NIPPON STEEL TECHNICAL REPORT No. 71 OCTOBER 1996

UDC669.017:620.181:669.14.018.8-194.57

Hot Recrystallization Behavior of SUS 430 Stainless Steel

Ken Kimura*1 Akio Yamamoto*1
Tetsurou Takeshita*1 Jirou Harase*2

Abstract:

The hot recrystallization behavior of SUS 430 stainless steel was studied to improve its ridging resistance. When SUS 430 was tested under simulated continuous rolling conditions in which the microstructure is not in equilibrium, it was found that hot recrystallization in the $\alpha \rightarrow \gamma$ *two-phase region is delayed when it competes with the* $\alpha \rightarrow \gamma$ *transformation. The optimum hot rolling conditions to promote hot recrystallization were studied based on this finding. The feasibility was confirmed of a new SUS 430 sheet production process that can eliminate the annealing of hot-rolled sheets without increased ridging.*

1. Introduction

SUS 430 (17Cr) is representative of ferritic stainless steels and is widely used in kitchenware and household electrical appliances, among other products. Because SUS 430 does not contain nickel, it is relatively inexpensive, and has high corrosion resistance in interior environments. When formed, ferritic stainless steels sometime develop surface corrugations, called ridging or roping. Ridging mars the appearance of formed parts and interferes with the final polishing of formed parts. The cause of ridging is not yet clear. Some researchers think that ridging results from the difference in plastic anisotropy between a colony of grains oriented in a certain direction and other colonies owing to the solidification microstructure[1]. To destroy such colonies, hot-rolled strip was annealed or cold-rolled strip was given an in-process anneal to promote the recrystallization of the strip and to prevent ridging.

Improving the productivity of materials is indispensable in saving finite energy resources. Along these lines, the previous report[2] described the technology of continuously annealing at a high temperature for a short time hot-rolled strip of SUS 430 steel and then adding aluminum. This was tried instead of the conventional method of annealing hot-rolled strip in a bell-type furnace at a low temperature for a long time. The new technology allowed the annealing of hot-rolled strip to be completed in about 20 or so minutes and improved the productivity of SUS 430 materials. This productivity can be enhanced further if hot-rolled strip annealing is eliminated. Elimination of the annealing step, however, leaves coarse colonies and goes down the level of ridging. Full recrystallization microstructure does not evolve in the hot-rolled strip, and there is the possibility that if recrystallization is promoted in the hot rolling step, ridging in hot-rolled strip may not goes down when the annealing step is eliminated.

This study clarified the hot recrystallization behavior of SUS 430 stainless steel and investigated the new process whereby the

*1 Technical Development Bureau

*2 Formerly Technical Development Bureau

annealing of SUS 430 hot-rolled strip can be eliminated by promoting recrystallization in the hot rolling step[3].

2. Experimental Methods

2.1 Single-pass rolling test[4]

Wedge-shaped specimens as shown in **Fig. 1**(a) were machined from the columnar grain portions of continuously cast slabs of steel with the chemical composition A listed in **Table 1**. These were test rolled in a single pass on a two-high mill as shown in **Fig. 1**(b). The specimens were heated to 1,173-1,453°C, air cooled, and examined as to their recrystallized fraction. The recrystallized fraction was the cross-sectional area percentage of recrystallized grains counted in the optical microstructure of each specimen.

2.2 Plain-strain compression test[5-7]

Specimens, measuring 10 mm thick and 15 mm wide, were machined from hot-rolled sheets of the chemical composition B shown in **Table 1** and were compression tested by inducing plane strain with upper and lower hammers[8]. (This compression test is hereinafter referred to as the hot working simulator test.) As shown in **Fig. 2**, the hot working simulator test consisted of heating the specimens to 1,250°C, rapid cooling to the temperature T_d, holding for the time A, working, holding for the time B, and then water cooling. The recrystallized fraction of a specimen was determined by measuring the length of recrystallized grains relative to the total width from the optical microstructure of the plane-strained region of the specimen.

3. Experimental Results

3.1 Investigation of recrystallization behavior by single-pass rolling test[4]

Photo 1 shows the microstructures of specimens with different heating temperatures and rolling reductions. From **Photo 1**, it can been seen that the specimen does not develop a recrystallization structure when it is heated to 1,173 K and the rolling reduction is lowered greatly. When the specimen is heated to 1,323 K,

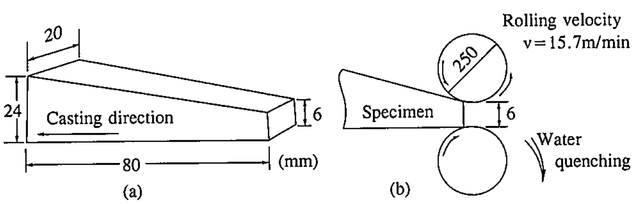


Fig. 1 Single-pass rolling test specimen (a) and rolling conditions (b)[4]

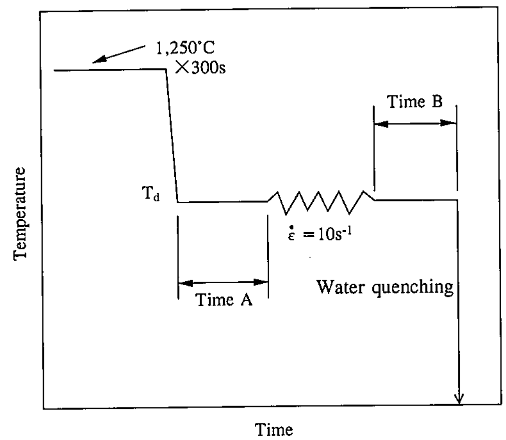


Fig. 2 Working heat cycle of hot working simulator test[5]

Table 1 Chemical compositions of test steels

(wt%)

	C	Si	Mn	P	S	Ni	Cr	Al	N
A	0.05	0.59	0.49	0.03	0.004	0.10	16.7	0.038	0.010
B	0.05	0.3	0.15	0.03	0.005	—	16.5	0.12-0.16	0.01
C	0.05	0.32	0.12	0.03	0.004	—	16.3	0.17	0.01

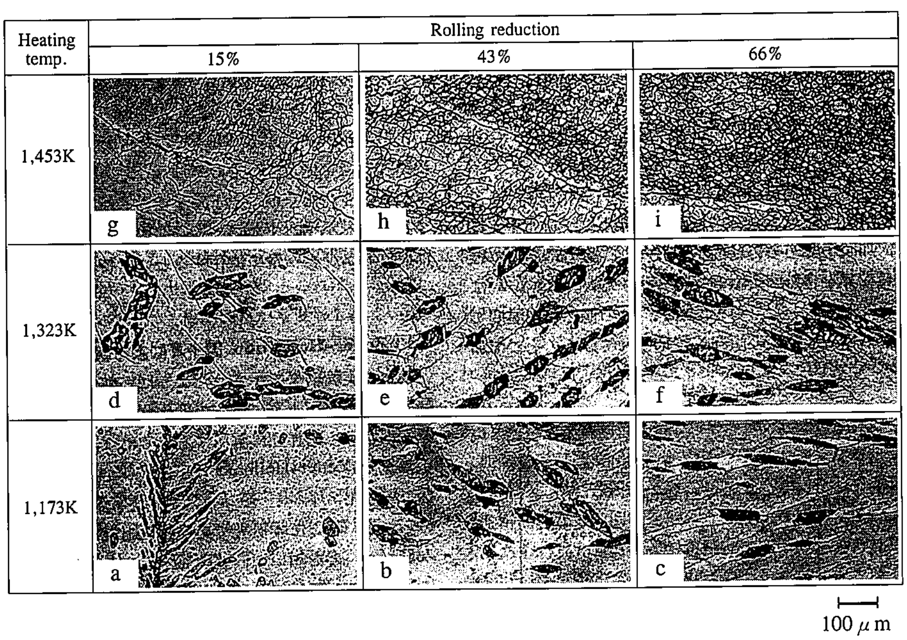


Photo 1 Microstructures of specimens with different heating temperatures and rolling reductions[4]

the formation of recrystallized grains from within and around the deformation bands is recognized, and the degree of this formation rises with increasing rolling reduction. **Fig.** 3 shows the recrystallized fraction determined from the optical microstructures as a function of the heating temperature and rolling reduction. When the heating temperature is not higher than 1,323 K, the structure changes from deformation structure to recrystallization structure as the heating temperature rises. A further gain in heat produces a recovery structure, which inhibits the progress of recrystallization. As a result, a nose is found to form at about 1,273 K in the recrystallization behavior curves of the SUS 430 stainless steel. (See **Fig.** 3.)

3.2 Investigation of recrystallization behavior by hot working simulator test[5-7]

The effects of holding time B and holding temperature T_d on the recrystallized fraction are shown in **Fig.** 4. The recrystallized fraction rises with increasing holding time and temperature.

The effect of ferrite-to-austenite ($\alpha \rightarrow \gamma$) transformation on recrystallization is shown next. To illustrate the effect of the transformation more clearly, the recrystallized fraction is plotted based on Avrami's equation[9] in **Fig.** 5. The amount of the austenite (γ) phase before working was changed by changing holding time A (10 and 300 seconds). Another test was conducted at 1,200°C (ferrite or α single phase) as a comparison. When the working temperature is 1,100°C in the $\alpha + \gamma$ two-phase region, recrystallization is delayed at a time A of 10 seconds (■) as compared at a time A of 300 seconds (□). When the working temperature is 1,200°C in the α single-phase region, the effect of time A on the recrystallization behavior is not recognized. Recrystallization proceeds with increasing time A, irrespective of the working temperature and holding time before working.

The optical microstructures of specimens after working at 1,100°C in the $\alpha + \gamma$ two-phase region are shown in **Photo** 2. When time A is 10 seconds, the amount of the γ phase is very small immediately after working as shown in **Photo** 2(a). When time B is 10 seconds, the amount of the γ phase is increased as shown in **Photo** 2(b), no recrystallized grains are observed. When time B is 30 seconds, the γ phase increases in amount, and recrystallized grains are observed in the vicinity of the γ phase precipitated at the grain boundaries. (See **Photo** 2(c)). When time A is 300 seconds, the amount of the γ phase is large at 10 seconds after working, as shown in **Photo** 2(d). This suggests sufficient progress of transformation before working. Recrystallization is already initiated at 10 seconds after working.

4. Discussion

4.1 Recrystallization behavior of SUS 430[7]

The delay of recrystallization when the holding time is short at 1,100°C in the $\alpha + \gamma$ two-phase region will be discussed. When the holding time in the $\alpha + \gamma$ two-phase region is short, the γ phase is considered to precipitate before working and to be almost in equilibrium. When the holding time is short, transformation occurs after working, as shown in **Photo** 2(a) to **Photo** 2(c). Among the possible transformation nuclei $\alpha \rightarrow \gamma$ are α - α and α - γ grain boundaries. These transformation nuclei are the same as the recrystallization nuclei. When transformation preferentially proceeds after working, the recrystallization nuclei are considered to decrease. When the holding time before working is short, as in **Fig.** 5, the straight lines do not change in slope and shift toward the high end of the time range. This suggests

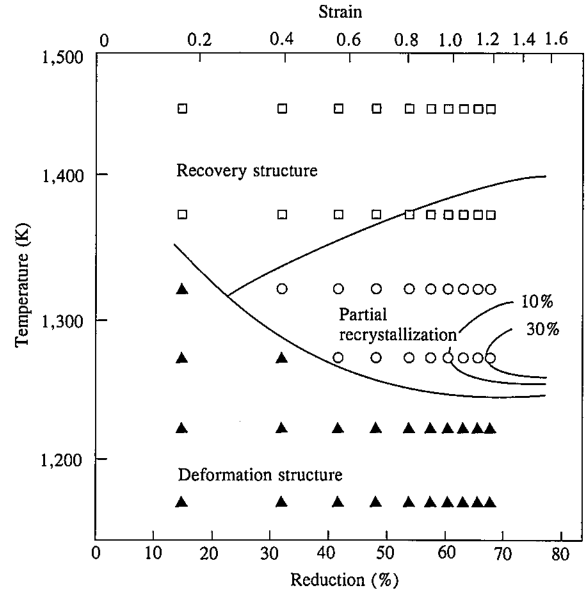


Fig. 3 Effects of working temperature and rolling reduction on recrystallized fraction[4)]

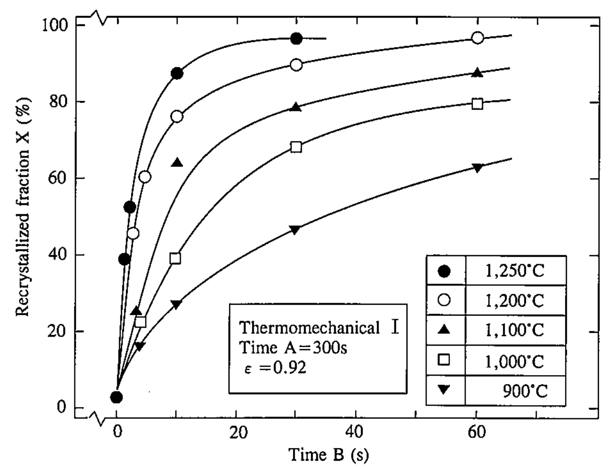


Fig. 4 Effects of holding time and temperature on recrystallization behavior[7)]

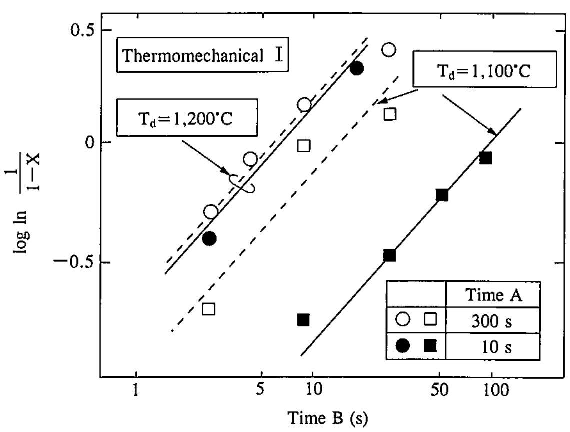


Fig. 5 Effects of holding time and temperature on recrystallization behavior[7)]

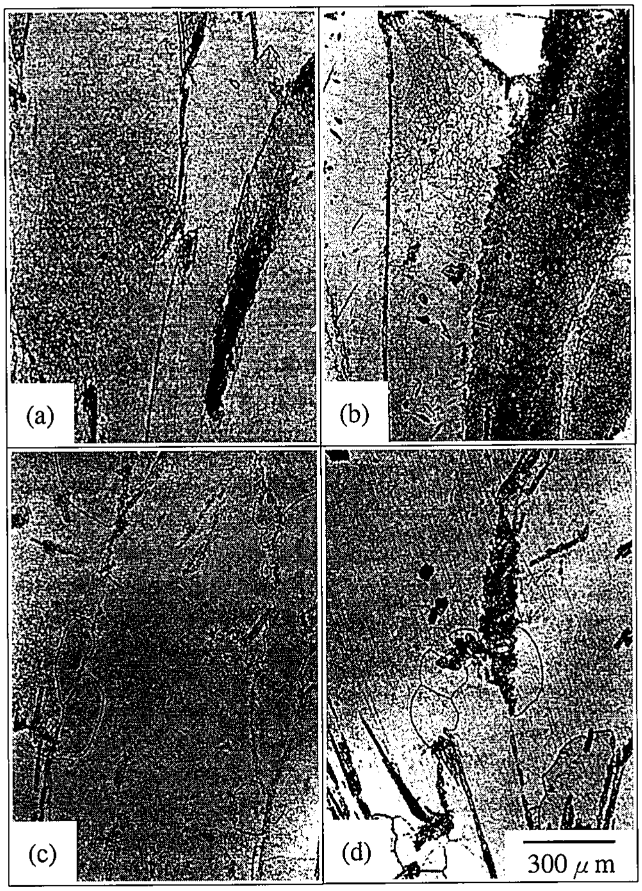


Photo 2 Microstructures after working (ε = 0.92, 1,100°C)[7]
(a) Time A=10s, Time B=0s
(b) Time A=10s, Time B=10s
(c) Time A=10s. Time B=30s
(d) Time A=300s, Time B=10s

that the $\alpha \rightarrow \gamma$ transformation proceeds after working and delays the start of recrystallization.

With wedge-shaped specimens, a recrystallization nose (see **Fig. 4**) was recognized in the single-pass rolling experiment. The temperature of 1,373 K at which recrystallization is delayed is the temperature at which the γ phase precipitates in the largest amount. The progress of transformation after working is considered to have delayed recrystallization and produced the recrystallization nose.

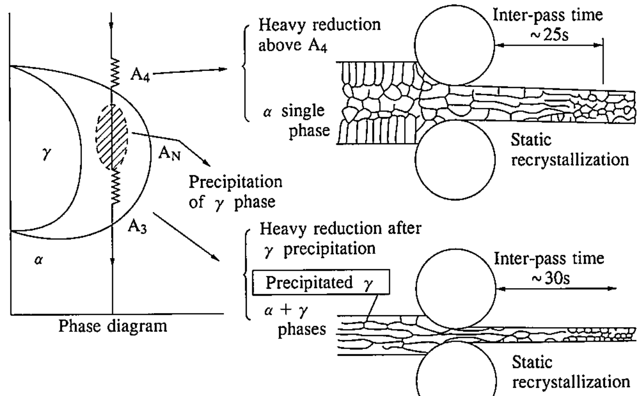


Fig. 6 Schematic illustration of rough rolling with $\alpha \rightarrow \gamma$ transformation and recrysallization taken into account[10]

4.2 Design of hot rolling process to improve ridging resistance[3,10]

The process of promoting recrysallization in the rough rolling step was studied to improve the ridging resistance of SUS 430. At equivalent rough rolling temperatures of about 1,000 to 1,200°C, the γ phase is present in SUS 430 stainless steel. As clarified in the preceding section, transformation progression is feared to retard the start of recrystallization. Working and holding in the α single-phase region or working and holding in the $\alpha + \gamma$ two-phase temperature region after the finish of transformation were thought to be effective in promoting recrystallization in the rough rolling step. This process is schematically illustrated in **Fig. 6**. It features the following:

1) Promotion of recrystallization in α single-phase region in early rough rolling stands

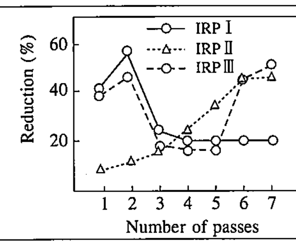
2) Promotion of $\alpha \rightarrow \gamma$ transformation by increasing inter-pass time during rough rolling

3) Promotion of recrystallization after rough rolling by heavily reducing the later rough rolling stands

Making use of inter-pass time during rough rolling is named the inter-pass recrystallization process (IRP).

A test was conducted to confirm the effectiveness of the IRP in improving the ridging resistance of SUS 430. Hot-rolling samples, measuring 200 mm thick, 200 mm wide and 250 mm long, were machined from continuously cast slabs of steel composition

Table 2 Hot rolling conditions in laboratory hot rolling test

Specimen	Al (%)	Soaking temperature (°C)	Rough rolling conditions		Rough rolling finish temperature (°C)	Finish rolling temperature		Rough rolling redution
			Schedule	Inter-pass time		Start (°C)	Finish (°C)	
a	0.17	1,200	IRP I	15s	1,035	975	850	
b	0.17	1,200	IRP I	25s	1,001	931	862	
c	0.17	1,200	IRP II	15s	1,115	986	899	
d	0.17	1,200	IRP II	25s	1,087	974	912	
e	0.13	1,200	IRP III	25s	1,038	950	809	
f	0.13	1,300	IRP III	25s	1,134	1,002	891	

C in **Table 1**, rough rolled to a thickness of 20 mm, and finish rolled to a hot-rolled sheet thickness of 3.8 mm. The rough rolling pass schedules are shown in **Table 2**. Heavy reductions were taken in early rough rolling stands (pass schedule IRP I), in later rough rolling stands (pass schedule IRP II), or in both early and later rough rolling stands (pass schedule III). Pass schedules IRP I, II and III were investigated for the above-mentioned effects 1), 2) and 3), respectively. The hot-rolled sheets in the non-annealed condition were cold rolled at 80% reduction and annealed at 870°C for 60 seconds. Tension test specimens were machined from the cold-rolled and annealed sheets, tension tested, and inspected as to the r value and ridging height.

Fig. 7 shows the effects of hot rolling conditions on the r value and ridging height. Comparison of a, b, c and d in **Fig. 7** indicates that the ridging resistance improves with increasing inter-pass time. The ridging resistance is higher with pass schedule IRP II than with pass schedule IRP I. That is, increasing the inter-pass time during rough rolling is considered to promote the $\alpha \rightarrow \gamma$ transformation, and increasing the reduction on later rough rolling stands is considered to promote recrystallization after rough rolling, refine the grain size and produce random grain orientations. Comparison of e and f in **Fig. 7** shows that pass schedule IRP III, aimed at recrystallization in the α region, is more effective in improving ridging resistance. The ridging height is similar to that of annealed hot-rolled sheets, as shown in d and f in **Fig. 7**. As discussed above, it was confirmed that when hot-rolled sheet annealing is eliminated, promotion of recrysallization in the hot rolling step provides hot-rolled strip with the same ridging resistance as obtained when the hot-rolled strip is annealed.

A test was run on a production mill to verify the validity of pass schedule IRP II. The hot rolling conditions are given in **Table 3**. Hot-rolled strip was given a treatment equivalent to coiling (600 or 650°C), cold rolled from 3 to 0.4 mm, and annealed at 875°C for 60 seconds. The treatment equivalent to coiling was performed to decompose the α' phase without recrystallization, in order to eliminate the effect of the α' phase on reducing the ridging tendency and to singularly extract the effect of the pass schedule IRP II on improving the ridging resistance.

As shown in **Table 3**, the IRP improves ridging resistance. **Fig. 8** shows the results of the {200} pole figures of hot rough-rolled specimens as analyzed by the vector method[11]. From **Fig. 8**, it is evident that the texture of IRP specimen N is randomized as compared with the control specimen C. The ND//{100} intensity is especially reduced. This confirms that recrystallization in the rough hot rolling stage promoted random grain orientations.

5. Conclusions

The hot recrystallization behavior of the SUS 430 stainless steel was investigated, and a study was made of the feasibility of a new SUS 430 manufacturing process that can eliminate the hot-rolled strip annealing step without affecting ridging resistance and other quality properties by capitalizing on the effects of hot recrystallization behavior. The following findings were obtained:

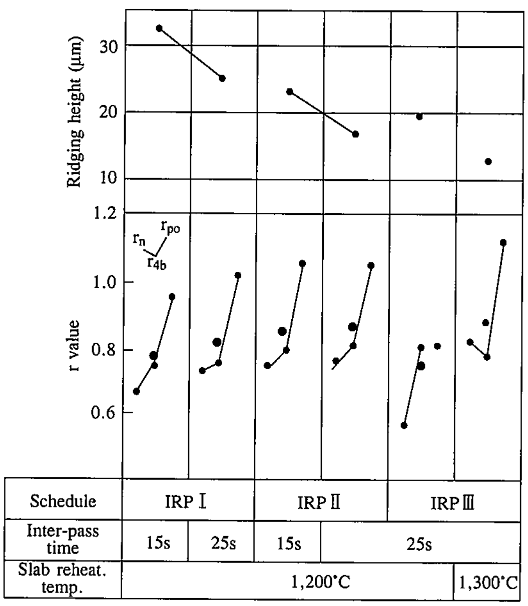


Fig. 7 Effects of rough rolling conditions on ridging height and r value of product sheet[10]

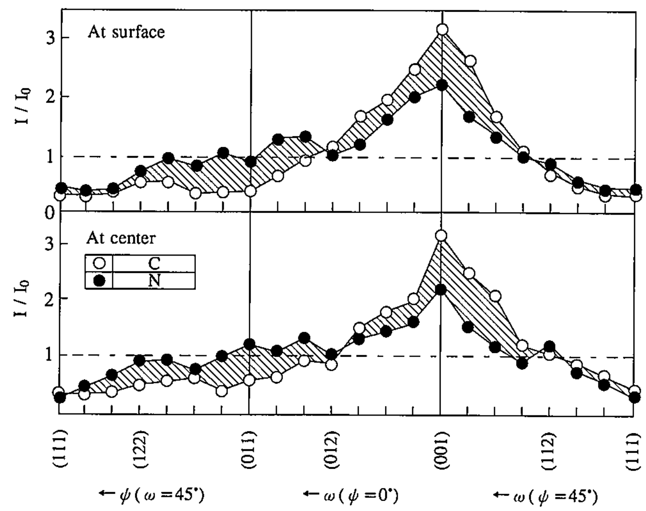


Fig. 8 Grain orientation distribution of specimens rough rolled on production mill[3]

Table 3 Production mill hot rolling conditions and sheet product properties

Specimen	Rough rolling conditions								Rough rolling finish temperature (°C)	Finish rolling temperature		Coiling temperature (°C)	Formability of final annealed sheet	
	Redution (%) /pass							Inter-pass time (last 4 passes)		Start (°C)	Finish (°C)		Ridging height (μm)	r value
	1	2	3	4	5	6	7							
C	12.0	25.0	30.3	31.3	38.0	36.7	32.3	15s	1,052	999	894	600	56	1.46
N	10.2	16.8	21.9	31.5	32.7	39.4	40.0	25s×4	1,014	975	900	650	32	1.43

(1) SUS 430 recrystallization is delayed when it completes with a transformation.

(2) The hot recrystallization of SUS 430 is promoted by allowing a long inter-pass time during rough rolling and taking heavy reductions on later rough rolling stands. This rolling practice provides high ridging resistance even when the annealing of hot-rolled strip is eliminated.

References

1) Matsuo, S.: Bul. Jpn. Inst. Met. 19 (3), 192 (1977)
2) Sawatani, Y., Yoshimura, H., Ashiura, T., Ishii, M., Wakamatsu, M., Yamamoto, A.: Seitetsu Kenkyu. (310), 335 (1982)
3) Harase, J., Ohta, K., Takeshita, T., Kawamo, Y.: Proc. Int. Conf. Stainless Steels '91, 1991, p. 1
4) Yoshimura, H., Ishii, M.: Tetsu-to-Hagané. 69, 1440 (1983)
5) Takeshita, T., Abe, M., Sellars, C.M.: CAMP-ISIJ. 7 (8), 788 (1994)
6) Takeshita, T., Harase, J., Yada, H., Ohta, K.: Tetsu-to-Hagané. 70 (13), S1405 (1984)
7) Takeshita, T., Harase, J., Yada, H.: Trans. ISIJ. 27, 432 (1987)
8) Yada, H., Matsuzu, N., Najima, K., Watanabe, K., Tokita, H.: Trans. ISIJ. 23, 100 (1983)
9) Avrami, M.: J. Chem. Phys. 7, 1103 (1939)
10) Harase, J., Takeshita, T., Ohta, K., Suzuki, T., Shimizu, A.: CAMP-ISIJ. 1, 1906 (1988)
11) Ruer, D., Baro, B.: J. Appl. Cryst. 10, 458 (1977)