Super Short Interval Multi-pass Rolling Process for Ultrafine-grained Hot Strip

Manabu ETOU,1) Suguhiro FUKUSHIMA,1) Tamotsu SASAKI,1) Youichi HARAGUCHI,1) Kaori MIYATA,2) Masayuki WAKITA,2) Toshiro TOMIDA,2) Norio IMAI,2) Mitsuru YOSHIDA2) and Yasutaka OKADA2)

1) Corporate Research & Development Laboratories, Sumitomo Metal Industries, Ltd., 3 Hikari, Kashima, Ibaraki 314-0014 Japan. 2) Corporate Research & Development Laboratories, Sumitomo Metal Industries, Ltd., 1-8 Fuso-cho, Amagasaki, Hyogo 660-0891 Japan.

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As a process to manufacture ultrafine-grained hot strip or plate of which ferrite grain size was about 1 μm, heavy reduction hot rolling at relatively low temperature, such as larger than 70% reduction per pass at lower than 700°C, had been presented. However, it is quite difficult to apply the process to commercial production because the rolling load is very large. A new process of multi-pass rolling at extremely short interval has been proposed and developed in order to manufacture ultrafine-grained hot strip at ordinary rolling load. Authors named it “Super Short interval Multi-pass Rolling (SSMR) process”. Ultrafine-grained hot strip of 1.2 mm thick was successfully manufactured in laboratory with the simple chemical composition of 0.15%C–0.74%Mn. Its grain size was 0.9 μm at 50 μm beneath the surface and 1.2 μm on the average over the thickness. The rolling load in SSMR was smaller than 30 kN/mm and it was relatively small owing to relatively small reduction, smaller than 50% per pass, and relatively high temperature, higher than 820°C. Consequently it was confirmed that the rolling load in SSMR process could be reduced to half compared to the previously presented process of heavy reduction hot rolling at low temperature.

KEY WORDS: rolling; grain refinement; grain size; ferrite transformation; C–Mn steel; multi-pass; yield strength; rolling load; cooling.

1. Introduction

Ultrafine-grained steel is recently noticed as an environmental conscious structural material in the near future. By the advantage of its high strength property, the amount of steel used in constructions or vehicles can be reduced. Especially the lightening of automotive bodies is greatly expected for energy saving and CO₂ emission reduction. Because the high strength is attributed to grain refinement and not to microalloying elements, alloys can be saved and consequently the steel products recycling can be promoted.

For manufacturing ultrafine-grained steel, several processes have been proposed in the last decade.1–4) One of those is the large reduction hot rolling at relatively low temperature, such as larger than 70% reduction per pass at lower than 700°C. As representative one, the ferrite grain refinement by the heavy deformation in under-cooled austenite region was presented by Japanese national project called Super Metal Project.5–7) They achieved to obtain ultrafine ferrite grains of about 1 μm in laboratory using a C–Mn steel including small amount of Nb or Ti. However, as the rolling load in their experiments was extremely large, it had been thought quite difficult to apply the process to commercial production. For example, the rolling load per unit width at finish rolling would reach more than 60kN/mm which is three or four times as large as that of conventional hot strip rolling. In such a large load rolling, seizure on roll surface may occur. Also, the load in wide strip rolling will exceed the designable capacity of rolling mill.

The new national project named PROTEUS Project was carried out to develop the production technology for ultrafine-grained hot strip.8) A plain C–Mn steel popularly used for sheet products was chosen as a standard specimen, which contained no Nb or Ti that had been used often in research works for ultrafine-grained steel on the purpose of grain growth restraining. One of the aims of this material choice was to try manufacturing the completely environment-conscious ultrafine-grained steel with no microalloying elements. Another aim was to develop a fundamental production technology that can be applied to various steels. This research is a part of PROTEUS Project.

This research had focused on the finish rolling technology to manufacture the ultrafine-grained hot strip with proper rolling load, which is realizable in commercial production. The rolling load in the previously presented process must be reduced vastly, whereas the grain refining effect of rolling deformation must not be lessened. For this conflicting subject, the multi-pass rolling with short inter-pass time was supposed to be one of the best solutions. By shortening the interval time of the successive passes, even though the reduction at each pass is not so large, the effective strain for grain refining may be accumulated as much as in the large reduction single pass rolling.
Yada et al. researched the grain refinement by the multi-pass deformation test. At the 2-pass compression test the shorter the inter-pass time was, the finer the ferrite grain became, although the minimum grain size of 2.5 μm was coarser than that of 1.5 μm in the large reduction single pass test. Hence, authors investigated the optimum condition and the limitation of grain refinement in the short interval multi-pass rolling by laboratory experiment simulating a hot strip mill.

2. Concept of “SSMR” Process

To make the short interval multi-pass rolling process function well, reduction per pass, inter-pass time, number of passes and rolling temperature should be optimized. Rolling temperature affects the rolling load as well as the reduction per pass. The lower the material temperature is, the larger the rolling load becomes. In addition, if the temperature falls below the ferrite transformation temperature before the final pass, the microstructure of the rolled strip is supposed to contain deformed ferrite grains or abnormally grown grains, which are not preferable for mechanical properties of the strip. Therefore the rolling in the stable austenite temperature region was searched for the new process.

In order to shorten the inter-pass time, the rolling stands must be placed close each other and rolling speed must be fast. However, when the rolling speed increases, the heat generation in rolling becomes large. For the purpose of the effective strain accumulation, excessive temperature rise should be avoided because the restoration of the strain proceeds fast in high temperature. Therefore the rapid cooling right after each rolling pass is necessary to compensate the generated heat. Immediate cooling after rolling is also required for inducing ferrite transformation and for restraining the grain growth after the transformation.

The basic concept of the newly proposed process is as follows. In downstream stands of hot finishing mill, more than two stands including the final one are equipped at extremely short distance. At those stands high speed and moderately large reduction rolling of 40–50% per pass is performed. Strip temperature is controlled around Af₃, the para-equilibrium transformation temperature from austenite to ferrite, by inter-pass cooling. Then the strip is cooled down to appropriate temperature immediately. Authors named this process “Super Short interval Multi-pass Rolling (SSMR) process”.

3. Experiments

3.1. Experimental Equipments

Figure 1 is a schematic illustration of the experimental equipment. Table 1 and Table 2 are its specifications. Rolling section is composed of 3 rolling stands those scales are almost 1/4 of commercial hot strip mill. We call those 3 rolling stands F1, F2 and F3. The distance between F2 and F3 is extremely close such as 1 m.

Table 1. Specification of model rolling mill.

|                  | F1 | F2 | F3 |
|------------------|----|----|----|
| WR diameter /mm  | 200| 200| 220|
| WR barrel length /mm | 400| 400| 400|
| Rolling load /K  | 3000| 2500| 2500|
| Rolling speed /m/min | 540| 360| 720|
| Motor power /KW   | 700| 700| 700|

Table 2. Specification of cooling equipment.

|                  | Inter pass | After pass | Run out table |
|------------------|------------|------------|---------------|
| Length m         | - | 0.7 | 7.2 |
| Total flow m³/min | 1.5 | 1.6 | 5.0 |
| Pressure /MPa    | 0.2 - 1.5 | 0.2 - 1.5 | 0.5 |
| Spray header     | upper | 12 | 88  |
|                  | lower | 12 | 88  |

Table 3. Chemical composition of specimen (wt.%).

| C  | Si  | Mn  | P   | S   | Al  | N   | Nb  | Ti  |
|----|-----|-----|-----|-----|-----|-----|-----|-----|
| 0.15 | 0.01 | 0.74 | 0.02 | 0.006 | 0.022 | 0.0022 | 0   | 0   |
inter-stand cooling. After rolling they were cooled immediately down to about 620°C by rapid water-cooling. The rapid cooling started within 0.05 s after the final pass rolling and its rate was over 1 000°C·s⁻¹. After that they were cooled in the air to the room temperature.

Other than that, continuous 2-pass rolling tests were carried out using F2 and F3 stands in order to examine the deformation resistance of specimen and its work-hardening characteristics in multi-pass rolling. The reduction of each pass was varied between 12% and 67%. The inter-pass times were set to 0.4 s, 0.6 s, and 1.1 s. The thickness of specimen before the second pass was unified as 4.0 mm regardless of the reduction variation in the first pass by preparing the initial thickness appropriately. Rolling temperature was controlled around 830°C. Rolling load was measured by load sells in the mill, and the forward slips in rolling were measured by the marking-off printing method.

4. Results

4.1. Microstructure

Figure 2 shows the typical microstructure of the rolled sheet. The ferrite grain size was 0.9 μm at 50 μm beneath the surface and 1.2 μm as average through the thickness. Ultrafine-grained steel sheet was successfully made by SSMR process.

Most of the ferrite grains were equiaxed and not elongated in the rolling direction. It was proved by EBSP analysis that those grains had random orientation and more than 80% of grain boundaries were high angle ones of which misorientations were over 15 degrees. Besides, the dislocation density has been revealed to be quite low by TEM analysis.⁴,¹⁵)

Figure 3 shows the influence of the final pass rolling temperature on the microstructure. Because the heat generation by plastic deformation in high speed and large reduction rolling was very large, the exit temperature became 910°C without inter-pass cooling between F2 and F3 stand. It resulted in ferrite grain coarsening. When the exit temperature was controlled to 820°C, right above Ae₃ temperature, by the inter-pass cooling, the equiaxed ultrafine ferrite grains could be obtained. When the inter-pass cooling was too strong, the exit temperature decreased to 740°C and the ferrite grain was elongated in the rolling direction. In this case the ferrite transformation was thought to occur before the final pass. Hence, it is quite important to control the rolling temperature around Ae₃ in SSMR process.

The influence of the final pass rolling conditions on ferrite grain refinement is shown in Figs. 4 and 5. The larger the reduction was, the finer the ferrite grain became. However, when the reduction was larger than 50%, the finer grain was not be obtained because the temperature increase by the adiabatic deformation heat could not be compensated enough by the cooling equipment. The shorter the inter-pass time was, the finer the ferrite grain became. This result positively proves that the strain accumulation during short interval multipass rolling contributed the ferrite grain refinement.

Figure 6 shows the influence of the combination of rolling conditions of reduction, inter-pass time and cooling. In the conventional mill, final rolling reduction is usually limited to 30% at most. In the compact mill, final rolling reduction can be increased to 50%, however the rolling speed is not so fast as conventional mill. Therefore the final inter-pass time is more than 1.0 s. Ferrite grain size was about 5 μm in the case of the mass production conventional hot strip mill simulation. In the case of the compact mill simulation, since rolling reduction was increased to 50% per pass, the ferrite grain size became 2.5 μm. In the case of the proposed SSMR process, ferrite grain size was about 1 μm.

4.2. Mechanical Property

Figure 7 shows the yield strength of the sheet rolled by
SSMR process as a function of ferrite grain size comparing with some previous studies\textsuperscript{16,17} and a Hall–Petch equation proposed by Takaki \textit{et al.}\textsuperscript{18} The yield strength is increased over 700 MPa with reducing the grain size to 1 μm in good agreement with the Hall–Petch relationship. The stress–strain curves of the rolled sheets with various grain sizes are shown in Fig. 8\textsuperscript{19–21}. Because the chemical composition of the used specimen corresponds to 440 MPa commercial products, the S–S curve of 4.5 μm specimen rolled in the laboratory was similar to the one of 440 MPa commercially manufactured sheet. As the grain size decreased, the tensile strength increased and the elongation decreased. However the total elongation was kept more than 15% even though the yield strength increases up to 650 MPa with grain refinement to 1.2 μm. When the grain size is smaller than 1.8 μm, work hardening cannot be observed.

4.3. Deformation Resistance in Rolling

The mean deformation resistance $K_{fm}$ of specimen was calculated backward from the rolling force and the forward slip using the Orowan’s heterogeneous compression theory. The comparisons of $K_{fms}$ between the first and the second passes are shown in Figs. 9 and 10. At the second pass $K_{fm}$ was always larger than that of the first passes. Although it is not very obvious, as the inter-pass time became short, $K_{fm}$ at second pass became large slightly. It indicates the strain accumulation during the short interval multi-pass rolling.

Two curves in these figures are calculated results based
on a simple work-hardening assumption. If we assume a flow stress of a specimen expressed by an exponential function of strain such as Eq. (1), Kfm, the mean value of it, is also expressed by an exponential function of strain as Eq. (2).

\[ \sigma = A e^n \] \hspace{1cm} (1)

\[ K_{fm} = \int \frac{\sigma d\varepsilon}{\varepsilon} = B e^n \] \hspace{1cm} (2)

where \(\sigma\) is flow stress and \(\varepsilon\) is strain. \(A\) is a coefficient in which the effect of a strain rate, temperature and so on are included. Beside, authors assumed that those functions could be applied to the accumulated strain in the multi-pass rolling. The equation for the Kfm at the second pass can be expressed as Eq. (3).

\[ K_{fm2} = \int_{\varepsilon_1}^{\varepsilon_1+\varepsilon_2} \frac{\sigma d\varepsilon}{\varepsilon_2} = B \left( (\varepsilon_1 + \varepsilon_2)^{n+1} - \varepsilon_1^{n+1} \right) \] \hspace{1cm} (3)

where \(\varepsilon_1\) and \(\varepsilon_2\) are strains at the first and the second pass respectively. \(\varepsilon_R\) represents the remaining strain at the beginning of the second pass. And it was assumed the product of the first pass strain \(\varepsilon_1\) and remaining ratio \(R\). The solid curves in Figs. 9 and 10 are calculated results by the Eq. (2) with the estimated values 284 for \(B\) and 0.32 for \(n\), those are mentioned later. The dotted curves are obtained by the Eq. (3) with 0.5 for \(R\). The experimental data of the second pass Kfm were almost on this calculated Kfm, lines assuming the strain remaining of 50%. However, to analyze the strain accumulation effect in the multi-pass rolling from the deformation resistance, it seems to be required more accuracy and number of the experimental data.

In Fig. 11 the second pass Kfm are plotted with the total strain \(\varepsilon_1 + \varepsilon_2\), added to the first pass Kfm with \(\varepsilon_1\). They can be approximated well by a single curve of the Eq. (2) with 284 for \(B\) and 0.32 for \(n\). This graph may not be appropriate to analyze the work hardening phenomenon but is helpful to overlook the Kfm change through the multi-pass rolling.

### 5. Discussion about Rolling Load in SSMR Process

Kfm at the final pass of SSMR process are put on the graph of Fig. 11. The total strain in this case is the sum of the last 2 passes' strains. The region surrounded by dotted line in the upper part of the graph indicates the condition of the low temperature large reduction rolling. In the followings, the low temperature large reduction rolling process is symbolically denoted as “Super Metal process”, the name of the previous research. Kfm of a SM490 equivalent steel at 700°C deduced from their experimental data\(^22\) was around 450 N/mm\(^2\). Kfm at the SSMR final pass were from 300 to 350 N/mm\(^2\) and about 30% smaller than that in Super Metal process. Concerning a rolling load, the reduction per pass must be considered. The difference in the reductions of 50% in SSMR and 70% in Super Metal enlarges the difference in rolling load in addition to the influence of the Kfm difference.

In order to discuss the possibility to apply SSMR process to commercial mill, rolling load must be evaluated in the commercial mill scale. Especially large work roll diameter more than 400 mm must be taken into account. As a result that authors estimated the designable maximum load capacity of rolling mill, it was 60,000 kN for 2,000 mm wide strip, which is 30 kN/mm per unit width. Figure 12 is the calculated result of the final pass rolling load for the commercial scale SSMR process assuming Kfm in Fig. 11. The parameters were work roll diameter and rolling friction coefficient where the rolling reduction and the exit thickness was fixed on 50% and 2 mm respectively. From the result it was verified that the work roll diameter must be smaller
than 700 mm and the rolling friction coefficient $\mu$ must be reduced to less than 0.2.

Above result proved that it is able to apply SSMR to designate commercial mill. However, the rolling force of 30 kN/mm is still large. In order to make the most of the mill capacity, lubrication technology for friction reduction and seizure prevention must be improved. In addition, work rolls are desired made stronger to withstand the high pressure.

6. Conclusions

The new process of the extremely short interval multipass rolling, SSMR, for manufacturing the ultrafine-grained hot strip was proposed. The grain refinement effect and the rolling load of SSMR process were investigated using a plain C–Mn steel and the realization of its commercial scale mill was studied. The results are summarized as follows.

(1) The ferrite grains were remarkably refined to almost 1 $\mu$m by the SSMR process, 40 to 50% reduction 3-pass continuous rolling at the final pass-interval of 0.17 s at the temperature around $Ae_3$.

(2) The microstructure of the rolled sheet was equiaxed ferrite grains with high angle boundaries.

(3) The yield strength of the sheet was well agreed with the Hall–Petch relationship and the maximum yield strength was 700 MPa.

(4) The increase in the deformation resistance during multi-pass rolling was observed and the work-hardening effect by the strain accumulation was inferred.

(5) The mean deformation resistance at the SSMR final pass was 300 to 350 N/mm². The rolling load in SSMR could be reduced to half compared to the previously presented process of the low temperature large reduction rolling.

(6) It is possible to design the commercial scale mill for SSMR process.

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