

## ROLLING CONDITIONS FOR HIGH R-VALUE OF HOT ROLLED STEEL SHEETS ANALYZED BY COMPUTER SIMULATIONS MODEL FOR MICRO-STRUCTURE

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### ABSTRACT

Hot rolled steel sheets with high  $r$ -value were developed. The steel was rolled with more than 50% reduction at each final three stands near the  $A_{r3}$  temperature. The condition was investigated by a computer simulation model for micro-structures and a transformation texture model. Dynamically recrystallized  $\gamma$  with random texture transforms to  $\alpha$  with random texture or that with  $\{110\}<001>$  orientation. Average  $r$ -value reaches 1.0 or more with random orientation. On the other hand, more than 1.2 of average  $r$ -value was maintained when the  $\{110\}<001>$   $\alpha$  was hot rolled giving recrystallized  $\{112\}\sim\{111\}<011>$   $\alpha$  texture.

### 1. INTRODUCTIONS

Since hot rolled steel sheets with the same strength and elongation as cold rolled steel sheets don't show as good drawability as cold rolled one, cold rolled steel sheets are commonly used as drawable thin steel sheets. Recently, however, the demand for lower cost has roused a keen interest in employing hot rolled steel sheets in place of cold rolled steel sheets. Some trials, that increases an average  $r$ -value of hot rolled steel sheets, have been carried out.<sup>1-3)</sup> In this paper, the relation between the  $r$ -value and the volume fractions of micro-structure which are calculated by a computer simulation model<sup>4-5)</sup>, and simulations by a transformation texture model<sup>6-7)</sup> are reported.

### 2. EXPERIMENTAL PROCEDURE

Chemical compositions of steels used in the experiments are shown in Table 1. Steels were hot rolled in laboratory and in mill scale. Typical schedules of the rolling test are shown in Table 2. After rolling, specimens with and without an one hour annealing at 750 °C for recrystallization were prepared. The effect of high reduction on texture and  $r$ -value were investigated.

The volume fractions of micro-structure after rolling were calculated, using the computer simulation model for micro-structures.<sup>4-5)</sup> Transformation textures of test specimens were calculated by the model<sup>6-7)</sup> and investigated through electron channeling patterns.

Table 1 Chemical compositions (wt.%)

C	Si	Mn	P	S	Al	N	Ti
.0017	.012	.17	.013	.005	.022	.0017	.048
-.0033	-.024	-.22	-.018	-.011	-.065	-.0032	-.058

Table 2 Schedule of rolling test (laboratory test)

Final reduction (%)	Schedule of rolling (thickness: mm)						
Test ①	55	36.0	21.6	13.0	5.8	2.6	1.2
	50	27.0	16.2	9.7	4.8	2.4	1.2
	40	34.2	15.4	9.2	5.5	3.3	2.0
	30	37.9	21.6	9.7	5.8	3.5	2.4
Test ②	55	30.0	13.1		5.9	2.7	1.2
		(rough rolling)					

3. RESULT

3.1 Effect of rolling conditions

Fig.1 shows the changes in the relative intensity of {hkl} at midsection. The {111} relative intensity in conventional draft steels is about 1.0 when the rolling finishing temperature is above 850°C. As the temperature goes down, however, it increases gradually and reaches the value 6 below 750°C. The relative intensity of {100} of as-rolled sheets is between 1 and 2 when finishing temperature is above 850°C, and it has a maximum value between 750 and 850°C. No dependence of finishing temperature on the {110} intensity was observed.

In the case of high reduction as-rolled steel sheets the {100} intensity above 750°C is the same as the intensity of conventional draft steels. But the {111} intensity is higher than that of conventional draft steels.

Above 850°C, the {100} and {111} intensities of high reduction as-rolled steel sheets and those after annealing are the same. In this temperature range, as-rolled steel sheets are expected only to contain transformed ferrite. If these are annealed at 750°C, the texture doesn't change. In the range of 750 to 850°C, the {111} intensity increases whereas the {100} intensity decreases after annealing. In this range, however, recrystal-

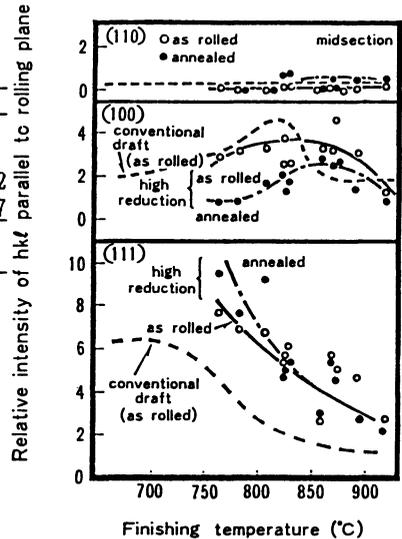


Fig.1 Changes in rolling and annealing texture with draft schedule and finishing temperature

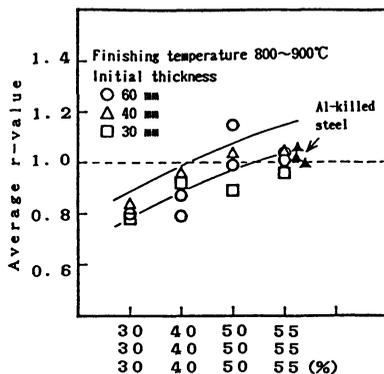


Fig. 2 Change in average r-value with reduction of final three stands and initial thickness (Test①)

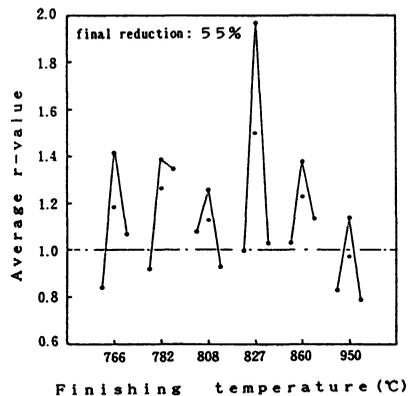


Fig. 3 Average r-value of high reduction steel sheet (Test②)

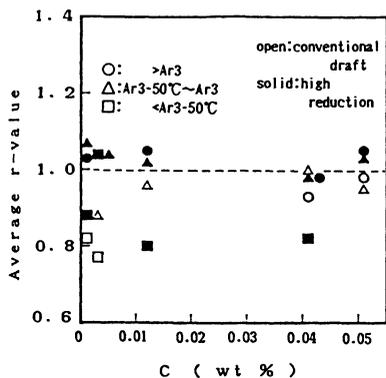


Fig. 4 Relationship between average  $r$ -value and carbon content

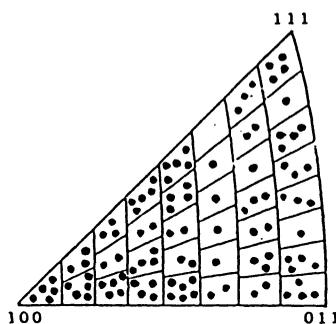


Fig. 5 Transformation texture from dynamically recrystallized  $\gamma$  1-pass deformed 75% at 950°C

lized ferrite grains are dominant before annealing because of high reductions. Furthermore, a small amount of residual strain increases the intensities after annealing.

As shown in Fig.1, the change in the  $\{111\}$  and  $\{100\}$  intensities of high reduction steels differ from those of conventional draft one. Fig. 2 shows the effect of reductions of final three stands in the range of 800 to 900°C on the average  $r$ -value. The rolling schedule is Test① in Table 2. When each reduction of final three stands is more than 50% and bar thickness is over 40mm, high average of  $r$ -values between 1.0 to 1.2 are obtained.

Fig.3 depicts the  $r$ -value of test pieces which were rolled with high reduction at temperature in  $\alpha$  region above 760°C after a rough rolling at a low temperature in  $\gamma$  region namely at 950°C, with the aim of refining  $\gamma$  grains. The rolling schedule was Test ② in Table 2. Most of average  $r$ -values exceed 1.2. When  $\gamma$  grains are refined, which transform to fine ferrite and make the recrystallization of ferrite easy to take place.

The  $r$ -value of cold rolled steel sheets is affected by solute carbon.<sup>6-9)</sup> Fig.4 describes the influence of carbon content on the  $r$ -value of hot rolled steel sheets rolled with more than 50% reduction at each final three stands.(Test① in Table 2) It should be noted that the average  $r$ -value reaches over 1.0 irrespective of carbon content. But at lower temperatures, the average remains below 1.0.

#### 4. DISCUSSION

##### 4.1 Analysis for high reduction steels by a transformation texture model

Furubayashi has developed a computer simulation model for transformation textures that are calculated from initial conditions of texture before transformation.<sup>6-7)</sup> Nagashima expanded this model to deal with initial conditions of texture and applications.<sup>10)</sup>

The authors have used this model to study transformation texture of high reduction steel sheets. In the high reduction tests, the rolling starting temperatures were in  $\gamma$  region, and three finishing rolling temperature ranges, in  $\gamma$ , in  $\alpha + \gamma$  and in  $\alpha$  range were selected. The initial texture was assumed to be random, as shown in Fig. 5.

Fig.5 shows the orientations of high reduction steels which were investigated by electron channeling patterns (ECP). The specimen was deformed more than 75% at 950°C. Calculated micro-structures were all dynamically recrystallized  $\gamma$ . The orientation of dynamically recrystal-

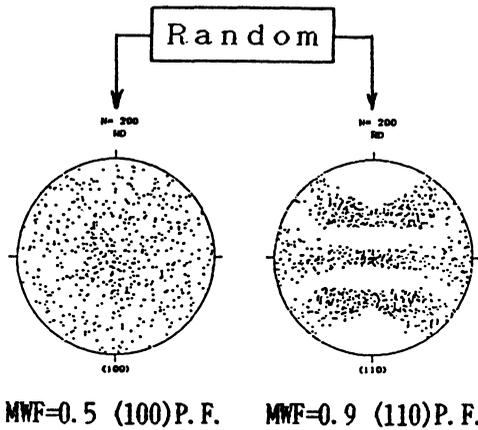


Fig. 6 Simulated (100) and (110) pole figure showing transformation texture

lized  $\gamma$  is considered to be random texture.<sup>11)</sup>

Fig. 6 shows the results of calculated transformation texture. In this model, a minimum work factor (M.W.F) which are influenced by strain and rolling temperature was used. When the M.W.F. is small, the calculated transformation texture is random whereas it has the stable orientation (110)<001> when the M.W.F. is large.

When the (110)<001> ferrite is rolled, the stable orientation becomes {554}<225> or (111)<112>, and (112)  $\sim$  (111)<011> after annealing.

The  $\gamma$  with random orientation by high reduction rolling in  $\gamma$  region transform to  $\alpha$  with random orientation or (110)<001>. The (110)<001> changes into (112)  $\sim$  (111)<011> because it is rolled in  $\alpha$  range and recrystallizes. That is the reason why the r-value of the high reduction steel sheets increases.

#### 4.2 An application of a computer simulation model for micro-structure

The authors have been developed a computer simulation model for micro-structures.<sup>4-5)</sup> The model simulates the hot rolling processes; heating, rolling and coiling processes. After that mechanical properties (YP, TS, EI) are predicted. When calculation has been stopped at the end of the rolling, volume fractions of dynamically recrystallized  $\gamma$ , statically recrystallized  $\gamma$ , non-recrystallized  $\gamma$ , and in the case of  $\alpha + \gamma$  rolling finishing range, recrystallized  $\alpha$  and deformed  $\alpha$  are calculated by this model.

It has been well established that the r-value of a steel sheet is influenced by the texture. In the case of hot rolled steel sheets, the final texture will be determined by ferrite transformation and rolling. This transformation texture is influenced by the micro-structure before the transformation. Relationship between the calculated micro-structures and r-value was investigated. Fig. 7 shows the calculation flow of the model.

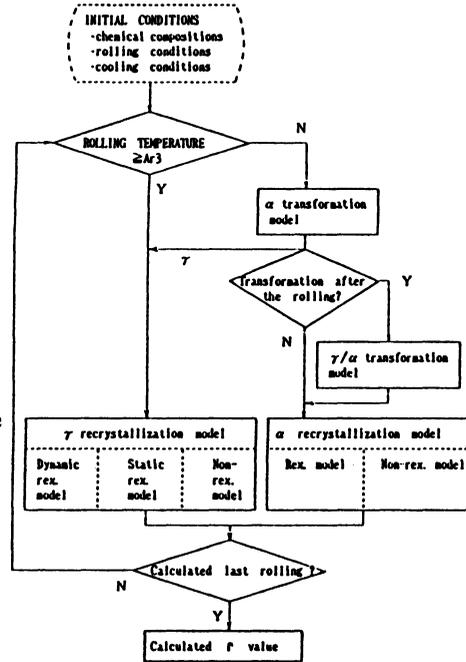


Fig. 7 Available part of structure and property model for average r-value

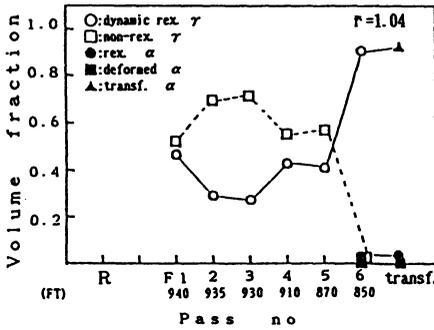


Fig. 8 Variation of calculated volume fraction of micro-structures after rolling (Test ①)

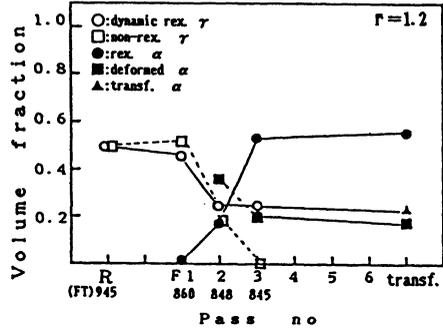


Fig.9 Variation of calculated volume fraction of micro-structures after rolling (Test ②)

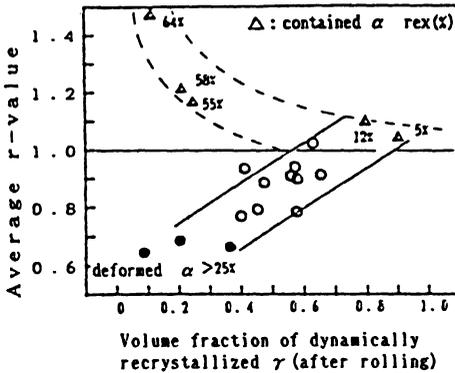


Fig. 10 Effect of calculated volume fraction of dynamically recrystallized  $\gamma$  and recrystallized  $\alpha$  on average r-value

Table 3 Example of calculation

FT0	FT	FT speed	$\gamma/\alpha$	trans.	rex.	def.	$\bar{r}$	final red%
°C	°C	m/m	$\gamma_d$	$\gamma_s$	$\gamma_{nr}$	$\alpha$	$\alpha$	(last-3st)
1045	880	310	0.59	0.34	0.07		0.90	57(87.3)
980	855	510	0.58	0.29	0.13		0.78	47(84.4)
1020	835	600	0.21	0.42	0.37		0.69	20(62.5)
930	825	550	0.37	0.06	0.04	0.18	0.35	40(81.4)
1080	970	510	0.57	0.43			0.91	54(86.7)
1120	855	310	0.64	0.26	0.10		1.04	55(88.6)

FT0: rolling starting temperature,  $\bar{r}$ : average r-value  
 FT: rolling finishing temperature,  
 $\gamma_d$ : dynamically recrystallized  $\gamma$   
 $\gamma_s$ : statically recrystallized  $\gamma$   
 $\gamma_{nr}$ : non-recrystallized  $\gamma$   
 rex:  $\alpha$ : recrystallized  $\alpha$   
 def:  $\alpha$ : deformed  $\alpha$   
 final red.: final and final three reduction

Fig.8 shows the the changes of volume fraction of micro-structures after high reduction rolling above 850°C. 0.9 of micro-structure were dynamically recrystallized  $\gamma$  at the end of the rolling. The average r-value becomes 1.04 after transformation.

Fig.9 shows the calculated results for steels which were rolled isothermally with high reduction at lower rolling starting temperatures. After the F1-stand rolling the micro-structures were dynamically recrystallized and non-recrystallization  $\gamma$ . The volume fraction of recrystallized  $\alpha$  at the end of the rolling exceeded 0.5. The average r-value of this specimen was 1.2.

Fig.10 shows the relationship between average r-values and calculated volume fractions of micro-structures. As the volume fraction of dynamically recrystallized  $\gamma$  increases, the average r-value increases gradually and reaches about 1.0. When the volume fraction of recrystallized ferrite increases, the average r-value increases moreover. But when the volume fraction of deformed ferrite goes up, the average r-value decreases remarkably. It means that volume fractions of dynamically recrystallized  $\gamma$  with random orientation and recrystallized  $\alpha$  with  $\{112\} \sim \{111\} \langle 011 \rangle$  after finishing rolling are useful for the

increase of the  $r$ -value. According to the results in Fig.10, average  $r$ -values,  $R_c$ , can be expressed as

$$R_c = 0.97 \times (D\gamma)^{0.5} + 1.84 \times (D\alpha)^2 + 0.147 \dots (1)$$

where  $D\gamma$  and  $D\alpha$  indicate the volume fractions of dynamically recrystallized  $\gamma$  and recrystallized  $\alpha$ .

Table 3 shows the calculated examples. Since high reductions help the increase in volume fractions of dynamically recrystallized  $\gamma$  and recrystallized  $\alpha$ , the average  $r$ -values become higher. The average  $r$ -value goes down with the increase of volume fractions of non-recrystallized  $\gamma$  and deformed  $\alpha$ .

The model can then be used for finding an optimum rolling condition to increase the  $r$ -value.

## 5. CONCLUSION

Three ranges of finishing temperature were characterized in relation to the  $r$ -value. Hot rolled steel sheets with high  $r$ -value could be produced by high reduction hot rolling at above 750°C. Major findings are summarized as follow;

- 1) When each of the final three reductions is more than 50%, the average  $r$ -value rises about 1.0~1.2. Then  $r$ -value is not affected by carbon content. Refinement of  $\gamma$  grains is effective for the acceleration of ferrite recrystallization giving high average  $r$ -values.
- 2) The fraction of dynamically recrystallized  $\gamma$  and recrystallized  $\alpha$  at the end of finishing rolling, which can be calculated through the model of micro-structure, and the  $r$ -value correlated. As the volume fraction of dynamically recrystallized  $\gamma$  goes up, the average  $r$ -value increases to 1.0. As the volume fraction of recrystallized  $\alpha$  increases, the average  $r$ -value increases and exceeds 1.2. However, non-recrystallized  $\gamma$  and deformed  $\alpha$  at the end of finishing rolling decrease the average  $r$ -value.
- 3) The average  $r$ -value is predicted by equation (1) through the volume fractions of dynamically recrystallized  $\gamma$  and recrystallized  $\alpha$ .

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