Transformation Characteristics of Large Steel Forgings

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INSPITE of voluminous papers hitherto published on the heat treatment of large steel forgings, it would not be exaggerated to say that the transformation characteristics of them are not fully known yet. The cause is attributed, to our best knowledge, to those factors as inner local properties of original ingots, effects of forging and accompanied soaking, liberation and transmission of latent heat of transformation, hydrogen retained at the deep portions, thermal and transformation stresses etc. which refuse analogy with the results obtained by means of small specimens.

As a contribution to this problem in this paper, isothermal transformation characteristics of several forgings were investigated using a number of small specimens cut out from various parts of them. Further, to throw some lights upon the cause of ununiformness found in this investigation, two ingots with different solidification rate were made from a heat of basic arc furnace, and the effects of solidification rate, forging and soaking were comparatively studied.

Analyses of steels tested were chosen from those which have slower speed of transformation.

Experimental procedure

From each slice cut perpendicularly to the centre axis of forgings or ingots, a bar of 120mm square or so is removed along a radius. (Fig. 1) The thin rods are taken from several points along the radius. The rods are severed into pieces of about $8 \times 8 \times 5\text{mm}^3$. These pieces of each rod are assumed to have the same transformation property.

The temperature of isothermal transformation is selected as T_1 which is the pearlite nose of the S curve corresponding to the ladle analysis of the forging or ingot (Fig. 2).

After held for 30 minutes at 850°C in air, each group of specimens is plunged into a lead bath the temperature of which is kept at the nose with a fluctuation of ± 2°C or under by an automatic regulator. The specimens left there are picked up one by one, then quenched into ice water. From these series of specimens, the termination of isothermal transformation at a spot is decided by the drop of hardness and microscopic examination.

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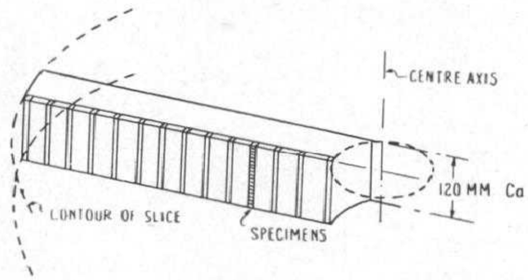


Fig. 1.
Preparation of specimens.

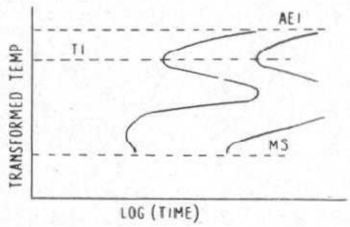


Fig. 2.
Selected temperature of isothermal transformation.

Results with large forgings

Three of the forgings which were examined are as follows, the chemical compositions of which are in Table I.

TABLE I

Chemical composition of tested forgings (ladle analysis).

Tested forging	C	Si	Mn	P	S	Ni	Cr	Mo	V
1	0·33	0·38	0·52	0·019	0·021	3·60	0·15	0·44	0·13
2	0·28	0·32	0·61	0·019	0·026	—	1·25	0·32	—
3	0·35	0·27	0·52	0·016	0·019	2·43	1·54	0·28	—

Rejected generator shaft

Fig. 3 shows the time required for the completion of isothermal transformation as related to the slices and radii, with corresponding distribution of several elements which exert an influence of retardation on transformation. The temperature of isothermal transformation was decided as 600°C. The original ingot

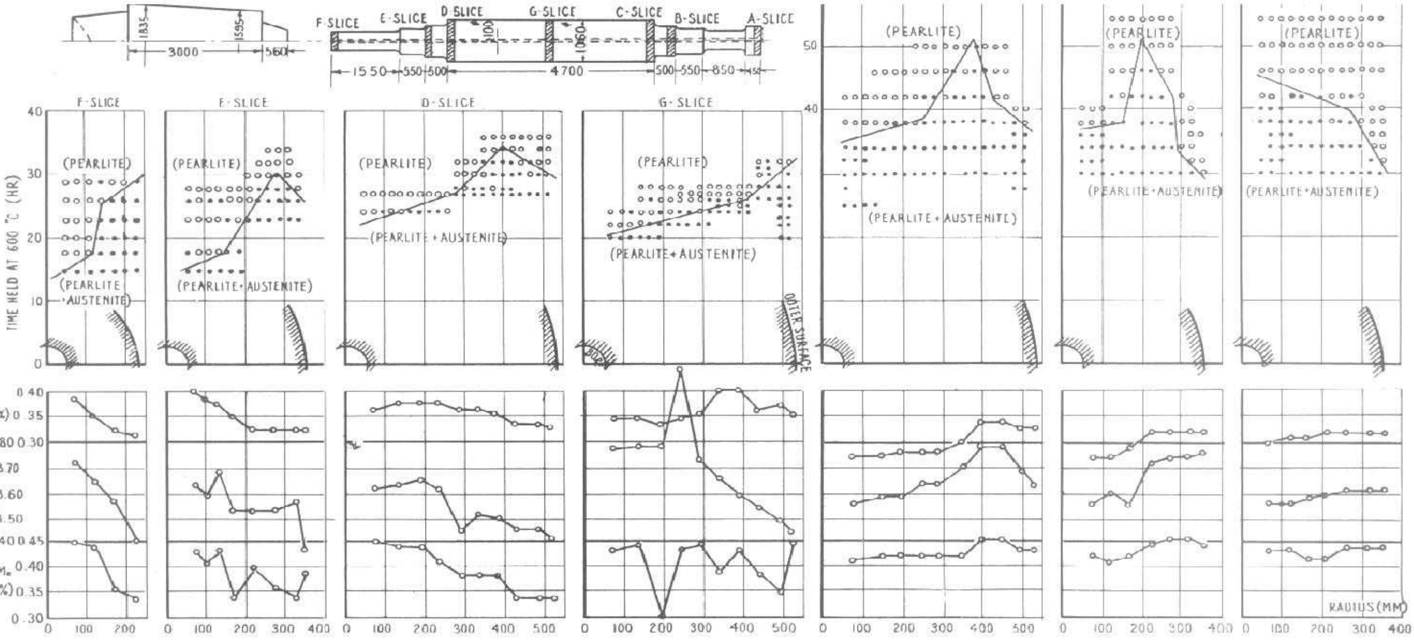


Fig. 3.

Time for the completion of isothermal transformation as related to the slices and radii and comparison with the macro-segregation of several elements. Generator shaft.

is 75ᵗ of weight. The forging was upsetted and squeezed, annealed, rough turned, and quenched and tempered.

It is noticed, from Fig. 3, that the time of transformation is almost identical, i.e. 30+5 hours, for the outer zones of each slice, while in the core zones the time is shorter at the top side and longer at the bottom side of the original ingot.

Ununiformness of transformation time is, on the whole, quite distinct.

Discards of high pressure vessel for synthetic fertilyser

The result is shown in the left half of Fig. 4. Unlike the case of the above generator shaft, the distribution of the transformation time is rather parallel to the segregation of elements, but the degree seems to be not in proportion to the segregation. The transformation temperature was 660°C. The schedule of forging was upsetting, hot core punching, and mandrel forging from a 129ᵗ ingot (160ᵗ sink head). The two discards, top and bottom, were annealed to soften.

Disk cut out of a roll

The result is in the right half of Fig. 4. Though parallel to the distribution of alloying elements, their combined effects on transformation are beyond the quantitative surmise. Specimens were transformed at 630°C. The roll had been upsetted and forged down from a 130ᵗ ingot, then turned, and quenched and tempered.

Records of heating accompanied by forging for these three forgings are shown in Table II.

TABLE II

Records of heating for the tested forgings

Tested forging	Number of heating	Time of heating, hr. Total	Time held at 1,200°C
1	13	356,5	>174
2	10	288,5	>114
3	10	252	> 97

Some of the most notable points found through these examinations are added as follows.

(*a*) *Hardness versus carbon content*: Hardness distribution measured by the specimens quenched directly from austenite shows good correspondence to the segregation of carbon, while the time for the completion of undercooled austenite does not coincide, as described above, with the carbon distribution.

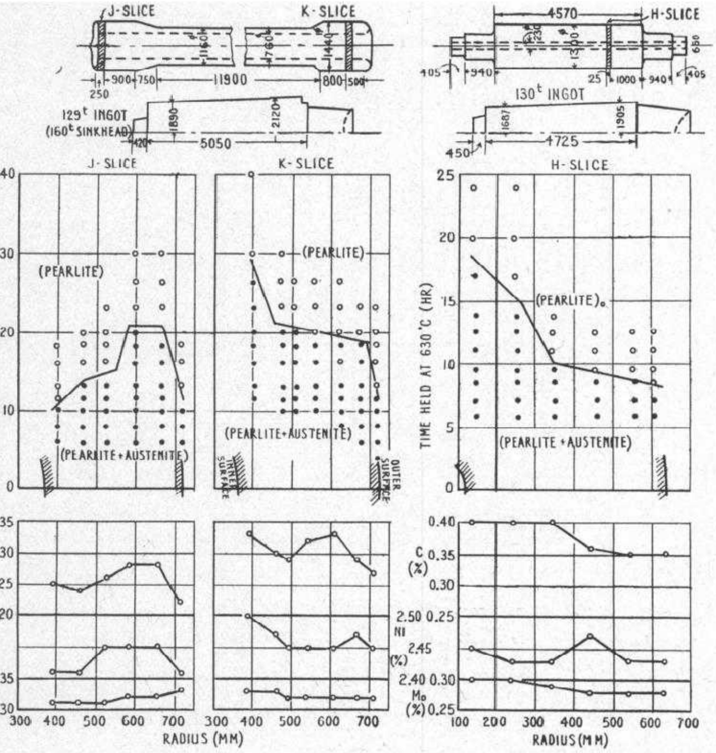


Fig. 4.

Time of completion of isothermal transformation as related to slices and radii and comparison with the macro-segregation of several elements. High pressure vessel and roll.

(*b*) *Segregation of elements versus time of transformation*: The relation between the segregation of elements and time of transformation, shown in Fig. 3 and 4, is far beyond the conjecture based on the known effect of alloying elements[1-10]. It must be borne in mind, in addition, that the segregation is usually defined by the analyses of samples taken by drills of 10 mm dia. or more, that is, not a value representing a point but some mean value for certain space.

(*c*) *Effect of shift of transformation temperature*: Even if the transformation temperature is shifted, e.g. to 630°C or 660°C in the case of Fig. 3, the distribution of transformation time show quite similar tendency as that at 600°C. This indicates that the ununiformness is not resulted from the local variation of shape of *S* curve.

1 H. Lange and K. Mathieu : Mitt. K.W.I. fur Eisenforschung, 20 (1938), S. 125.
2 E. S. Davenport : Metal Progress, 35 (1939), p 623.
3 J. R. Blanchard, R. M. Parke and A. J. Herzig : Trans. ASM, 29 (1941), p 317.
4 B. M. Lorig : Trans. AIME, 150 (1942), p 283.
5 T. Murakami and Y. Imai : J. Japan Inst. Metals, 6 (1942), p 145.
6 T. Murakami and Y. Imai : ibid., 7 (1943), p 145.
7 Y. Imai : ibid., 8 (1944), p 166.
8 Y. Imai : ibid., 8 (1944), p 265.
9 USS Research Laboratory : Atlas of Isothermal Transformation Diagram.
10 Atlas of Isothermal Transformation Diagrams of B. S. En Steels, Iron and Steel Inst., Special Report No. 40, (1949).

(*d*) *Hardness vs. time and structure vs. time relationships during isothermal treatment*: In nearly all of examination, the termination of transformation took a certain additional time τ_2 after the drop-off of hardness (time τ_1) as shown in Fig. 5. The ratio τ_2/τ_1 is approximate.

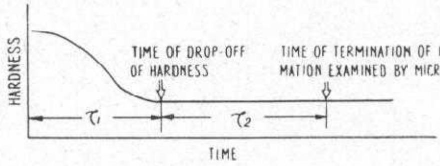


Fig. 5.

Relation between the drop of hardness and structure during isothermal transformation.

The ratio showed slight variation along radius. This suggests that the stabilisation of under cooled austenite differs locally in the large-forgings.

Forging		τ_2/τ_1
Generator shaft, and roll	...	1—2
High pressure vessel	...	0—1/2

Effect of solidification rate of original ingot on the transformation characteristics

As a first step to the explanation of this finding effect of solidification rate of original ingot was taken up. Two ingots, i.e. 3·4t octagonal and 5t round section, were cast from a Heroult heat in iron and sand mould, respectively. Time required for the solidification of body (to the root of feeder head) is 1 hour and 31 minutes, and 5 hours and 57 minutes, respectively. Time of solidification for sand mould ingot is nearly equal to that of about 25t ingot cast in iron mould. The solidification rate was measured by "bar-test" using 9 mm dia. steel bar. Chemical composition of the heat is shown in Table III.

TABLE III

Chemical composition of tested ingots (ladle analysis).

C	Si	Mn	P	S	Ni	Cr	Mo
0·30	0·34	0·70	0·015	0·007	1·77	0·76	0·30

As shown in Fig. 6, time to complete isothermal transformation at 650°C of the specimens taken from the sand cast ingot is twice longer than that of iron mould ingot.

The keypoint of longer transformation time of the sand cast ingot is, as shown in Fig. 7 by an example, that the drop of hardness is stopped at about 3 hours from the beginning of transformation while the completion of transformation by means of microscopical examination takes additional 5 hours. (cf. Fig. 5).

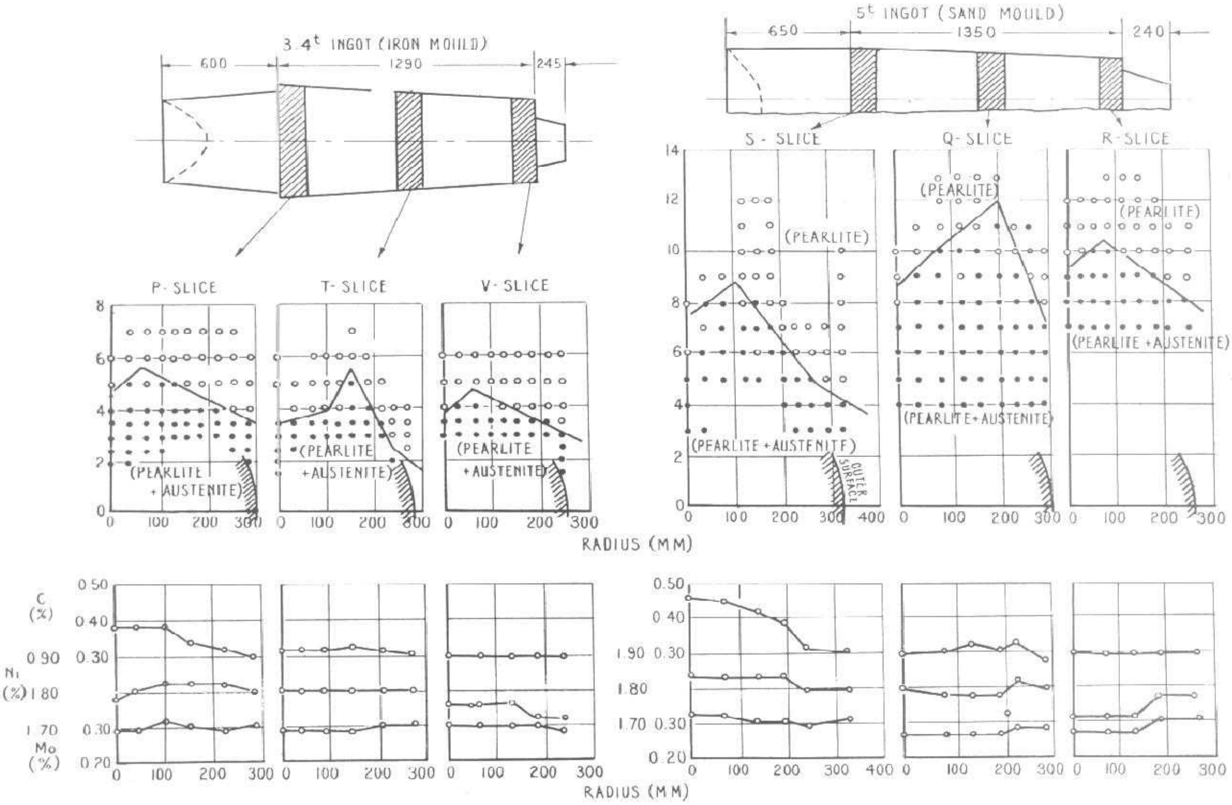


Fig. 6.

Time for the completion of isothermal transformation as related to the slices and radii and relation to the macro-segregation of several elements. Effect of solidification rate.

Further, the time of transformation can hardly be correlated with segregation of elements, just as the above mentioned examples of forging.

Effect of forging and soaking on the transformation characteristics

To inquire further cause of the ununiformness, the remaining blocks of each slice of iron-mould and sand-cast ingots were forged and soaked.

A hammering of forging ratio 4 (radially squeeged) proved to shorten the transformation time, and the effect of forging is quite remarkable for the sand cast ingot, as shown in Fig. 8. Fig. 9 is the effect of magnitude of forging ratio for the *Q*-slice, in which a light forging of forging ratio 1·3 is already sufficient for reducing the transformation time.

A soaking of 240 hours in a gas fired furnace has brought the same results, putting back the transformation time of sand mould ingot nearly to that of iron mould ingot.

Discussion of the results

The results of examination are of themselves sufficient to explain some of the causes of this phenomenon. Briefly speaking, the local ununiformness of transformation time is originated in the solidification of ingot, and the larger is the ingot the slower becomes the transformation. The longer time of transformation of ingots is made shorter by forging and high temperature soaking. Figs. 5 and 7 indicate that the spots at which the last islets of austenite complete their transformation are of very small size, thence, that the cause is attributable to "micro-segregation".

In finer scope, the micro-segregation is presumably of the nature that the distribution of sub-microscopic inclusions and of those elements as C, Ni, Cr, Mo in the matrix plays a leading role not forgetting its change by thermal cycles or plastic deformation. It should also be noticed that the micro-segregation in ordinary sense has nothing to do with; a new scope of segregation which awaits further detailed studies.

Similar results were published by Prof. Troiano et al.[11, 12] in which relation to the hydrogen theory

[11] J. B. Gero and A. R. Troiano: Iron Age, 171 (1953), No. 13, p. 134.

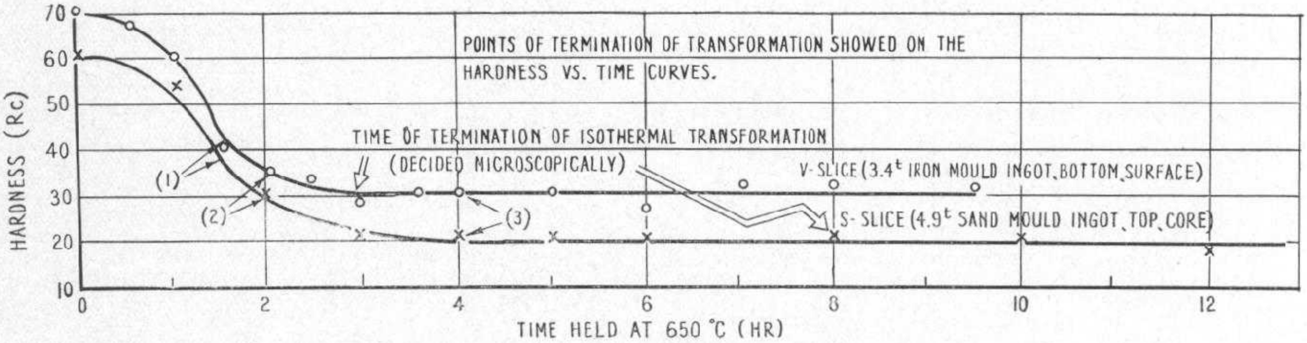
[12] A. W. Dana, Jr., F. J. Shortsleeve, and A. R. Troiano: Trans. AIME, Aug. 1955, J. Metals, p. 895.

of flaking is discussed.

Summary and conclusions

It was found that the time of isothermal transformation measured with small specimens (size $8 \times 8 \times 5$ mm^3) which were taken from various parts of large steel forging (original ingot weight 75–160^t) shows a remarkable ununiformness throughout the forging. Its degree does not necessarily coincide with the known effect of alloying elements.

Two ingots, i.e. 3·4^t cast in iron mould and 5^t cast in sand mould, were made from a Ni-Cr-Mo heat. Comparative study of these ingots revealed

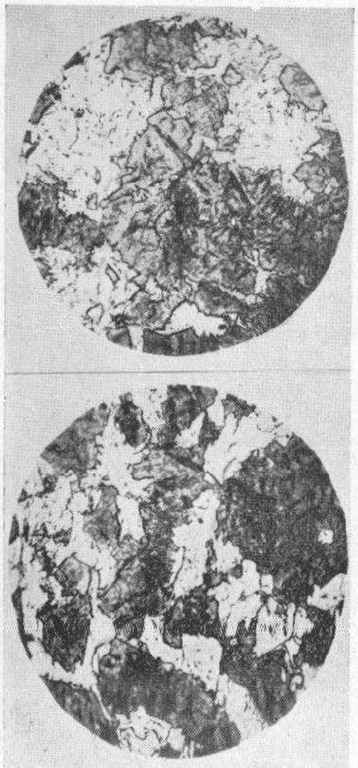


V-slice Held for 1·5 hr. then quenched in ice water.

Structure: ferrite + pearlite + martensite

S-slice As above.

Structure: As above.

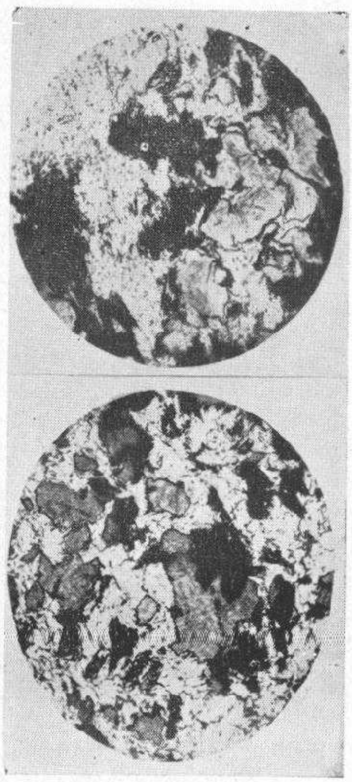


V-slice Held for 2 hr. then quenched in ice water.

Structure: ferrite + pearlite + martensite.

S-slice As above.

Structure: As above.



V-slice Held for 4 hr. than quenched in ice water.

Structure: ferrite + pearlite.

S-slice As above.

Structure: ferrite + pearlite + martensite. ×400

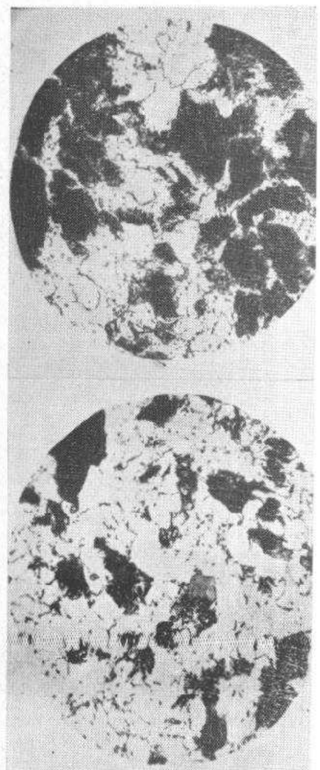


Fig. 7.

Relation between the drop of hardness and structure during isothermal transformation at 650°C. Specimens were taken from 3·4^t (iron mould) and 4·9^t (sand mould) ingots.

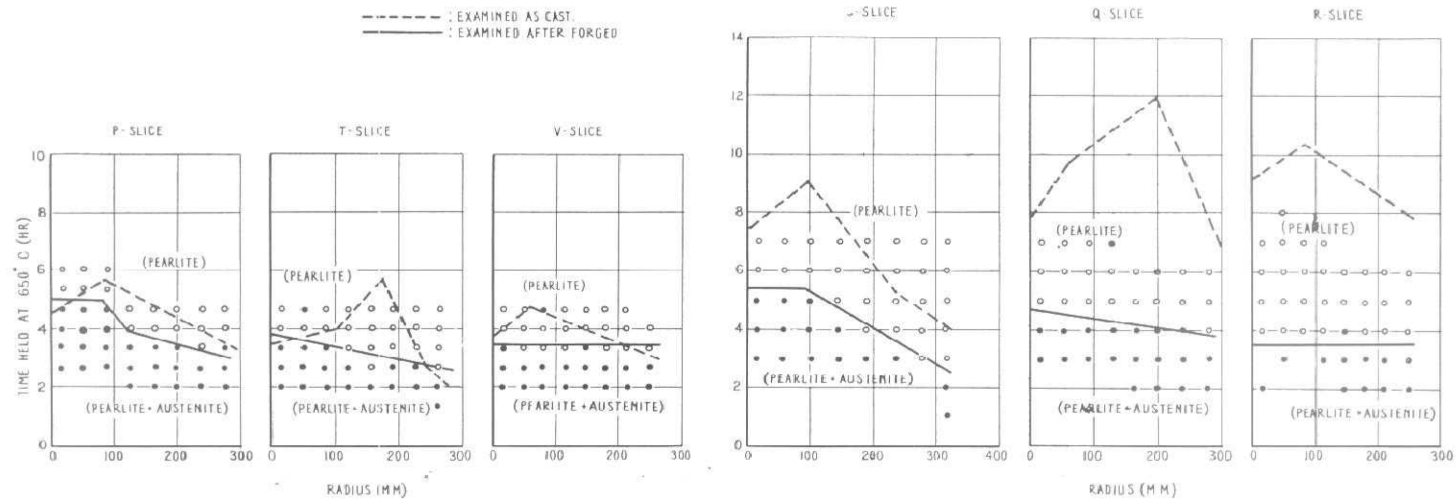


Fig. 8.

Transformation characteristics examined as cast and after forged. Full and dotted lines show the completion of isothermal transformation at 650 C. Forging ratio is 4.

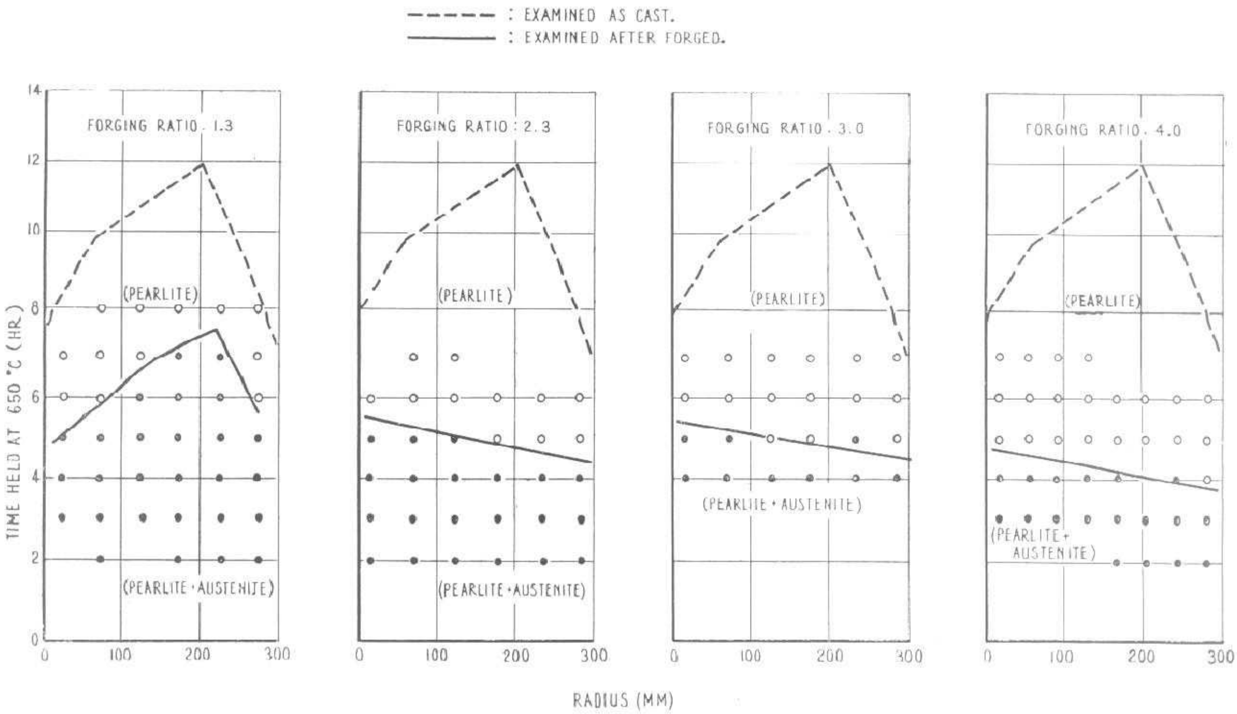


Fig. 9.

Effect of forging ratio upon the time of termination of isothermal transformation. Q-slice hammered.

that the time of isothermal transformation of the specimens taken from the sand cast ingot is twice longer than that of iron mould ingot. The difference is considerably decreased by forging with forging ratio 1·3 and nearly eliminated by forging with forging ratio 4. The difference is almost eliminated by soaking for 240 hours at 1,150–1,200°C, as well.

Much more experiments are necessary for the full explanation of this finding, to which further studies are continued. When this phenomenon is analysed in detail, effects of transformation heat and hydrogen etc. on the transformation of large steel forgings en bloc will be clarified.

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