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Technical Report

Development of NSSC® PDX—a Ferritic Stainless Steel with Excellent Formability

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Abstract

A new ferritic stainless steel "NSSC PDX" having excellent formability and good ridging property was developed. An excellent formability was obtained by means of decreasing impurities. A good ridging property was attained by microstructural controls that were composed of the refinement of solidification structure and the accelerating recrystallization on the way of hot-rolling process. This new ferritic stainless steel is applied in new fields and is expected to broaden them in the future.

1. Introduction

Various kinds of stainless steel have been used for electrical appliances, building materials, kitchen facilities, and a wide variety of other applications thanks to their excellent appearance and corrosion resistance. While the grade of stainless steel most widely used is an austenitic stainless steel, SUS304 (18Cr-8Ni (mass %)) as defined under JIS, accounting for more than half of all demand for stainless steels, demand for ferritic stainless steels has been increasing lasting recent years.

The advantages of ferritic stainless steels over SUS304 include price stability due to very low or no content of Ni, a low thermal expansion coefficient, and low sensitivity to stress corrosion cracking. Typical shortcomings of these steels, on the other hand, are poor formability and the occurrence of ridging. For example, with respect to ductility, an important indicator of formability, a typical ferritic stainless steel, JIS SUS430 (17Cr), has a ductility of about 30 percent, whereas that of SUS304 can exceed 50 percent. Furthermore, with respect to r-value, an indicator of deep drawability, although SUS430 is better (a maximum r-value of roughly 1.5) than SUS304 (roughly 0.9), the value is not high enough for applications requiring good formability.

Another problem of ferritic stainless steels is ridging; creases, or ridges, appear on sheet surfaces after forming work because of plastic anisotropy of crystal grains. In the case of ferritic stainless steels especially, groups of crystal grains with similar orientations (such groups hereafter being referred to as colonies) are aligned in the rolling direction, and under forming work, the colonies deform as if each of them were a coarse crystal grain, resulting in ridging. When this occurs, the beautiful appearance characteristic of stainless steel is lost, and surface polishing is required after forming work. When replacing SUS304 with a ferritic stainless steel, therefore, it is necessary for the new material to have good formability as well as good anti-ridging properties.

In consideration of the above, the authors developed a new grade of stainless steel, NSSC PDX, having the highest level of formability of ferritic stainless steels in the 17%-Cr system and good anti-ridging properties through control of the metallographic structure by integrating the manufacturing processes from smelting, casting, hot and cold rolling to annealing. This paper explains the philosophy of the control of metallographic structure for the development of the steel and its advantageous properties.

2. Development Targets

The targets for the development were set as follows. Regarding ductility, an important indicator of formability, the target was set at roughly 40 percent, between SUS430, one of the best of the conventional ferritic stainless steels, and SUS304. With respect to deep drawability, another important indicator of formability, the target r-value after one stage of cold rolling was set at 2.0 or higher, the highest level for conventional stainless steels. Regarding ridging, a ridging height after a tensile test of 15 μm or less was sought so that any ridging after forming work was within acceptable limits. A target corrosion resistance equal to or better than that of SUS430 was envisaged.

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3. Control of Metallographic Structure

3.1 Formability

It is widely known that tensile strength increases and ductility is lowered as the content of Si, Mn, P and other impurity elements increases[1], but the effects of each of them on the ductility of ferritic stainless steels have not been clarified. In view of this, the authors examined the effects of various impurity elements on the ductility (total elongation) of ferritic stainless steels. Ingots of 17Cr, ultra-low-C and ultra-low-N steels containing different amounts of Si, Ti and P were prepared using laboratory facilities, hot rolled, cold rolled and annealed into sheets 0.5 mm in thickness, and the sheets were subjected to a tensile test. **Fig. 1** shows the effects of Si, Ti and P on ductility. The elements between the square brackets of the horizontal axis mean their contents as mass percentage, and their coefficients were defined through statistical processing. The graph shows that ductility decreases with increasing amounts of these elements, and of these three elements, P has the strongest influence on ductility.

In order to increase the r-value of ferritic stainless steels, it is effective to decrease C and N and fix them as precipitates[2]. Accordingly, C and N content was minimized using SUS-REDA[3], a unique smelting process capable of decreasing their contents to very low levels. Of such elements as Ti, Nb, etc. considered effective in fixing C and N, Ti was selected in appreciation of its effect in increasing the r-value while minimizing the increase in strength. The use of the SUS-REDA process is also advantageous in terms of ductility, because it can decrease the C and N content and, consequently, only a small amount of Ti is required to fix them.

Based on the above, the basic chemical composition of the new steel was defined as follows: the amounts of P, Si and Mn would be less than those of conventional ferritic stainless steels, the contents of C and N as low as practically possible using SUS-REDA, with the C and N fixed by addition of Ti.

3.2 Anti-ridging properties

It is known that the anti-ridging properties of ferritic stainless steels deteriorate with decreasing amounts of C and N. This is because when the amounts of C, N and other impurity elements are low, the solidified structure tends to become coarse, and coarse grains form colonies that cause ridging[4, 5]. It follows, therefore, that, to prevent ridging from occurring, it is necessary to divide the colonies into smaller groups of crystal grains. So as to divide the colonies of ferritic stainless steel containing very low amounts of C and N, it is effective to utilize recrystallization. It is already known that the colonies are divided into smaller groups and anti-ridging properties improve when cold rolling and annealing are repeated several times to have the material undergo deformation and recrystallization repetitively. However, what is called two-stage cold rolling whereby cold rolling and annealing are applied twice each is very costly. Therefore, as a method for obtaining such recrystallized structure more than once through one stage of cold rolling, the authors worked out a new process of metallographic structure control whereby the material was made to recrystallize completely in one stage of hot rolling. Because recrystallization is known to depend on the initial grain size and rolling conditions[6, 7], the authors decided to minimize the solidification structure during continuous casting and optimally set the conditions for hot roughing rolling to obtain the recrystallized structure at the end of the roughing rolling.

3.2.1 Control of solidification structure

Measures such as low-temperature casting, electromagnetic stirring in the mold and addition of non-metallic inclusions are considered effective in obtaining a fine solidification structure during continuous casting. Looking for a stable method to obtain a fine solidification structure, the authors studied use of heterogeneous nucleation, and through examination of the effects of various non-metallic inclusions on the solidification structure, clarified that suitable combinations of different kinds of non-metallic inclusions would be effective for the purpose. **Fig. 2** schematically shows the concept of the control method for the solidification structure thus worked out. Oxides in molten steel do not serve as the nuclei for the solidification of the ferrite phase in conventional steels, and as a consequence, crystals take the shape of columnar grains. In contrast, using the developed process, fine particles of oxides of an Al-Mg-Ti system are dispersed in molten steel, where they serve as the nuclei for the crystallization of TiN, and then, around the TiN crystals thus formed, ferrite solidifies in small equiaxed grains. The use of such multi-layered compounds as the nuclei for ferrite solidification proved effective in obtaining a fine solidification structure with the addition of only a small amount of Ti.

3.2.2 Optimization of conditions for hot roughing rolling

The authors investigated the effects of hot working on the recrystallization of the developed steel during hot rolling. For this purpose, using a Formaster, a type of tester to apply hot working to test pieces and then cool them under different conditions to examine the change of metallographic structure, they subjected specimens to hot working under conditions shown in **Fig. 3**, but changing the strain, strain velocity and temperature. In order to study the effects of the initial grain size, the heating temperature before the working was also changed. In addition, the effects of the working temperature on

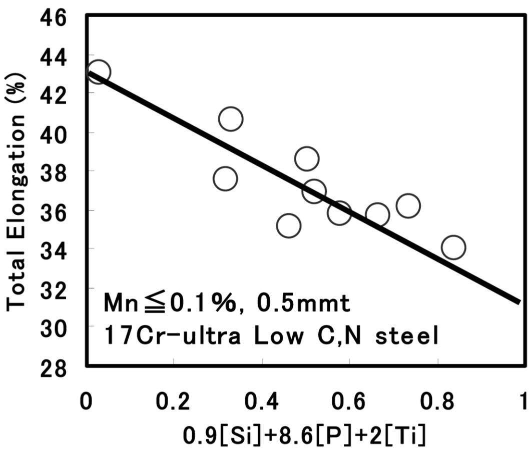

Fig. 1 Relationship between total elongation and Si, P, Ti contents in 17Cr-ultra low C, N steels

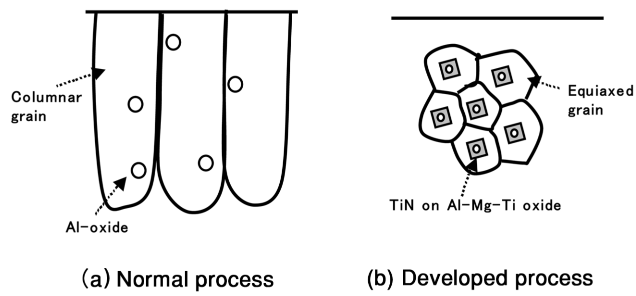

Fig. 2 Schematic figures showing relations between oxides and solidification structures

the time for 50 percent recrystallization ($t_{0.5}$ (s)) were examined by holding worked specimens at the working temperature for different periods, water cooling them, and then investigating the ratio of the recrystallized structure. As a result, the following equation was obtained:

$$t_{0.5} = 8.4 \times 10^{-11} \cdot d_0^{1} \cdot \varepsilon^{-1.5} \cdot \varepsilon'^{-0.4} \cdot \exp(Q/RT),$$

where, d_0 is the grain size of initial crystals (μm), ε is strain, ε' is strain velocity (1/s), Q is activation energy (200 kJ/mol), R is the gas constant, and T is temperature (K). Using this recrystallization equation, the authors studied the conditions of hot roughing rolling to have the material recrystallize after it.

Fig. 4 shows the metallographic structure after hot roughing rolling obtainable through combination of said solidification structure control and the optimization of the conditions of hot roughing rolling. Whereas in the material obtained through conventional processes there are many portions that have not recrystallized completely and are stretched in the rolling direction as seen in Frame (a), the material obtained through the developed method consists of completely recrystallized structure as seen in Frame (b). Then, the material manufactured by the developed process was subjected to hot finishing rolling and hot-band annealing. **Fig. 5** compares the grain size distribution of a specimen thus obtained with that of another manufactured through conventional processes. The crystal grains in red are those having their <100> directions oriented in the strip plane direction (normal direction) ± 15° (such crystal grains are hereafter referred to as the ND//<100> grains); these grains are known to cause ridging[6]. Both the specimens derived from conventional and the developed process, shown in Frames (a) and (b), respectively, are composed of recrystallized structures consisting of roughly equiaxed grains, but they are very different in terms of the distribution of crystal orientations: whereas many ND//<100> grains are aligned in the rolling direction in the specimen by the conventional process (a), the percentage area of such grains is smaller in the specimen by the developed process (b), and no alignment in the rolling direction is seen.

The reason for the above is presumably as follows: Under the conventional process, there are many non-recrystallized grains in a steel strip after hot roughing rolling, and when the material recrystallizes during hot-band annealing, each of the non-recrystallized grains breaks into crystal grains with similar orientations. Under the developed process, by contrast, the material recrystallizes completely into small grains after hot roughing rolling, and the small grains thus formed change their orientations during subsequent hot finishing rolling, resulting in a comparatively random distribution of crystal orientations.

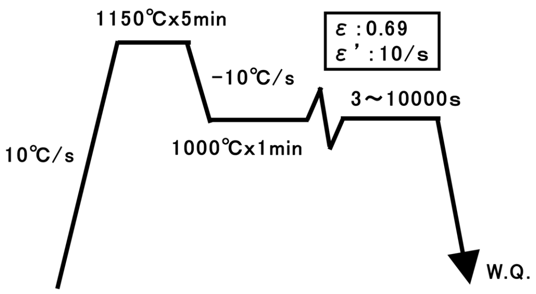

Fig. 3 Experimental conditions

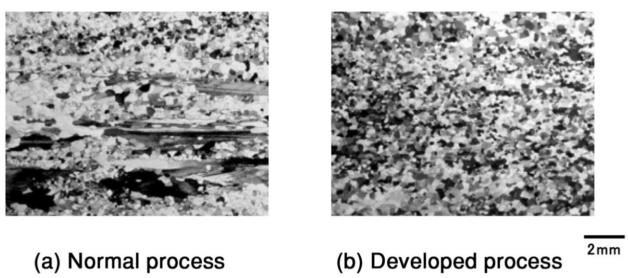

Fig. 4 Optical micrographs after rough-rolling

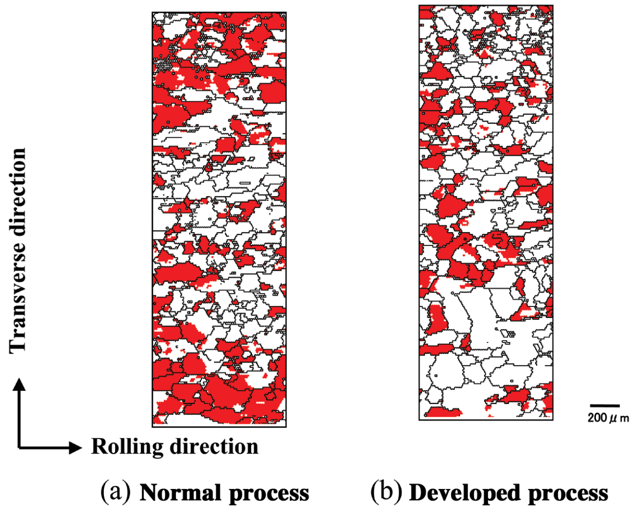

Fig. 5 Orientation image mapping (OIM) of specimens after hot-band annealing (red areas show grains having < 100 > ± 15° from normal direction)

The developed process is effective not only for enhancing anti-ridging properties but also in improving the r-value. In order to improve the r-value, it is desirable to ensure that the pre-cold-rolling metallographic structure is a fine texture with a high r-value[8]. The ND//<100> grains reduce the r-value, and in addition, their size is comparatively large. It follows, therefore, that the pre-cold-rolling metallographic structure obtained through the developed process, which is capable of decreasing the percentage area of such grains, is desirable for increasing the r-value from the viewpoint of either crystal grain size or texture. In fact, the structural control of the developed process brings about a high r-value as explained later.

As has been described, by controlling the metallographic structure through the integrated manufacturing processes from smelting, casting, hot and cold rolling to annealing, it became possible to accelerate recrystallization during hot rolling, break the colonies into small grains and obtain a pre-cold-rolling metallographic structure desirable for increasing r-value, without involving an additional process step.

4. Chemical Composition and Properties of Developed Steel

Table 1 shows a typical example of the chemical composition of the developed steel. The steel contains C, N, Si, Mn and P in smaller amounts than SUS430, and its Ti content is sufficient to fix C and N in small amounts. **Table 2** shows the mechanical properties of sheets of JIS 2B finish and 1.0 mm in thickness of the developed steel together with those of comparative steels (SUS430 and SUS430LX). The developed steel exhibits an elongation of 38 percent, far higher than that of conventional ferritic stainless steels. Its r-value of 2.0 is

Table 1 Chemical compositions of NSSC PDX, SUS430LX and SUS430 (mass%)

Steel	C	Si	Mn	P	S	Cr	Ti	N
NSSC PDX	0.003	0.06	0.12	0.014	0.002	16.5	0.16	0.009
SUS430LX	0.012	0.25	0.82	0.023	0.008	16.3	0.37	0.012
SUS430	0.051	0.49	0.59	0.027	0.005	16.8	-	0.025

Table 2 Mechanical properties, hardness and average r-value of NSSC PDX, SUS430LX and SUS430

Steel	0.2PS (N/mm^2)	TS (N/mm^2)	Elongation (%)	Hardness (Hv)	Average r-value
NSSC PDX	237	370	38	130	2.0
SUS430LX	270	416	33	133	1.7
SUS430	319	486	28	151	1.1

higher than that of the comparative steels by as much as 0.3 or more. Then, the authors tested the formability of the developed steel using a small forming tester for laboratory use. **Fig. 6** shows the limit drawing ratios of the steels measured by the TZP test; the dotted line indicates that of SUS304. The limit-drawing ratio of the developed steel is higher than that of conventional ferritic steels and SUS304. Thus, the developed steel proved to be superior to comparative steels in formability in terms of ductility, r-value and limit drawing ratio.

Next, the authors tested the anti-ridging properties of the developed steel. **Fig. 7** shows the appearances of specimens of the developed steel and SUS430 after a cup-drawing test to respective limit-drawing ratios. Whereas ridging occurred at the sidewall of the SUS430 specimen, the ridging of the developed steel was far milder in spite of the higher forming height. Thus, the developed steel proved excellent also in anti-ridging properties.

In addition, using a combined cyclic corrosion test, the authors confirmed that the corrosion resistance of the developed steel was better than that of SUS430.

As has been described, a ferritic stainless steel, NSSC PDX, offering excellent formability and anti-ridging properties, has been developed based on a new smelting process to enable ultra-low content of C and N and integrated metallographic structure control from smelting, solidification, hot and cold rolling to annealing.

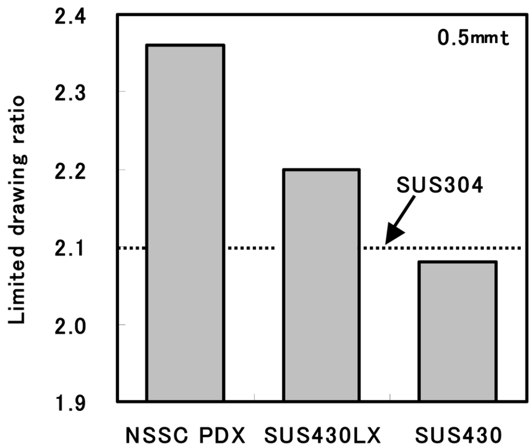

Fig. 6 Limited drawing ratio of NSSC PDX, SUS430LX and SUS430

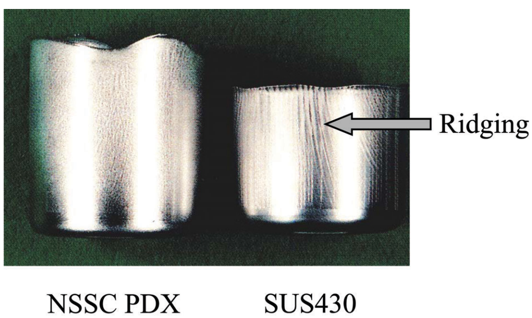

Fig. 7 Samples after cylindrical drawing tests

5. Applications of Developed Steel

Taking advantage of its excellent formability, the developed steel, NSSC PDX, began to be used for heavy forming applications for which conventional ferritic stainless steels could not be used. **Fig. 8** shows an example of its use for a component of a combustion apparatus. This specific component was previously fabricated by caulking, but the use of the developed steel made it possible to form it in one piece without cracking or ridging. More recently, the developed steel has been used for refrigerator panels taking advantage of its low proof stress and good surface appearance with clear film coating. Another new application now being studied is to form thin sheets of NSSC PDX into flexible pipes for the connecting tubes between outdoor and indoor units of air conditioners for residence use. Thus, use of the developed steel is expanding to cover an ever-wider variety of products in appreciation of its excellent properties.

6. Closing

A new grade of steel with the highest level of formability and anti-ridging properties of ferritic stainless steels has been developed through studies and tests. With respect to formability, high ductility

Fig. 8 Example of press forming

was sought by decreasing the content of P, Si and Mn, minimizing the content of C and N by employing a high purity smelting process, and adding the minimum required amount of Ti. The reduction in the C and N content, in combination with the fine and random pre-cold-rolling structure, was effective also in enhancing deep drawability. Anti-ridging properties were significantly improved, without an additional process, through the synergistic effects of the technology to obtain a fine solidification structure and optimally setting the conditions for hot rolling to ensure the material recrystallizes during roughing rolling. The new high-formability ferritic stainless steel, NSSC PDX, thus developed has been used for heavy forming applications for which conventional ferritic stainless steels could not be used, and its use is expected to expand to cover a wider variety of fields.

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