—TECHNICAL PAPERS*—

ON THE RIMMING ACTION**

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1. Introduction :

Due to rimming action the circumstances of the solidification of rimming-steel ingots is remarkably different from that of killed steel ingots. Concerning the mechanism of solidification of rimming-steel ingots, a minute research has already been made qualitatively by A. Hultgren and others, and J. Chipman has announced its quantitative study based on the segregation curve of 5-ton ingots. The influence of the intensity of rimming action, however, has not been so far discussed as yet.

In this article, therefore, an examination is chiefly made quantitatively with a small ingot of 150 kg about the solidification of rimming-steel ingots, approaching from the angle of the relation between the strength of rimming action and the segregation curves, and also about the influence of the size of ingots together with the difference of rimming action according with the top or the bottom of the ingot, etc.

2. On the Intensity of Rimming Action :

Figuring out the variations of the rate of gas generation by measuring the changing amount of the generated gas observable with the progress of time during solidification of rimming-steel, it is found that the rate of evolution will gradually be decreased with the time elapsed since the close of teeming as shown, for example, in Fig. 1. The proportion of the decrease, however, does not correspond with the rate of decrease of the boundary area dividing the solidified steel and the molten steel, which decreases with the progress of solidification. Therefore, it admits of no doubt that the decrease of the rate of producing gas has an influence upon solidification through rimming action.

Accordingly the intensity of rimming action is hereafter to be defined as follows :

$$\left(\begin{array}{c} \text{The intensity of} \\ \text{rimming action} \end{array} \right) = \left(\begin{array}{c} \text{The rate of gas} \\ \text{generation} \end{array} \right) / \left(\begin{array}{c} \text{The boundary area dividing the} \\ \text{solidified steel and the molten steel} \end{array} \right)$$

Where :

The rate of gas generation : 1/min

The dividing area : $\text{cm}^2 \div 1000$ (Here is considered the side only)

The intensity of rimming action differs according with difference of the top and the

* Two technical papers written hereinafter by Messrs. Shigetoshi Ishihara, Katsuro Inoue and Makoto Kato are those given prize as the most useful respectively in science and engineering concerned in accordance with provisions of Article 3 of the Dr. Tawara Memorial Fund Debenture Regulations of The Iron and Steel Institute of Japan.

** Abstract from the papers published in the Journal of the Iron & Steel Institute of Japan, Vol. 40, Nos. 4—5, April & May 1954, pp. 403—413 and 487—493.

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Fig. 1 A Quantity of gas and rate of occurrence (R 99)

Weight : 164 kg

Chemical composition :

C 0.08%, Mn 0.15%, O 0.050%

Temp. : 14°C

Fig. 1 B Quantity of gas and rate of occurrence (heavy T 13301)

Weight : 4,200 kg

Chemical composition :

C 0.10%, Mn 0.39%, O 0.023%

Temp. : 25°C

bottom of the ingot, but hereinafter the standard of the intensity of rimming action shall be that of medium height of the ingot.

And the rate of solidification of the ingot used in this experiment is $D(\text{cm}) = 0.23\sqrt{t(\text{sec})}$. Using this, the authors can figure out the boundary area dividing the solidified steel and the molten steel at any stage of solidification.

Fig. 2 A Segregation curve of R 94

Fig. 2 B Segregation curve of R 105

3. On Segregation :

Making an examination of the segregations of the medium height lying inwards from the skin of the ingot used in the present experiment, some examples of which are given in Fig. 2.

The segregation curve of each element is almost alike one another, but the degree of its bending is somewhat different according to different elements.

When the value of $C_{s-\min}/C_{l-0}$ is figured out from the results obtained with the small ingots, expressing the value of ladle analysis as C_{l-0} and the lowest concentration of segregation curve as $C_{s-\min}$, the figures are obtained as are shown in Thble 1. p here is

Table 1. Relation between the $C_{s-\min}/C_{l-0}$ versus the segregation coefficient and the intensity of rimming action

Composition	R94	R97	R99	R105	R107	p	$1-p$
C	0.71	0.42	0.50	—	0.82	0.13	0.87
Mn	0.90	0.94	1.00	1.00	1.00	0.84	0.16
P	0.55	0.71	—	0.50	0.80	0.13	0.87
S	0.50	0.60	0.41	0.50	0.63	0.05	0.95
Cu	0.90	0.93	0.90	0.87	0.95	0.56	0.44
Intensity of rimming action	1.39	1.27	2.50	—	0.68	—	—

the ratio worked out by Chipman of the concentration of liquidus against that of solidus to conjugate with them, and $1-p$ is what is called segregation coefficient. According to this table, it is clarified that when the value of p is the smaller, the value of $C_{s-\min}/C_{l-0}$ is also the smaller, besides the fact that the greater the intensity of the rimming action is, the smaller this value.

4. Qualitative Examination of Segregation Curves :

The segregations mentioned above are peculiar to rimming-steel ingots. Let us next look into qualitatively the reason why such segregation curves are obtained.

Considering a binary system of Fe- M , “ ab ” in Fig. 3, shall be liquidus line, and “ ac ” solidus line.

When the liquid having the concentration value of x_0 is solidified, the first crystal will have M concentration on “ ac ” line to conjugate with x_0 , but owing to rapid cooling the concentration of solidus will macroscopically be y_0 which is becoming almost x_0 .

Fig. 3. Examination of the origin of segregation curves

In case of rimming-steel ingots, however, as rimming action takes place in the meantime, the M concentration of liquidus right adjoining to this crystal...hereinafter called ‘the nearest liquidus film’...will be washed away and mixed up with residual liquidus. In other words, the M concentration of the nearest liquidus film in rimming-steel ingots will be by far the smaller compared with that of the killed steel ingots (x_1).

Therefore, the M concentration resulting from the solidification of this x_1 will also naturally have the smaller value than that obtained in case of killed steel. Besides, because of rimming action the entrapment in rimming-steel ingots is much smaller and so the M concentration of the solid phase will become considerably smaller than x_1 and considered to be y_1 .

In the same way, so far as there takes place some degree of rimming action, the M concentration of solid phase will gradually be declining as the cooling velocity decreases, and the segregation curves will change as $y_0, y_1, y_2, \dots$.

Sometime after teeming finished, the temperature of residual liquid will get lowered, and the entrapment will become great owing to the increase of viscosity and the enfeebling of rimming action, thereby the M concentration of solid phase also changing for the greater ($y_1', y_2', \dots$) and after agreeing with that of the nearest liquidus film at x_m , it will become just as in the case of killed ingots.

The qualitative consideration mentioned so far explained the influence of the intensity of rimming action upon segregation, but this explanation does not apply to such elements as C or O that will go off the ingots. In this case the equilibrium $C-O$ must be considered.

5. Quantitative Checking of Mechanism of Solidification :

The concrete factors controlling the solidification to be observed peculiarly to the ingots of rimming-steel, as is mentioned before, are the following 3: Intensity of rimming action; cooling velocity; and physical natures of molten steel (the latter half of rim solidification).

Assuming the concentration of the component contained in the nearest liquidus film to be of C_f and C_l is considered to depend on the intensity of rimming action G .

$$C_f = \frac{C_l}{\alpha - \alpha' / G} \dots \dots \dots (1) \quad (\alpha, \alpha' \text{ are constant})$$

And the following 3 are counted as the factors controlling the intensity of entrapment:

- a) Rate of solidification V
- b) Intensity of rimming action G
- c) Change of physical state of molten steel (This is for convenience's sake taken to be the function of fraction of cross-section solidified X)

However, V also being the function of X , the intensity of entrapment f is, therefore, expressed by next equation :—

$$f = f_0 - \beta F_3(X) F_2(G) \dots \dots \dots (2)$$

Where β is constant, f_0 the intensity of entrapment when $G=0$ i. e. that of the killed steel ingots.

And C_s , the concentration of solid phase that is being solidified moment by moment has the correlation given in (3) against f and C_f .

$$C_s = (1-f) \cdot p \cdot C_f + f \cdot C_f \dots \dots \dots (3)$$

Here, p is, as mentioned before, the ratio of the concentration of liquidus against the concentration of solidus to conjugate with this, and the first term of the right side of the equation is the concentration of solid phase resulting from a micro solidification,

and the second term is that brought upon by entrapment. And therefore, from equations 1), 2), and 3), equation (4) will be introduced :—

$$C_s/C_l = \frac{1}{\alpha - \alpha'/G} \{p + (1-p)f_0 - \beta(1-p) \cdot F_3(X) \cdot F_1(G)\} \dots (4)$$

When plotting the experimental values concerning the small sized ingots, supposing each of p and X in (4) to be constant, and assuming C_s/C_l to be function of G only, one can obtain Fig. 4.

Fig. 4. Relation between C_s/C_l - G
 $\bullet \dots P$ $\times \dots S$

From this, the following is obviously inferred :

$$\frac{\partial C_s/C_l}{\partial G} = K \quad (K \text{ is the function of } X)$$

$$C_s/C_l = 1.0 \text{ at } G=0$$

Using this relation, from (4) is obtained :

$$\alpha' = 0 \quad \text{and} \quad F_1(G) = \beta' \cdot G \quad (\beta' : \text{constant})$$

Hence equation (4) will be constructed as follows :

$$C_s/C_l = \frac{p + (1-p)f_0}{\alpha} - \frac{\beta\beta'(1-p)F_3(X)}{\alpha} \cdot G \dots (5)$$

And therefore,

$$C_s/C_l = 1 - \gamma(1-p)F_3(X) \cdot G \dots (6)$$

$$(\gamma = \beta \cdot \beta' / \alpha : \text{constant})$$

Figuring out the coefficient ($\theta = \gamma(1-p)F_3(X)$) of equation (5) from the inclination of each straight line given in Fig. 4, the result is as shown in Table 2.

Plotting from Table 2 the relation of θ - p , assuming X to be constant, and also θ - X , supposing p is constant, the result will be just as shown in Fig. 5 and Fig. 6. θ will be able to be expressed as the second degree equation concerning p approximately, and the

Table 2. Values of θ

Composition	p	X					
		0.1	0.2	0.3	0.4	0.5	0.6
Cu	0.56	0.033	0.059	0.082	0.090	0.082	0.056
P	0.13	0.146	0.213	0.270	0.290	0.228	0.090
S	0.05	0.146	0.235	0.318	0.370	0.305	0.230

Fig. 5. Relation between θ - p Fig. 6. Relation between θ - X

4th degree equation concerning X .

Consequently, calculating the most appropriate value of θ , using these two terms,

$$\theta = [3.2(1-p)^2 + 0.63(1-p)] (-X^4 + 0.33X) \dots \dots \dots (7)$$

As was mentioned before, X here is representing for solidification rate V , and the physical state of molten steel η .

$$F_3(X) = -X^4 + 0.33X \dots \dots \dots (8)$$

However, as is obvious from Fig. 6, when $X < 0.4$, $F_3(X)$ will rise up almost in a straight line, but when $X > 0.4$, it will decrease fairly rapidly, so when $X < 0.4$, the term of X , and when $X > 0.4$, the term of X^4 seem to influence. It is meant by this that the X that decides $F_3(X)$ is of different natures, depending upon the value of X i. e. the first half and the latter half of rim solidification. Briefly, when $X < 0.4$, the solidification rate (against X there is a relation as is given in Fig. 7) plays the dominant part, and in case of $X > 0.4$, η (the curve relation as is given in Fig. 7 is supposed to exist) will have great influence, and as the combined results of these two factors, $F_3(X)$ represented by Curve 3 in Fig. 7 is considered to be given.

As a result, the function $F_3(X)$ can be shown as follows :

$$F_3(X) = -\delta' \eta + \delta'' \cdot 1/V \dots \dots \dots (9)$$

Where δ' and δ'' are constant, and therefore from (8), (9)

Fig. 7. Relation among $V \cdot \eta \cdot F_3(X)$

$$0.33X = \delta'' \cdot 1/V$$

However from solidification rate constant $K=0.23$, the following relation will be obtained approximately.

$$V \cdot X = 0.0047$$

$$\delta'' = 0.00155$$

So equation (8) will be

$$F_3(X) = -X^4 + 0.00155/V \dots\dots\dots (10)$$

And therefore, from (6) and (7) the following will be obtained.

$$C_s/C_l = 1 - [3.2(1-p)^2 + 0.63(1-p)] \cdot (-X^4 + 0.00155/V) \cdot G \dots (11)$$

Equation (11) will be an empirical formula showing quantitatively the concentration ratio of solid phase against liquid phase of ingots used in this experiment.

6. Correction of the Empirical Formula against the Size of Ingots :

Equation (11) is an empirical formula obtained with the small ingots used in the present investigation, but considering from the results of many experiments, the value of X to satisfy $F_3(X) = 0$ (the value of X at the expiration of solidification of rim) does not depend on the size of ingots, but in the ordinary rimmed steel ingots is $0.6 \sim 0.7$. It is perhaps because when the size of the ingot grows large and as the result $1/V$ becomes big, $\eta(X^4 \text{ term})$ will also change.

Therefore, although there is not without some doubts about the essential meaning of η , it is reasonable to make a partial correction of equation (10) as in the following :

$$F_3(X) = -\xi X^4 + 0.00155/V \dots\dots\dots (12)$$

The value of ξ here should be fixed so as to be $F_3(X) = 0$ at the boundary of rim and core. When the ingot grows larger, the value of ξ also is to become greater.

From equation (12), equation (11) is to be corrected as follows :—

$$C_s/C_l = 1 - [3.2](1-p)^2 + 0.63(1-p)] \cdot (-\xi \cdot X^4 + 0.00155/V) \cdot G \dots (13)$$

7. Examples of Application of the Empirical Formula :

From equation (13), the segregation curves of ingots can be obtained :

i) In case of an element that is not going off ingots :

$$C_l = \frac{1}{1-X} \left(C_{l-0} - \int_0^X C_s dX \right)$$

Therefore,

$$\frac{1-X}{1-F(p)F(X)} \cdot C_s = C_{l-0} - \int_0^X C_s dX$$

$$\text{Where } F(p) = 3.2(1-p)^2 + 0.63(1-p)$$

$$F(X) = (-\xi X^4 + 0.00155/V) \cdot G$$

From this,

$$\log C_s/C_{l-0} = \log \frac{1-F(p)F(X)}{1-X} - 0.433 \int_0^X \frac{1-F(p)F(X)}{1-X} dX \dots (14)$$

Briefly, when $F(X)$ is obtained, the conjugated values of C_s i. e. the segregation curve can be worked out.

ii) In case of C :

$$C_t = \frac{1}{1-X} \left(C_{t-0} - \int_0^x C_s \cdot dX - \int_0^x g_s \cdot dX \right)$$

The " g_s " in this equation denotes the amount of departed C in any X in % against the amount of the solidified at the moment.

$$C_s = C_{t-0} \cdot l \left(- \int_0^x F_a(X) dX \right) - e \left(- \int_0^x F_a(X) dX \right) \\ \times \int_0^x F_b(X) \cdot l \left(\int_0^x F_a(X) dX \cdot dX \right) \dots \dots \dots (15)$$

Here

$$F_a(X) = \left\{ \frac{1-F(p)F(X)}{1-X} \cdot \frac{1}{1-X} + \frac{F(p)F'(X)}{1-F(p)F(X)} \right\}$$

$$F_b(X) = \frac{1-F(p)F(X)}{1-X} g_s$$

iii) Applying (14), (15) to a few examples, the following are obtained :

a) About C of R 94 (Cf. Table 1):

The numerical values necessary for calculation are as given in Table 3. Figuring out from (15), using these values, the curve shown in Fig. 8 was obtained. Here marked • is the actual values, which agree with the theoretical values very well. And this can be applied very well with other ingots.

Fig. 8. Segregation curve of C by calculation (R 95)

Table 3. Functional values of R-94

X	0.1	0.2	0.3	0.4	0.5	0.60
g_s	0.0047	0.0082	0.0110	0.0118	0.0084	0
$G=F_2(X)$	1.9	1.58	1.39	1.14	0.77	0
$F(p)$	—	—	2.97	—	—	—
$F(X)$	0.0608	0.101	0.127	0.121	0.0778	0
C_s	0.092	0.079	0.073	0.076	0.098	0.140

b) An example of ingots for practical purpose :

Figuring out from (14) the segregation curves of the Mn, Cu and S of the ingot used in the experiment by Chipman (in this ingot, $\xi=0.5$) the results will be like dotted lines given in Fig. 9. Marked • are the values of actual analysis and there is some difference between the two. This is perhaps because while the gas that has connection with the rimming action at the middle height is only part of the total gas produced, for convenience's sake, the total gas producing rate is used. At the middle height it should be computed from the actually measured gas producing rate multiplied by a certain coefficient a (<1). Taking " a " on a certain point on the segregation curve of actually measured Cu in Fig. 9, so that the measured results agree (in this case a will be 0.25), from which segregation curve of Cu, Mn and S is calculated the results are solid lines as shown in Fig. 9, which are quite correspondent with the values of actual measurement.

8. Discrepancies of Segregation Degree Caused according to the Size of Ingots :

As is obvious from (13), the differences of degrees of segregation to be caused due to the size of ingots depend upon G , V , $\eta(X^4)$. The greater is the size of ingots, $F_3(X) = -\xi X^4 + 0.00155/V$ will also be the greater. On the other hand, comparing the small ingots used in the present experiment with the practical ingots used by Chipman, G of the greater ingots is the smaller, and the degree far exceeds the greatness of $F_3(X)$, and hence the greater the ingots, the degree of segregation will be the smaller.

9. Differences of the Intensity of Rimming Action according to the Depth of Ingots from the Top :

The smaller is the depth from the top, the ferro-static pressure is also smaller and as the result the amount of gas produced will be the greater, and that the amount of gas coming from the lower parts is greater, the rimming action is naturally much more briskly taking place.

Figuring out the segregation curves by using :—

$$C_s/C_t = 1 - [3.2(1-p)^2 + 0.63(1-p)] \cdot (-\xi X^4 + 0.00155/V) \cdot aG \dots \dots \dots (16)$$

Instead of (13) and comparing with actual curves at each height of the ingots, it is possible to find out the value of a at each height. In Fig. 10 are given the values of a

Fig. 10. Change of a

10. Conclusion :

From the intensity of rimming action and the segregation curves obtained by the experiments conducted with small ingots, the mechanism of solidification is studied toge-

Fig. 9. Segregation curve of the Mn, Cu, S by calculation (at the middle height of ingot)

at different heights obtained with the ingots used in the present experiment and those used by Chipman. The value of “ a ” here is the averaged one of those obtained in connection with different X_s' (in case of $X < 0.4$ deviation of the value of a is scarce). According to Fig. 10 at about 1700~1800 mm. from the top of the ingot, $a \approx 0$ is seen, which shows there is some limits to the height of rimming steel ingots.

Using this a , the segregation of all the points of rim zone in rimming-steel ingots can be figure out.

ther with the influence of the size of ingots, and the empirical formula to be used for figuring out the segregation of the common rimming-steel ingots is proposed. And this has been checked with some actual examples thereby to prove its propriety.

References :

- 1) A. Hultgren, G. Phragmen : Trans. A. I. M. E. **135** (1939) 133
- 2) A. Hayes, J. Chipman : Trans. A. I. M. E. **135** (1939) 85
- 3) I. Kohira : Tech. Rep. of Research Department of Yawata, I. & St. Works Vol. **16**, No. 1 (1937) [in Japanese]
- 4) K. C. McCutcheon, J. Chipman : Trans. A. I. M. E. **131** (1938) 206
- 5) J. Chipman, C. R. Fondersmith : Trans. A. I. M. E. **125** (1937) 370