A Model Describing the Relationship between Hot Rolling Ratio and Charpy Shelf Energy*

By Hiroyoshi MATSUBARA,** Tatsumi OSUKA,** Isao KOZASU,*** and Koshiro TSUKADA**

The effect of hot rolling on ductility can be understood in terms of the improvement of as-cast structure by forging effect and change of shape and directionality of elongated non-metallic inclusions. In industrial rolling of hot strips and plates where rolling ratio is more than 20 to 30, the latter factor predominates. In this note, an attempt to describe the change of Charpy shelf energy with cross rolling ratio will be made assuming a simplified model, and subsequently a normalized shelf energy independent of cross rolling ratio will be given.

The information on the relation between cross rolling ratio and shelf energy so far reported may be briefly summarized as below. In the following, L is the final rolling direction and T denotes transverse direction to L ; R is the total rolling ratio (initial thickness/final thickness), and R_L and R_T are the rolling ratio in L and T directions respectively; and vE_{sL} and vE_{sT} are the shelf energy in L and T direction.

- (i) As R_L is increased, vE_{sT} is decreased.^{1, 2)}
- (ii) vE_{sL}/vE_{sT} is a function of R_L/R_T , and for values of R_L/R_T higher than 30, it approaches to a value of about 3.0 to 3.5.^{3, 4)} One directional rolling such as hot strip mill rolling results in $vE_{sL}/vE_{sT}=3.5$.
- (iii) The above two relationships are symmetrical in L and T directions.

These three relations indicate that vE_{sL} and vE_{sT} can be expressed as a decreasing function of R_T and R_L respectively, for example in terms of $1/R_T$ or $-\log R_T$. In the present case, taking $1/R_T$ for simplicity, one obtains (1) and (2) from the relation (i),

$$vE_{sL} = vE_s^*(1 + \alpha/R_T) \dots\dots\dots(1)$$

$$vE_{sT} = vE_s^*(1 + \alpha'/R_L) \dots\dots\dots(2)$$

where α and α' are constants, and vE_s^* is a normalized shelf energy that depends on sulfur content. Eliminating vE_s^* from (1) and (2), one obtains (3) which is equivalent to relation (ii) above.

$$f \equiv vE_{sL}/vE_{sT} = (R_L/R_T)(R_T + \alpha)/(R_L + \alpha') \dots\dots(3)$$

This equation may be rewritten using $R=R_L \cdot R_T$,

$$f = [\sqrt{R} + \alpha/\sqrt{Q}]/[\sqrt{R} + (\alpha'/\sqrt{Q})] \dots\dots(4)$$

where Q is the cross rolling ratio, R_L/R_T . Equation (4) may be fitted to measured f'_s (for example, Fig. 9 of Ref. 5)) taking α and α' as adjustable parameters. Figure 1 is an example of such fitting, which shows

satisfactory agreement for industrial Q range. The fact that α is larger than α' in Fig. 1 suggests that sulfide is more elongated in L direction than in T direction under same rolling ratio because of the generally lower rolling temperature in the final rolling.^{6, 7)}

The relationships so far obtained make possible the calculation of vE_s^* which is independent of R and Q . Although a quick glance at mill data suggests $(vE_{sL} + vE_{sT})/2$ or $\sqrt{vE_{sL} \cdot vE_{sT}}$ to be constant (Fig. 10 of Ref. 5), the following relation is obtained for the former assuming $\alpha = \alpha'$.

$$\frac{vE_{sL} + vE_{sT}}{2} = \left[1 + \frac{\alpha}{2\sqrt{R} \cdot Q} (Q + 1) \right] vE_s^* \dots\dots(5)$$

Fig. 1. Comparison of the measured and calculated ratio of shelf energy longitudinal to transverse

Fig. 2. Example of calculated correction factor (F_1) of shelf energy

$$R = 40, \alpha = \alpha' = 2.5$$

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** Fukuyama Works, Nippon Kokan K. K., Kokan-cho, Fukuyama 720.

*** Technical Research Center, Nippon Kokan K. K., Minamiwatarida-cho, Kawasaki-ku, Kawasaki 210.

Equation (5) indicates that the arithmetic average of ${}_vE_{sL}$ and ${}_vE_{sT}$ is influenced by R and Q . Figure 2 is a plot of [] in Eq. (5) (denoted as F_1) and $1/F_1$ for the case when $R=40$ and $\alpha=2.5$.^{*} From Fig. 2 it can be seen that the arithmetic average becomes lower at $Q \simeq 1$ than at $Q \gg 1$, which agrees well with the observation in mill rolling.⁵⁾

It is also possible to estimate ${}_vE_{sT}$ (or ${}_vE_{sL}$) for an arbitrary set of sulfur content and Q from Eq. (6) under the condition of a constant total rolling ratio if $S\%_0 - {}_vE_s^*$ (Fig. 11 of Ref. 5)) and $Q-f$ (Fig. 9 of Ref. 5)) relations are established from mill data.

$${}_vE_{sT} = \frac{2}{f+1} \cdot F_1 \cdot {}_vE_s^* \dots \dots \dots (6)$$

Similar relations may be obtained for the geometrical average though they are not elaborated here.

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* In connection with the relation (ii), this case corresponds to $f=1$ at $Q=1$ and $f=3.3$ at $Q=40$.