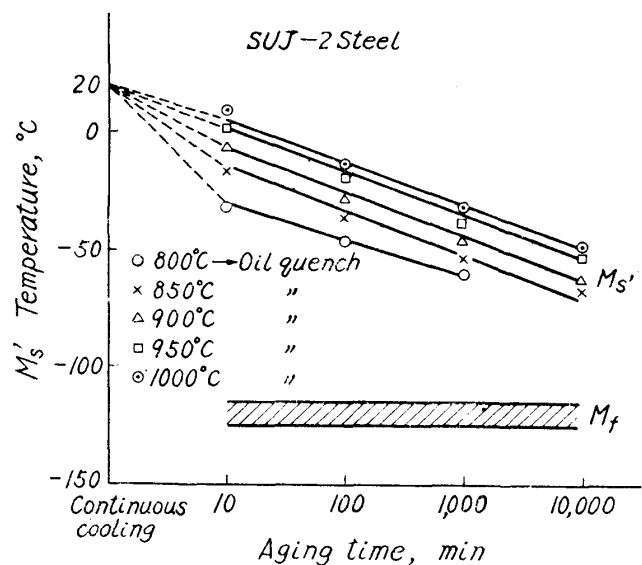


Fig. 5. Effect of room temperature aging on the transformation range of retained austenite during sub-zero cooling to  $-196^\circ\text{C}$ .

coincided almost with that of all martensite specimen, the amount of retained austenite was estimated from the ratio of the magnetic saturation value of the standard specimen to that of the quenched specimen. The intensity of magnetic field was about 1500 oersteds. Fig. 3 shows the relationship between the amount of retained austenite and the quenching temperature. Retained austenite increases with the rise in quenching temperature, and this change corresponds to the fall of  $M_s$  point.

2. Influence of quenching temperature and subsequent room temperature aging on  $M_s'$  point.

The dilatation curves of steel SUJ-2 during sub-zero cooling are shown in Fig. 4. Though a steel is quenched at  $1000^\circ\text{C}$  to room temperature and then aged at this temperature, the martensite transformation will not occur continuously at room temperature, but it will occur after super-cooling by a certain degree due to subsequent sub-zero cooling. The fall of  $M_s'$  point is caused by the increase in room temperature aging, that is, the stabilization occurs during room temperature aging. Fig. 5 shows the relationship between the room temperature aging and  $M_s'$  point of steel SUJ-2.  $M_s'$  point falls with the increase in aging time and with the lowering of quenching temperature.  $M_f$  point which finishes martensite transformation will not be influenced by room temperature aging. It is very interesting that there is no change in  $M_f$  point even though the concentration of austenite is changed by the change in quenching temperature.

Fig. 6 shows the relationship between the amount of expansion of retained austenite due to martensite transformation and room temperature aging. The amount of expansion decreases with the increase in aging time, that is, the amount of martensite transformation decreases with the increase in aging time. The increase in the amount of expansion is caused by the rise in quenching temperature, but the rate of change in the amount of expansion decreases with the rise in quenching temperature. This shows that retained austenite becomes hard to be stabilized by subsequent aging with the rise in quenching temperature, which coincides with the result by Averbach, Cohen and Fletcher.<sup>(13)</sup>

3. Influence of sub-zero treatment on magnetic properties

Fig. 7 shows the change in magnetic properties of steel SUJ-2 due to sub-zero treatment. The magnetic saturation ( $B_{\max}$ ) and the residual induction ( $Br$ ) were

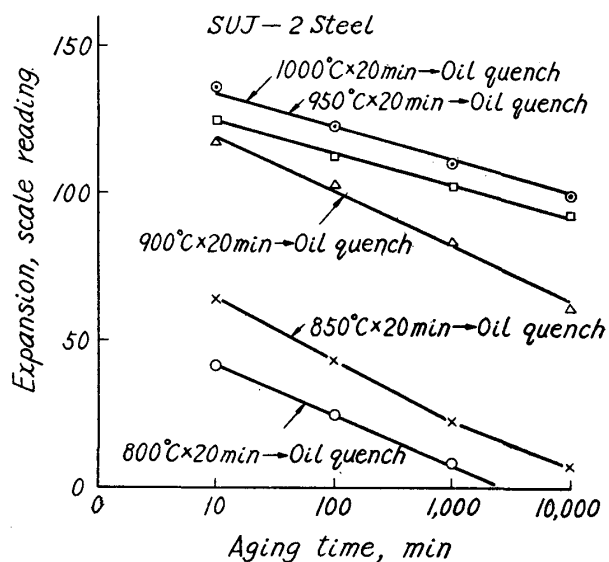


Fig. 6. Correlation between room temperature aging time after quenched at various austenitizing temperature and expansion amount of retained austenite into martensite transformation by following sub-zero treatment.

increased by sub-zero treatment. These specimens were subjected to sub-zero cooling to  $-196^{\circ}\text{C}$  immediately after quenching, and so most retained austenite was transformed into martensite. The reason why the increase in  $B_{\text{max}}$  of the specimens

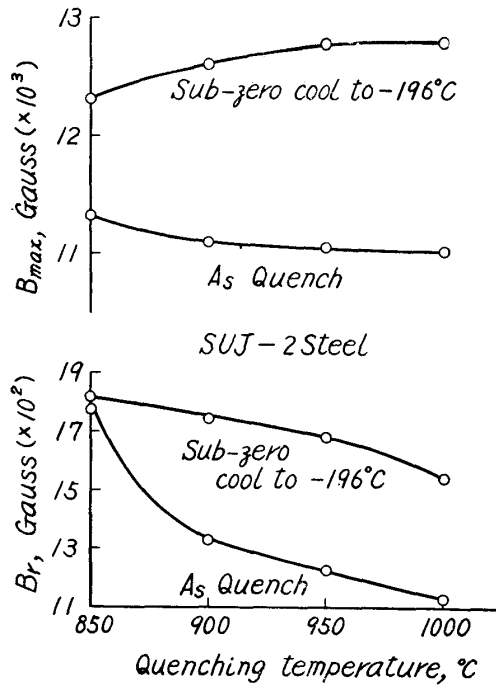


Fig. 7. Effect of sub-zero cooling on the magnetic properties of the ball-bearing steel quenched at various temperatures.

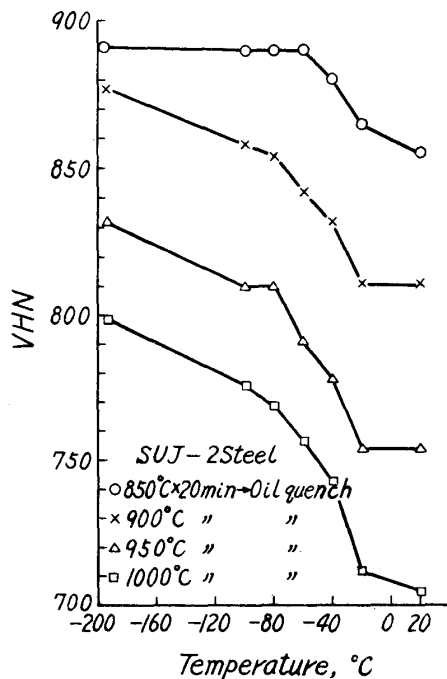


Fig. 8. Change in hardness of the ball-bearing steel quenched at various temperatures due to sub-zero cooling after aging.

cooled to sub-zero temperature after quenched at  $850^{\circ}$  and  $900^{\circ}\text{C}$  is small compared with those quenched at  $1000^{\circ}\text{C}$  is seemed to be due to the existence of chromium rich carbides. The value of  $B_r$  decreased with the increase in quenching temperature, but it could mostly be recovered by sub-zero treatment. Coercive force ( $H_c$ ) is decreased remarkably by sub-zero treatment. For instance, the coercive force of specimen quenched at  $850^{\circ}\text{C}$  decreased from 56.9 to 6 oersteds after subsequent sub-zero cooling.

4. Influence of sub-zero treatment on hardness

Fig. 8 shows the change in hardness of steel SUJ-2 due to sub-zero treatment. Specimens were cooled to sub-zero temperature after the aging at room temperature for 16 days. The temperature at which the hardness increased remarkably was about  $-20^{\circ}\text{C}$ , which was higher than  $M_s'$  point obtained from the dilatometric measurement. The reason for

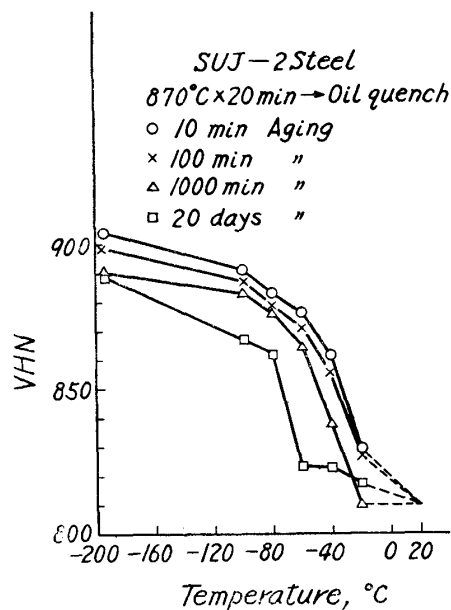


Fig. 9. Change in hardness of the ball-bearing steel quenched at  $870^{\circ}\text{C}$  due to sub-zero cooling after aging for various periods at room temperature.

this seems to be that the martensite transformation is accelerated with the subsequent sub-zero cooling, because the specimen is deformed by the hardness testing. The increase in hardness due to sub-zero cooling is caused by the rise in quenching temperature, but the ultimate hardness of specimen quenched at higher temperature to room temperature is lower than that quenched at lower temperature, because the hardness of quenched state decreases with the rise in quenching temperature. Fig. 9 shows the change in hardness of steel SUJ-2 quenched from 870°C due to subsequent sub-zero cooling after aging at room temperature for various periods. The increase in hardness due to sub-zero cooling lowered with the prolongation of aging time at room temperature, and the temperature at which the hardness begins to increase falls appreciably. This shows that retained austenite is stabilized by room temperature aging.

5. Influence of tempering

Fig. 10 shows the relationship in steel SUJ-2 between tempering time at 100°C and  $M_s'$  point at subsequent sub-zero cooling. The fall of  $M_s'$  points is caused by the lowering of quenching temperature. This tendency was the same as in the case of room temperature aging. The specimen quenched at 1000°C was most hard to be stabilized. The retained austenite became unstable and  $M_s'$  point began to rise by tempering over one hour at 100°C. The stabilization of retained austenite in steels quenched at 900°C and 950°C did not proceed above a certain degree though tempering time was prolonged. In the steel quenched at 850°C, the stabilization proceeded with the prolongation of tempering time, and in this case  $M_s'$  point neither rose nor remained constant; the stabilization occurred mainly within 1 minute tempering even the steel was quenched at any temperature.  $M_f$  point could not be changed

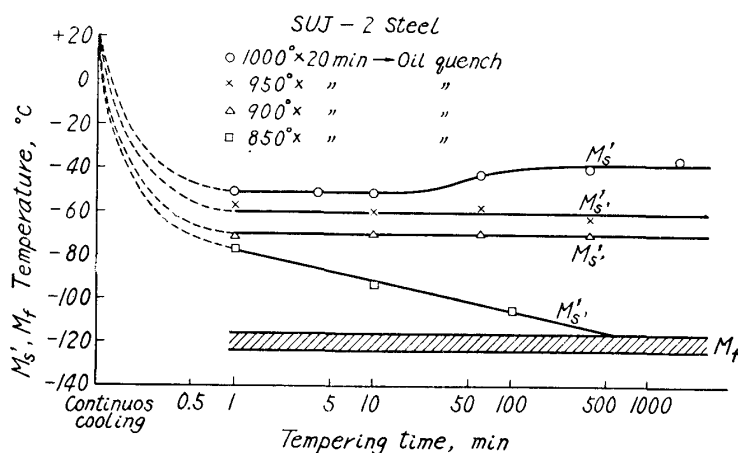


Fig. 10. Change of  $M_s'$  and  $M_f$  points by austenitizing temperatures, tempering temperatures and tempering times prior to sub-zero cooling.

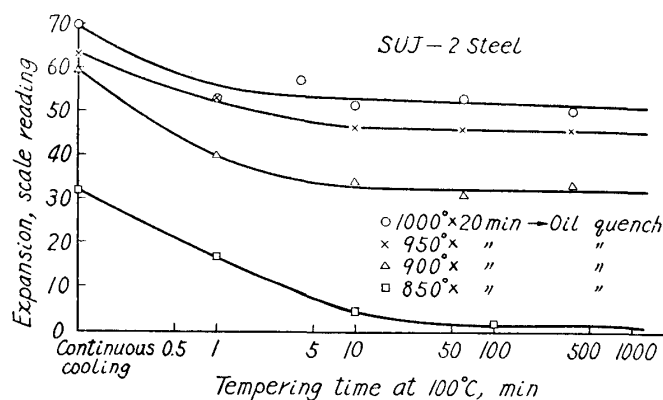


Fig. 11. Correlation between tempering time at 100°C after quenching at various austenitizing temperatures and expansion amount of retained austenite to martensite transformation by following sub-zero cooling.



by quenching temperature and tempering time, that is, it was about  $-120^{\circ} \pm 4^{\circ}\text{C}$ .

Fig. 11 shows the relationship between tempering time and amount of expansion of martensite transformation by sub-zero cooling after tempering at  $100^{\circ}\text{C}$ , the specimen being steel SUJ-2. The expansion decreased with the lowering of quenching temperature and with the increase in tempering time. As shown in Fig. 10,  $M_s'$  point of steel quenched at  $1000^{\circ}\text{C}$  rose, when tempering time was increased more than 1 hour at  $100^{\circ}\text{C}$ , but the phenomenon equivalent to this change was not observed in curves of expansion of martensite transformation shown in Fig. 11.

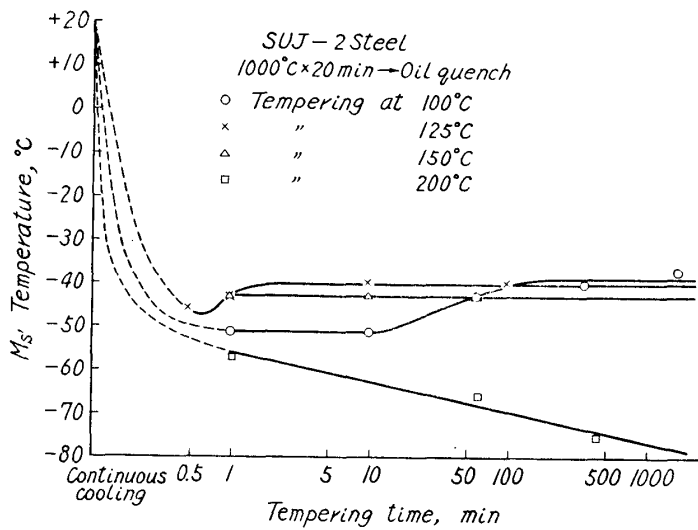


Fig. 12. Correlation between  $M_s'$  points and various tempering prior to sub-zero cooling.

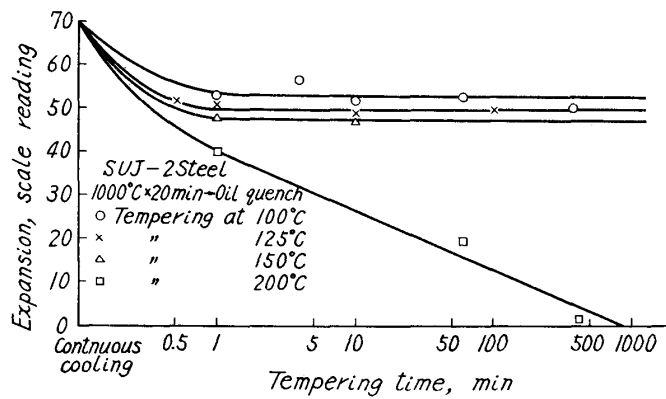


Fig. 13. Correlation between tempering times at various temperature and expansion amount of retained austenite to martensite transformation by following sub-zero cooling.

rise in tempering temperature, but no change could be observed in the tempering below  $150^{\circ}\text{C}$  for over 1 minute. The expansion of martensite transformation decreased with the increase in tempering time according to the decomposition of retained austenite by  $200^{\circ}\text{C}$  tempering. Fig. 14 shows the relationships of the tempering temperature to the expansion amount, to  $M_s'$  point and to  $M_f$  point in steel SUJ-2 quenched at  $1000^{\circ}\text{C}$ , tempering time being 10 minutes.  $M_s'$  point

Fig. 12 shows the change in  $M_s'$  point of steel SUJ-2 quenched at  $1000^{\circ}\text{C}$  due to the change in tempering time at various temperatures. The tempering time necessary to raise  $M_s'$  points of specimens tempered at  $125^{\circ}\text{C}$  and  $150^{\circ}\text{C}$  was shorter than that of the specimen at  $100^{\circ}\text{C}$ .

The rise of  $M_s'$  point shown again after the stabilization will be due to a certain conditioning occurring in retained austenite during tempering.  $M_s'$  point continuously fell with the increase in the tempering time at  $200^{\circ}\text{C}$ , which can not be considered to be due to the stabilization of retained austenite, because a part of retained austenite is decomposed by this tempering. Fig. 13 shows the change in the expansion of martensite transformation in steel SUJ-2 quenched at  $1000^{\circ}\text{C}$  by tempering time at various temperatures. The expansion decreased with the



decreased with the rise of tempering temperature to 100°C due to the stabilization of retained austenite, then increased with the rise of tempering temperature from 100° to 125°C and finally decreased above 125°C according to the decomposition of retained austenite. The change in  $M_f$  point could not be observed by tempering. The change equivalent to that in  $M_s'$  point could not be observed in the expansion of martensite transformation. Therefore, the amount of retained austenite that gives rise to a certain conditioning during tempering will be very small in steel SUJ-2. Fig. 15 shows the relationship among the quenching temperature,  $M_s'$  point and  $M_f$  point in steel SUJ-2. The form of the curve of  $M_s'$  point of the steel aged at room temperature for 10 minutes was of the same type as that tempered at 100°C for 1 minute.  $M_s'$  point of the steel tempered at 100°C for 6 hours, however, fell remarkably with the lowering of quenching temperature and rose conversely with the rise of quenching temperature.

#### IV. Discussion

The stabilization of austenite has been studied by many workers.<sup>(8)~(10)</sup><sup>(16)~(33)</sup> Previous work<sup>(13)</sup> has shown that retained austenite becomes hard to be stabilized by subsequent aging with the result of the rise of austenitizing temperature, which was also confirmed in the present work. Steel SUJ-2 is bearing steel containing high carbon and chromium, and so some undissolved carbides

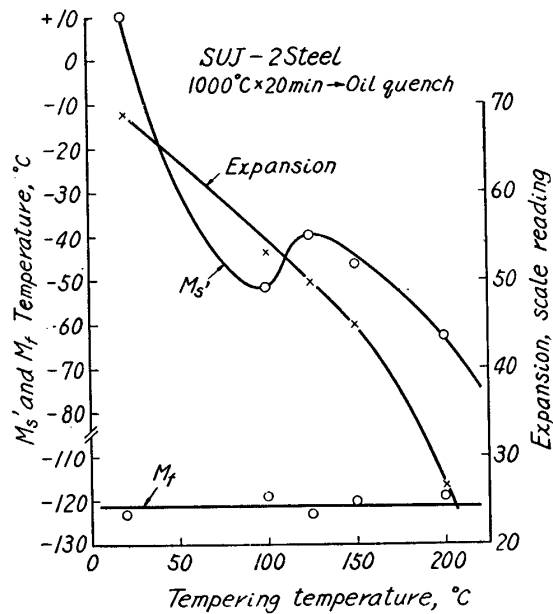


Fig. 14. Change of  $M_s'$ ,  $M_f$  points and expansion amount of retained austenite into martensite transformation by sub-zero cooling after various tempering.

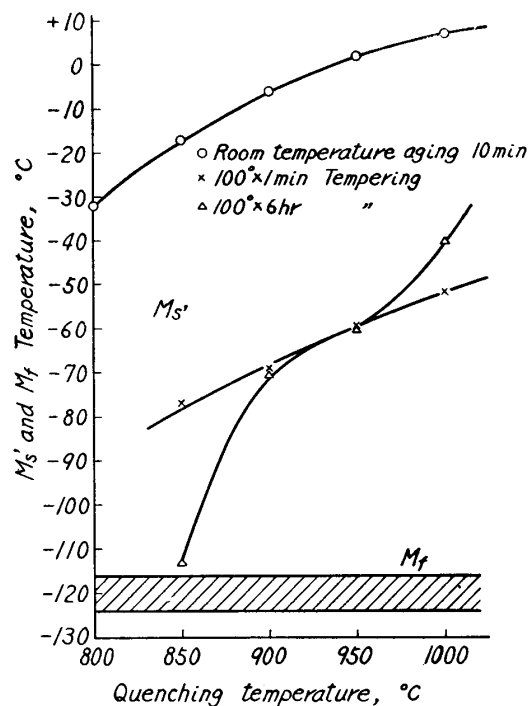


Fig. 15. Change of  $M_s'$  and  $M_f$  points that were affected by austenitizing temperature, tempering and aging conditions prior to sub-zero treatment.

(16) A. P. Gulyaev, *Metallurg*, **14** (1939), 64.

(17) H. P. Nielson and R. L. Dowdell, *Trans. Amer. Soc. Metals*, **22** (1934), 810.

(18) E. P. Klier and A. R. Troiano, *Trans. Amer. Inst. Min. Met. Eng.*, **162** (1945), 175.

(19) T. Lyman and A. R. Troiano, *Trans. Amer. Soc. Metals*, **37** (1946), 402.

(20) A. R. Troiano, *ibid.*, **41** (1949), 1093.

(21) Y. Imai and M. Izumiyama, *Nippon Kinzoku Gakkai-Si*, **19** (1955), 358.

exist in austenite at 950°C. Therefore, the concentration of austenite varies with the change in austenitizing temperature. Consequently, the reason for the difficult stabilization of retained austenite is not clear, that is, whether it is due to the change in austenitizing temperature itself or the change in the concentration of austenite follows the change in austenitizing temperature is undeterminable. To

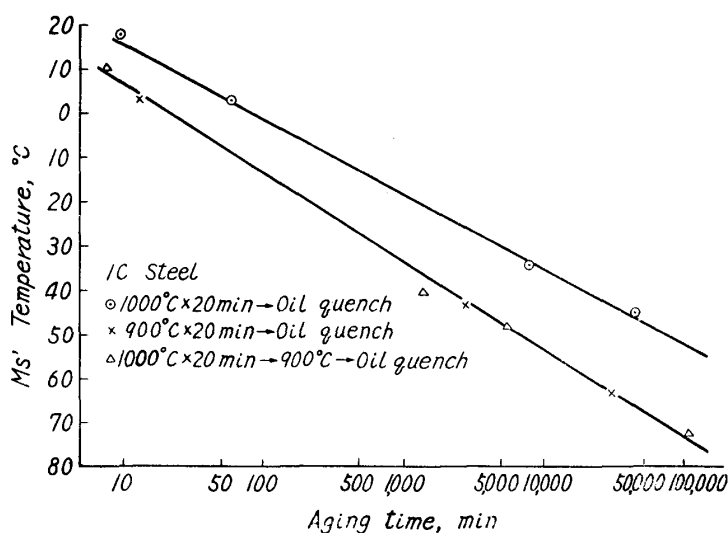


Fig. 16. Correlation between  $M_s'$  points and aging times by various austenitizing temperature.

clarify this point, steel 1C, in which carbides are easily dissolved by heating, was austenitized at 900° and 1000°C which is higher than  $Ac_3$  point. Fig. 16 shows this result. Carbides in this steel were dissolved perfectly in austenite, and austenite was homogenized within 20 minutes at 900° and 1000°C, but the specimen quenched at 1000°C was hard to be stabilized. Austenite grain size number of the specimen quenched at 900°C was 10 ASTM and that of the specimen quenched at 1000°C was 5.3 ASTM. So, the hard stabilization mentioned above may be due to the growth of austenite grain caused by the rise of austenitizing temperature. Further, steel 1C was quenched at 900°C immediately after heating at 1000°C and subsequent slow cooling to 900°C in furnace. The same austenite grain size as that in the steel quenched directly at 1000°C could be obtained by this treatment. The change in  $M_s'$  point by this treatment was just the same as that of the steel quenched directly at 900°C. This seems to show that austenite grain size for the stabilization is not influenced. Fig. 3 shows that the amount of prior martensite transformed during quenching to room temperature decreases with the rise of quenching temperature. Previous works<sup>(8),(9),(17),(32)</sup> have reported that the stabilization of retained austenite proceeds with the increase in the amount of martensite present at initial quenching.

- (22) Y. Imai and M. Izumiyama, *ibid.*, **20** (1956), 615.
- (23) J. H. Hollomon, L. D. Jaffe and D. C. Buffum, *J. Appl. Phys.*, **18** (1947), 780.
- (24) L. C. Chang and T. A. Read, *Trans. Amer. Inst. Min. Met. Eng.*, **189** (1951), 47.
- (25) J. S. Fisher, J. H. Hollomon and D. Turnbull, *ibid.*, **185** (1949), 691.
- (26) E. R. Morgan and T. Ko., *Acta. Met.*, **1** (1953), 36.
- (27) M. Cohen, *Trans. Amer. Soc. Metals*, **41** (1949), 35.
- (28) E. S. Machlin and M. Cohen, *J. Metals*, **4** (1952), 489.
- (29) J. Philibert, *Compt. Rend.*, **240** (1955), 190.
- (30) S. Okamoto and R. Odaka, *Nippon Kinzoku Gakkai-Si*, **16** (1952), 81.
- (31) Y. Imai and M. Izumiyama, *ibid.*, **21** (1957), 437.
- (32) S. G. Glover and T. B. Smith, *The Mechanism of Phase Transformation in Metals* (1956), 265.
- (33) J. Plateau, J. Duflot and C. Crussard, *Rev. Mét.*, **49** (1952), 815.

Therefore, when the quenching temperature is low, the stabilization will proceed remarkably with the increase in the amount of prior martensite. The existence of prior martensite is of very important factor in order to proceed the stabilization, but it can induce the stabilization even when there is no prior martensite. Morgan and Ko<sup>(26)</sup> has investigated the stabilization above  $M_s$  point, by using 1 per cent carbon steels containing up to 10 per cent nickel, and reported that  $M_s$  point could be depressed by isothermal holding at a certain temperature above  $M_s$  point. In the present experiment the same result was obtained by using 1 per cent carbon steel containing 5 per cent nickel as shown in Fig. 17. This  $M_s$  point was estimated by Greninger and Troiano<sup>(34)</sup> method. The change in  $M_s$  point caused by isothermal holding at 200°C above  $M_s$  seems to show the fact that the stabilization can occur without prior martensite. The stabilization above  $M_s$  point will occur probably by some internal rearrangement followed by the change in thermal stress in austenite during isothermal holding above  $M_s$  point. The existence of martensite is not always a necessary condition for the stabilization, but the stress followed by martensite transformation seems to give the influence. Therefore, if some stress such as thermal or mechanical stress is given, the stabilization will proceed without the stress of martensite transformation due to aging.

It has been observed that the forms of dilatation curves during sub-zero cooling are changed by prior aging. As shown in Fig. 4, dilatation curves obtained by continuous cooling from austenitizing temperature to sub-atmospheric

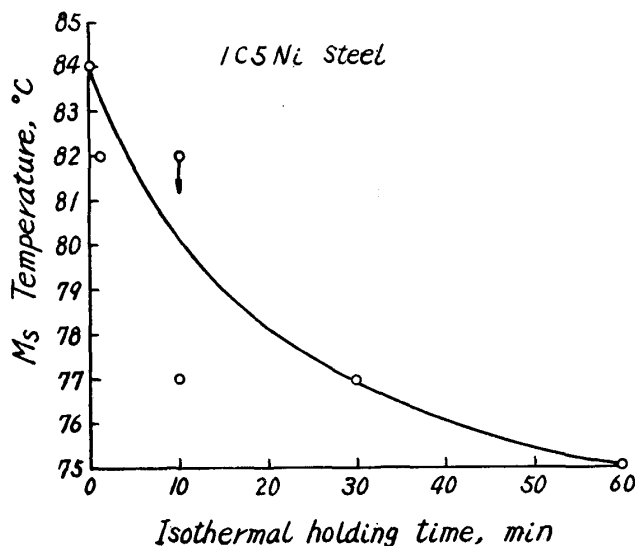


Fig. 17. Effect of isothermal holding time at 200°C on  $M_s$  points.

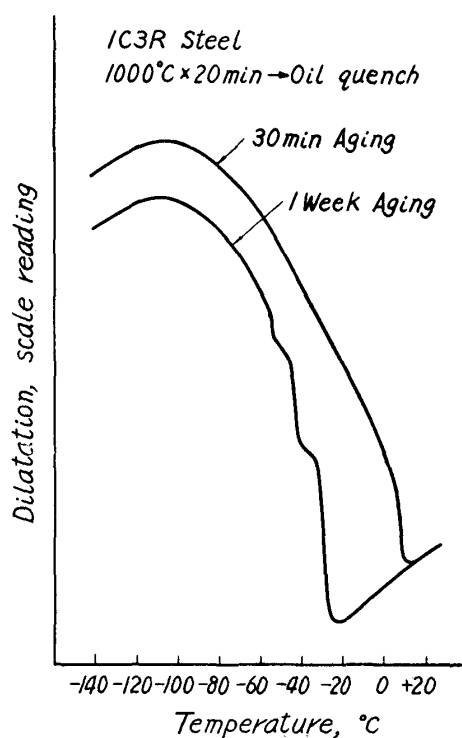


Fig. 18. Dilatometric changes of the 1C3R steel by sub-zero cooling after quenched at 1000° and aging at room temperature.

(34) A. B. Greninger and A. R. Troiano, Trans. Amer. Soc. Metals, 28 (1940), 537.

temperature are smooth, whereas curves obtained by aging for 13 minutes to 2 hours 55 minutes at room temperature after quenching are of step-like form. The form of curve becomes again smooth with the further increase in room temperature aging. Moreover, according to the additional experiment with steel 1C3R, the dilatation curves obtained by aging at room temperature for 30 minutes were

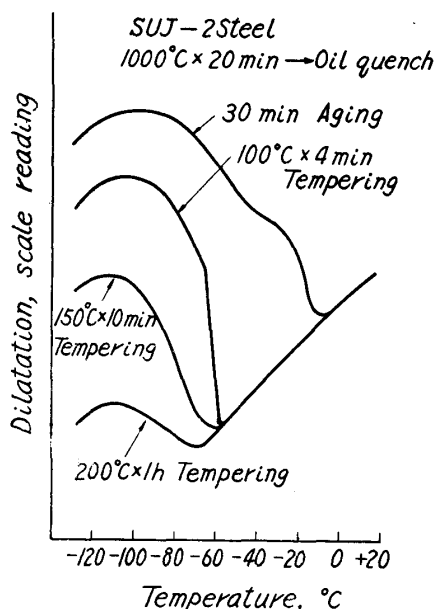


Fig. 19. Dilatometric changes of the ball-bearing steel by sub-zero cooling after quenching at 1000° and tempering at various temperature.

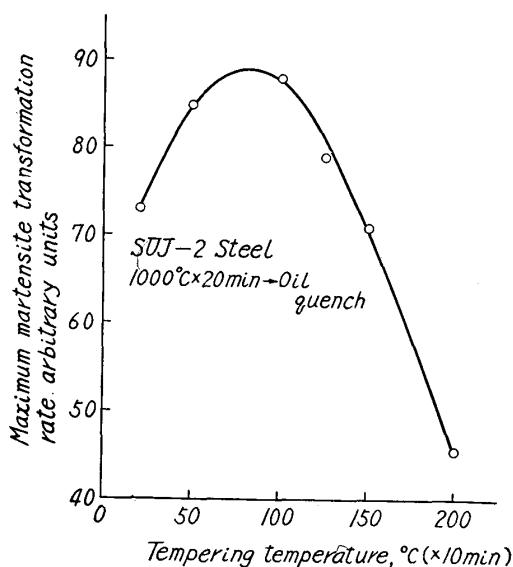


Fig. 20. Effect of tempering temperature on the maximum martensite transformation rate (maximum gradient of dilatation curve).

comparatively smooth, whereas those for a week were step-like as shown in Fig. 18.

Furthermore, the initial martensite transformation at  $M_s'$  point of the specimen aged for a week was burst transformation. Fig. 19 shows the dilatation curves of steel SUJ-2 during sub-zero cooling after various temperings. The gradients of the dilatation curves pass through the maximum at 100°C. The gradient can be considered as the rate of martensite transformation. Fig. 20 shows the relationship between the maximum gradient of dilatation curve and tempering temperature. Martensite transformation rate passes through the maximum at about 80°C. To take the mechanism of stabilization into consideration, it is very important that (1) the martensite transformation rate by stabilization passes through the maximum; (2) the dilatation curve becomes step-like; (3) bursting martensite transformation sometimes occurs.

The transformation of austenite into martensite induces a considerable stress in steel. To reduce this strain energy the mechanism of the motion and the multiplication of perfect dislocations must be considered. The propagation of martensite transformation is a certain sort of slip deformation, and therefore, the stabilization may be explained from age-hardening, in which, if the deformation is interrupted and the steel is aged, the stress necessary for slip will increase discontinuously at the subsequent deformation.

As the most probable mechanism of the stabilization, it may be suggested that the stabilization is caused by reducing the mobilities of dislocations during com-

paratively low temperature aging such as room temperature aging or further lower temperature aging, because interstitial solute atoms such as carbon or nitrogen will lock dislocations. On the other hand, the stabilization will also be caused by the mechanical blocking of the motion of dislocation lines that can be produced most directly by the precipitation of tiny particles of a second phase such as carbide or nitride in austenite during comparatively high temperature aging. Thus, it can be seen that the martensite transformation rate during sub-zero cooling passes through the maximum with the increase in aging, and that the bursting martensite transformation occurs by stabilization.

### Summary

- (1) Retained austenite becomes hard to be stabilized by subsequent aging with the rise of quenching temperature. This phenomenon seems to depend on the quenching temperature but to be independent of the change in the concentration of austenite or the growth of austenite grain followed by the change in quenching temperature.
- (2) Retained austenite becomes hard to be stabilized by subsequent tempering as the quenching temperature rises and becomes unstable by the tempering at 100°C for over 1 hour, and then  $M_s'$  point rises.
- (3) Of the magnetic properties,  $B_{\max}$  and  $Br$  are increased but  $H_c$  is decreased remarkably by sub-zero treatment.
- (4) The increase in hardness due to sub-zero cooling becomes remarkable with the rise of quenching temperature, but the ultimate hardness of steel quenched at higher temperature is lower than that of the steel quenched at lower temperature, because the hardness of the quenched state decreases with the rise of quenching temperature.
- (5) No change is observable in  $M_f$  point by the change in quenching temperature, room temperature aging and tempering.
- (6) Martensite transformation rate during sub-zero cooling increases with the increase in the stabilization of retained austenite, becomes sometimes bursting and afterward passes through a maximum.
- (7) Dilatation curves during sub-zero cooling become step-like with the increase in the stabilization and afterward become again smooth.
- (8) The stabilization can occur by isothermal holding above  $M_s$  point without prior martensite.
- (9) It is suggested that the stabilization of austenite can be explained by the mechanism similar to age-hardening.