The Mechanism of Ridging Formation in 17%-Chromium Stainless Steel Sheets*

By Hiroshi Takechi**, Hiroshi Kato**, Tatsuya Sunami**
and Tadashi Nakayama**

The mechanism of ridging formation in 17%-chromium stainless steel sheets was studied and a model was proposed. The characteristic surface relief due to ridging was well explained by the model; shear strains caused by tensile deformation in crystals oriented with $[011]$ parallel to the rolling direction. The presence of crystals with such orientations was confirmed experimentally. Although ridging has been believed to be formed only by deep drawing or tensile deformation of annealed sheets, it was observed even on the surfaces of cold-rolled sheets in the present study.

(Received June 2, 1967)

I. Introduction

Ferritic stainless steel sheets, such as 17%-chromium stainless steel sheets, tend to form small ridges or ropelike marks so called ridging or roping, on the sheet surfaces during tensile deformation along the rolling direction. The direction of ridging is always parallel to the rolling direction. The hills and valleys of ridging on the upper surface of a sheet correspond to the valleys and hills of ridging on the lower surface, respectively, and they form wavy undulations as shown in Fig. 1. This is one of the most characteristic properties of ridging.

Fig. 1 Hills and valleys of ridging on the cross-section normal to the rolling direction of the specimen. Behaviours on the upper surfaces of the sheets correspond to those which are on the lower surfaces, and wavy undulations are formed.

Since ridging occurs even in deep drawing and impairs the exterior appearance of the products, it is regarded as one of the most annoying phenomena in 17%-chromium stainless steel making. Therefore the mechanism of ridging formation and the method of prevention of ridging have hitherto been studied. Although it has been reported that the ridging tendency can be reduced by controlling the grain size and distribution of carbides by means of a suitable heat treatment or the addition of some elements^{(1)~(10)}, an economical and effective method for the prevention of ridging has not been developed.

On the other hand, no theory on the mechanism of ridging formation has been established at present. Appel et al.⁽⁹⁾ proposed that ridging has its origin in the differential yielding between the matrix and the transformed phase elongated in the rolling direction. Dennis⁽⁸⁾ suggested that ridging is related to the distribution of carbides. Both suggestions ascribed the occurrence of ridging to the differential yielding

- (1) G. D. Kiefer and J. A. Ferree : U. S. Patent No. 2, 772, 992 Dec. 4, 1956.
- (2) W. B. Leffingwell and C. W. Weesner : U. S. Patent No. 2,808, 353 Oct. 1, 1957.
- (3) J. H. Waxweiler : U. S. Patent No. 2, 851, 384 Sep. 9, 1958.
- (4) C. T. Evans : U. S. Patent No. 2, 965, 479 Dec. 20, 1960.
- (5) J. H. Waxweiler : U. S. Patent No. 3, 128, 211 April 7, 1964.
- (6) A. F. Graziano : U. S. Patent No. 3, 139, 358 June 30, 1964.
- (7) L. Nemethy and P. B. Dennis : Proc. Electr. Fur., 18 (1960), 342.
- (8) J. Thompson and J. L. Lamont : Proc. Electr. Fur., 19 (1961), 70.
- (9) H. G. Appel and H. Becker : Z. Metallk., 54 (1963), 724.
- (10) M. Hamasaki : The Research Reports, The Faculty of Engineering, Kagoshima University, 5 (1965), 1.

* Reported on Oct. 17, 1966, The Fall Meeting of The Japan Institute of Metals.

** Technical Research Institute, Yawata Iron and Steel Co. Ltd., Japan.

between the matrix and the second phases distributed along the rolling direction, on the basis of a morphological analogy between ridging and distribution of the second phases. Ohashi et al.⁽¹¹⁾ suggested that ridging is caused by a plastic anisotropy of crystals. They reported that ridging occurred corresponding to colonies which had been formed in the central layer of hot-rolled sheets. Although these investigations have explained some features of ridging, they cannot explain the most characteristic feature shown in Fig. 1.

In order to explain the characteristic profile of ridging, a new concept that is different from such a second phase described above must be introduced. The present authors supposed that ridging has its origin in a local plastic anisotropy due to some crystallographic anisotropy formed in steel sheets. At first, the presence of some preferred orientations was studied. The ridging phenomenon in ferritic stainless steels must originate from characteristic properties of ferritic stainless steels as compared with common carbon steels. One of such characteristics is lack of the ferrite-austenite transformation, and the other is the presence of many precipitates with a high dissolution temperature. The lack of the transformation means the absence of randomization in crystallographic orientations, and many precipitates probably prevent grain boundaries from migration during the final annealing. Both of them, therefore, may keep the rolling textures unchanged even after the final annealing. These speculations suggest that these steel sheets may have rolling textures as a major orientation.

The rolling textures in *bcc* metals are known to consist of a series of $(hkl)[011]$, that is, orientations between $(100)[011]$ and $(111)[011]$ ⁽¹²⁾. Hereafter, it is called an RD- $[011]$ fiber texture, and each component of it is generally called an RD- $[011]$ orientation. The rolling texture in 17%-chromium stainless steel which has *bcc* lattices are also expected to be the RD- $[011]$ fiber texture. Then the authors have investigated the plastic behaviours of crystals with the RD- $[011]$ orientation under the tensile condition in the $[011]$ direction, and have obtained a model for the ridging formation as described in the next section.

II. Model

Let us introduce a Cartesian coordinates system $oxyz$. If the direction cosines of the slip direction and of the direction normal to the slip plane in regards to the coordinate axes are denoted as shown in Table 1, the strain due to the single slip is represented by

$$E = d\gamma \begin{pmatrix} D_1 E_1 & D_2 E_1 & D_3 E_1 \\ D_1 E_2 & D_2 E_2 & D_3 E_2 \\ D_1 E_3 & D_2 E_3 & D_3 E_3 \end{pmatrix} \quad (1)$$

where $d\gamma$ is a magnitude of slip on the slip planes.

In a *bcc* crystal oriented with $[011]$ parallel to the tensile axis, two of the four $\langle 111 \rangle$ slip directions, $[111]$ and $[\bar{1}\bar{1}1]$, are oriented favorably to accomodate

an extension parallel to $[011]$. In *bcc* metals the active slip planes are reported as $\{110\}$, $\{112\}$, or $\{123\}$, etc. In case $[011]$ is oriented in a direction parallel to the tensile axis, two of the four $\{112\}$ planes, $(\bar{2}11)$ and (211) , are most highly stressed, so $\{112\}$ slip will be

Table 1 Direction cosines of slip directions and of directions normal to slip planes about coordinate axes x, y and z .

	slip direction	direction normal to slip plane
x	D_1	E_1
y	D_2	E_2
z	D_3	E_3

Table 2 Direction cosines of slip directions and of directions normal to slip planes about coordinate axes x, y and z .

	$(\bar{2}11)[111]$ slip system		$(211)[\bar{1}\bar{1}1]$ slip system	
	111	$\bar{2}11$	$\bar{1}\bar{1}1$	211
$x, 011$	$\frac{\sqrt{2}}{\sqrt{3}}$	$-\frac{1}{\sqrt{3}}$	$\frac{\sqrt{2}}{\sqrt{3}}$	$\frac{1}{\sqrt{3}}$
$y, 01\bar{1}$	0	0	0	0
$z, \bar{1}00$	$-\frac{1}{\sqrt{3}}$	$\frac{\sqrt{2}}{\sqrt{3}}$	$\frac{1}{\sqrt{3}}$	$-\frac{\sqrt{2}}{\sqrt{3}}$

assumed. Taking x as the $[011]$ tensile axis, with y and z parallel to $[01\bar{1}]$ and $[\bar{1}00]$, respectively, the direction cosines of the slip directions and of the directions normal to the slip planes about the coordinate axes are given by Table 2. Substitution of these values into Eq. (1) yields strains $E_{(\bar{2}11)}$ and $E_{(211)}$ due to $(\bar{2}11)[111]$ and $(211)[\bar{1}\bar{1}1]$ slips, respectively, as follows:

$$E_{(\bar{2}11)} = \frac{d\gamma}{3} \begin{pmatrix} \sqrt{2} & 0 & -1 \\ 0 & 0 & 0 \\ 2 & 0 & -\sqrt{2} \end{pmatrix}, \quad (2)$$

$$E_{(211)} = \frac{d\gamma}{3} \begin{pmatrix} \sqrt{2} & 0 & 1 \\ 0 & 0 & 0 \\ -2 & 0 & -\sqrt{2} \end{pmatrix}. \quad (3)$$

From the consideration of crystal rotations due to the both of slips, it can be concluded that the $(\bar{2}11)[111]$ slips are equal to the $(211)[\bar{1}\bar{1}1]$ slips under the $[011]$ tensile condition. In such a case the total strain E can be given as follows:

$$E = E_{(\bar{2}11)} + E_{(211)} = E_x \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -1 \end{pmatrix} \quad (4)$$

where E_x is the elongation along x direction. The change in crystal shape resulting from the strain E is shown in Fig. 2.

Any RD- $[011]$ orientation is characterized by θ which is the rotation angle from $(100)[011]$ around the $[011]$ axis. Let E_θ be the strain of crystal with the RD- $[011]$ orientation characterized by θ under the $[011]$ tensile condition, and E_θ can be easily given by the following procedures. To rotate the crystals about the coordinates system by θ around the x axis is the same operation as to rotate the coordinates system about the

(11) N. Ohashi, N. Kinoshita and S. Asakawa: Reported on Oct. 18, 1965, The Fall Meeting of The Japan Institute of Metals.

(12) E. A. Calnan and C. J. B. Clews: Phil. Mag., 42 (1951), 616.

crystals by $-\theta$ around the x axis. Then let us introduce a Cartesian coordinate system $0-x'y'z'$ shown in Fig. 3. Letting T be the coordinate transformation matrix, E_θ is given as follows;

Fig. 2 Change in shape of a crystal with the $(100)[011]$ orientation under the $[011]$ tensile condition.
(a): Before deformation.
(b): After deformation.

Fig. 3 The directional relations between $0-xyz$ and $0-x'y'z'$ systems.

Table 3 Direction cosines of coordinate axes x , y' and z' about x , y and z .

	x	y	z
x	1	0	0
y'	0	$\cos \theta$	$\sin \theta$
z'	0	$-\sin \theta$	$\cos \theta$

$$E_\theta = T E T^{-1} \quad (5)$$

where T^{-1} is the reciprocal matrix of T . As the direction cosines of x , y' and z' axes about x , y and z axes are shown in Table 3. T is given as follows;

$$T = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta & \sin \theta \\ 0 & -\sin \theta & \cos \theta \end{pmatrix}. \quad (6)$$

Substitution of the above form into Eq. (5) yields E_θ as follows:

$$E_\theta = E_x \begin{pmatrix} 1 & 0 & 0 \\ 0 & -\sin^2 \theta & -\frac{1}{2} \sin 2\theta \\ 0 & -\frac{1}{2} \sin 2\theta & -\cos^2 \theta \end{pmatrix}. \quad (7)$$

It is noted that E_θ has a shear component as a function of θ and it is plotted against θ in Fig. 4. The maximum shear strain corresponds to θ values of $\pm 45^\circ$, and the shape of crystal at cross-sections normal to the tensile axis changes as shown in Fig. 5.

Although Eqs. (4) and (7) are derived by assuming $\{112\}$ to be an active slip plane, it can be proved theoretically that the same results will be obtained even if it is assumed that $\{110\}$, $\{123\}$ or any $\{hkl\}$ is an active slip plane. Therefore the assumption of $\{112\}$ slip has no influence on the results.

If a specimen with a crystallographic orientation con-

Fig. 4 Ratio of shear component of E_θ to E_x vs. θ .

Fig. 5 Change in shape of a crystal at the cross-section normal to the tensile direction after tensile deformation. These crystals have the $[011]$ orientation, and $\theta = \pm 45^\circ$.

Fig. 6 Change in shape of the specimen by deformation.
(a): Before deformation.
(b): After deformation.

on a plane nearby (101); the orientations were examined by the transmission Laue method, and an accurate (101)[010] pattern shown in Photo. 1 (a) was obtained under the condition that the direction of the incident beam was rotated by 4° about the [010] axis from the direction normal to a crystal surface. Therefore the orientation of the single crystal is the one rotated by 4° about the [010] axis from (101)[010]. Etch pits of the crystal have a slightly deformed rhombic shape, and the ratio in diagonal length of rhombs with good symmetry is 1.4. These show that the directions of edges in the rhombs are $\langle 111 \rangle$, and the $\langle 111 \rangle$ axes lie on the surface planes of pits. Photo. 2 (a)

The ridging formation can be explained on the basis of the shear strains of crystals having RD-[011] orientations as described above. If the model is valid, there should be RD-[011] orientations in the sheets, and their configurations should correspond to the ridges as shown in Fig. 6. From these points of view, the authors made the following experiments.

In order to examine the correspondence between the RD-[011] orientation configuration and ridges, crystallographic orientations in a micro-region must be determined. This was made mainly by an observation of etch pits in the present study. At first, the crystallographic orientations of the etch pit surfaces were examined, since the etching reagent* used in the present study was different from that used for plain carbon steels. Photo. 1 (b) shows an appearance of etch pits

Photo. 2 Etch pits on the (001) $\overline{1}00$ single crystal of chromium stainless steel.
(a): Transmission Laue Photograph.
(b): Etch pits.

shows the Laue pattern of the other crystal. Since the incident beam was perpendicular to the crystal surface, the orientation of this crystal is $(001)[\bar{1}00]$. Edges of the etch pits in the crystal are parallel to $\langle 110 \rangle$ or $\langle 100 \rangle$ as shown in Photo. 2 (b). These show that $\langle 110 \rangle$ and $\langle 100 \rangle$ axes also lie on the pit planes. From observations of the etch pits described above, it can be concluded that the planes of pits are $\{110\}$ planes which contain $\langle 111 \rangle$, $\langle 110 \rangle$ and $\langle 100 \rangle$ axes.

* 100 cc of nitric acid (70% conc.) + 30 cc of hydrochloric acid (35% conc.) + 30 cc of glycerin.

The specimen prepared for the investigation on the correlation between the RD-[011] orientation configuration and ridges was a 17% Cr stainless steel sheet, which had a usual chemical composition, but showed an extremely strong tendency in ridging formation. Streaks parallel to the rolling direction were observed on the cold-rolled sheets of this specimen. An example of the streaks on the cold-rolled sheets is shown in Photo. 3. The surface condition of the cold-rolled sheets with the streaks in the transverse direction shows that these streaks are accompanied by the same undulation as in the case of ridging (Fig. 7). Then the cold-rolled sheets were annealed and elongated by 10%, and the correlation between streaks on the cold-rolled sheets and ridges after elongation was investigated. A part of the tensile specimen on which ridging was formed clearly after 10%-elongation is shown in Photo. 4. Since the grip section was not

Photo. 3 Streaks on the cold-rolled sheets. X1.

Fig. 7 Surface condition of the cold-rolled sheets with heavy streaks. Hills and valleys are same as those of ridging, and they form wavy undulations.

Photo. 4 Relation between streaks on the cold-rolled sheets and ridges formed by 10%-elongation. X1.

elongated, it is clear that the streaks in this section had existed on the cold-rolled sheets. Each of these streaks corresponds to those in ridging in the parallel section; the ridges formed by 10%-elongation are the same ones as observed on the cold-rolled sheets. These facts show that the streaks on the cold-rolled sheets are the same phenomenon as ridging. In the present paper the streaks on the cold-rolled sheets are called "cold rolling ridging", distinguished from the so-called "ridging".

3. Correspondence between ridges and RD-[011] orientation configuration

The cold-rolled sheets seem to have a sharper RD-[011] fiber texture than the annealed sheets, because the RD-[011] fiber texture formed by rolling deformation are thought to be decreased by recrystallization during the final annealing. Moreover, the ridges can be known precisely on the cold-rolled sheets by cold rolling ridging, and so the authors examined the correspondence between ridges and RD-[011] orientation configuration in the cold-rolled sheets.

Since the etching planes are {110}, the configuration of etch pits on the sheet plane of such a specimen as shown in Fig. 6 must be the one in Fig. 8. Then the authors made marks on the positions of valleys of the cold rolling ridging, and observed the etch pit configuration at a sheet plane of the central layer. One of the typical examples is shown in Photo. 5. The scratched line in the central position is the mark showing the position of a valley in cold rolling ridging.

Fig. 8 Etch pit configuration on the sheet planes expected from the RD-[011] fiber texture shown in Fig. 6. Mark A corresponds to a valley, and mark B to a peak.

Excellent agreement with the proposed model which is shown in Fig. 6 was obtained, and the correspondence between ridges and RD-[011] orientation configuration was proved. Such an excellent correspondence was obtained for all the six ridges examined. The textures of the cold-rolled sheets are shown in Fig. 9, from which it is clear that RD-[011] orientation are preferential.

The etch pit configuration on the cross-section normal to the rolling direction in the cold-rolled sheets was also observed in order to investigate the accumulation of RD-[011] fiber textures in the direction normal to the sheet plane. Wavy structures at the inner layer of a sheet are shown in Photo. 6 (a), and they are found to correspond to the ridges of cold rolling ridging. The etch pit configuration shows that the orientations of crystals are not RD-[011] orientations at the surface layer with about a quarter of the sheet thickness, but RD-[011] orientations at the central layer with about

Photo. 5 Etch pit configuration on the sheet planes in the central layer of cold-rolled sheets with heavy streaks. The scratched line corresponds to the position of valley in the cold rolling ridging. ($\times 500 \times 4/5$)

Fig. 9 {110} pole figure in the central layer of specimen; 17%-chromium stainless steel cold-rolled 70%.

Fig. 10 {110} pole figure in the central layer; 17%-chromium stainless steel cold rolled 70% and annealed at 840°C for 10 min.

a half of the sheet thickness. The rotating directions of the RD-[011] orientations from $(\bar{1}00)[011]$ are almost one-sided at the slope of ridges as shown in Photo. 6 (b). Such an accumulation of the one-sided RD-[011] orientations is supposed to be due to the grain growth during the slab heating and hot-rolling. Although the quantity of RD-[011] fiber textures in

Photo. 6 Structure and etch pit configuration on the cross-section normal to the rolling direction of the cold-rolled sheets.
(a): Structure which shows the undulation.
(b): Etch pit configuration.

the cold-rolled sheets decreased as a result of recrystallization during the final annealing, the RD-[011]

fiber textures are retained in large quantities in the heavy ridging specimen even after the final annealing, as shown in Fig. 10.

IV. Conclusion

Correspondence between ridges and RD- $\langle 011 \rangle$ orientation configuration predicted by the proposed model was proved experimentally. The ridging formation could be well explained by the shear strains when crystals having $\langle 011 \rangle$ parallel to the rolling direction were deformed under tensile stress along the $\langle 011 \rangle$

direction. Although ridging has been believed to be formed only by deep drawing or tensile deformation of the annealed sheets, it was observed even on the surfaces of cold-rolled sheets in the present study.

Acknowledgment

The authors wish to express their thanks to Dr. S. Nagashima and Mr. T. Muta for their helpful discussion and kind advice throughout this work, and to acknowledge the assistance of Mr. M. Tsuiki during the course of the present experiment.