

Recrystallization Texture Evolution of Cold Rolled and Asymmetrically Warm Rolled Austenitic Stainless Steel Sheets

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Abstract. A $\{111\}$ texture leads to good deep drawability but does not generally develop in face-centered cubic metals. One of the authors previously succeeded in $\{111\}$ recrystallization texture evolution by cold rolling, asymmetric warm rolling and subsequent solution treatment for Al-Mg-Si alloy sheets. In this study, rolling and recrystallization textures of austenitic stainless steel with low stacking fault energy have been investigated to reveal whether the $\{111\}$ texture can be formed by similar processing. Rolling texture changed from the α -fiber texture in 70% cold rolled sheets to an asymmetric texture on the TD axis consisting of $\{331\}\langle 116 \rangle$ - $\{111\}\langle 112 \rangle$ by additional 40% asymmetric warm rolling at 873 K. Correspondingly, pole density at the center of $\{111\}$ pole figure increased from 2.16 to 3.18. In addition, microstructural observation showed that there were two kinds of shear bands inclined at about 30° and 150° to RD on the longitudinal section. One was micro shear bands within grains and the other was shear bands passing through a number of grains. Recrystallization texture after annealing also showed an asymmetric texture on the TD axis, but consisted of $\{431\}\langle 257 \rangle$ - $\{331\}\langle 116 \rangle$ near to $\{110\}\langle 112 \rangle$ - $\{110\}\langle 001 \rangle$. The 1173 K-1800 s annealing decreased pole density at the center of $\{111\}$ pole figure to 0.78. In conclusion, the rolling texture with near- $\{111\}\langle 112 \rangle$ orientation was obtained in cold rolled and asymmetrically warm rolled austenitic stainless steel sheets. The recrystallization texture, however, changed to near- $\{110\}\langle 112 \rangle$ orientation as a main component.

1. Introduction

Control of recrystallization texture is necessary for improving sheet metal formability. $\{111\}$ textures with $\{111\}$ planes parallel to the sheet surface lead to good deep drawability¹⁾ but does not generally develop in f.c.c. metals. One of the authors²⁾ has recently succeeded in $\{111\}$ recrystallization texture evolution in mid-thickness by cold rolling, asymmetric warm rolling and subsequent solution treatment for Al-Mg-Si alloy sheets with high SFE (stacking fault energy).

Recrystallization texture depends on rolling texture. There are two kinds of rolling texture in f.c.c metals, namely pure-metal and alloy types. The SFE of aluminum and copper showing pure-metal type rolling texture are 166 mJm^{-2} and 78 mJm^{-2} , respectively, and the SFE of stainless steel and brass showing alloy type rolling texture are 21 mJm^{-2} and 20 mJm^{-2} , respectively³⁾. 95% cold rolled pure copper has the β -fiber texture ($\{112\}\langle 111 \rangle$ - $\{123\}\langle 634 \rangle$ - $\{011\}\langle 211 \rangle$)³⁾. In contrast, 95% cold rolled brass has the α -fiber texture ($\{011\}\langle 211 \rangle$ - $\{011\}\langle 100 \rangle$)³⁾. The recrystallization texture of pure copper



consists mainly of cube orientation $\{001\}\langle 100\rangle$, and that of brass has $\{236\}\langle 385\rangle$ or $\{113\}\langle 121\rangle$ as a preferred orientation³⁾. Morii et al.⁴⁾ explained the formation process of rolling texture in brass. Rolling texture at low reductions in thickness was formed by slip and deformation twinning. Crystallographic rotation caused the $\{111\}$ twin planes to be parallel to the sheet surface with shear banding in twin-deformed grains at middle rolling reductions ranging from 40% to 80%. Two sets of large shear bands crossing each other decrease the twins at high rolling reductions exceeds 80%. As the area of the shear bands increases, $\{011\}$ -oriented grains increase. Nezakat et al.⁵⁾ also showed that $(111)[1\bar{1}0]$ and $(111)[\bar{1}\bar{1}2]$ orientations as weak components formed at cold rolling reductions of 70% or more in SUS 316L austenitic stainless steel. Williams⁶⁾ mentioned that simple shear deformation in brass formed a shear texture consisting of $(111)[01\bar{1}]$, $(111)[11\bar{2}]$ and $(100)[011]$ orientations similar to simple shear deformation in aluminum.

Recently, hydrogen energy is expected as clean energy. Stable austenitic stainless steel for which hydrogen embrittlement hardly occurs is useful as parts in hydrogen⁷⁾. However, the improvement in deformability by the TRIP (transformation induced plasticity) effect observed in metastable austenitic stainless steel⁸⁾ cannot be used in stable austenitic stainless steel. This is unfavorable for deep drawing. In this study, rolling and recrystallization textures of SUS316L stable austenitic stainless steel with low stacking fault energy were investigated in order to reveal whether the $\{111\}$ texture favorable for deep drawing can be developed through cold rolling and additional asymmetric warm rolling or not.

2. Experimental

Table 1 shows the chemical composition of SUS316L used in this study. The starting materials were hot-rolled sheets with a thickness of 5 mm. The thickness of the hot-rolled sheets was reduced to 70% by cold rolling at room temperature. These sheets were further rolled by asymmetric warm rolling using the laboratory two-high rolling mill with different roll diameters of 96 and 144 mm (in upper and lower rolls, respectively) at heating temperature of 873 K in a furnace. The asymmetric warm rolling was performed without changing the front and back of sheet surface and with using the exact rolling direction of not 180° but 0°. Embrittlement due to the sigma phase⁹⁾ would not occur at this rolling temperature. The rolling reduction of asymmetric warm rolling was set to a low reduction of 40%. In fact this reduction required many passes of 30 to 32 on the above rolling mill.

Annealing for recrystallization was conducted after the above combined rolling. Annealing temperature was determined from a softening curve drawn by the results of micro Vickers hardness tests of isochronally annealed samples for 1800 s. Annealing time was determined from a softening curve obtained by isothermal annealing at 1173 K. The annealing time of 0 s means the time when samples were put in a furnace. Microstructures of rolled and annealed samples were observed by an optical microscope. The grain size was measured by the intercept method. $\{111\}$, $\{100\}$ and $\{110\}$ incomplete pole figures viewed from the side of a roll with larger diameter were measured by the Schulz reflection method¹⁰⁾ using MoK α radiation in order to examine rolling and recrystallization textures.

Table 1. Chemical composition of SUS316L stainless steel used in this study (mass %).

C	Si	Mn	P	S	Ni	Cr	Mo	N	Fe
0.01	0.50	0.84	0.03	0.00	12.0	17.4	2.0	0.01	Bal.

3. Results

3.1. Microstructures

Figure 1 shows Vickers hardness of samples annealed for 1800 s at various temperatures after cold rolling and asymmetric warm rolling (combined rolling). Since a slope of the softening curve varied at 1123 K, the finished temperature of recrystallization is considered to be more than 1123 K. Figure 2 shows the relationship between annealing time and Vickers hardness of the annealed samples at 1173 K. It is considered that recrystallization was finished after annealing of 300 or 1800 s when the Vickers

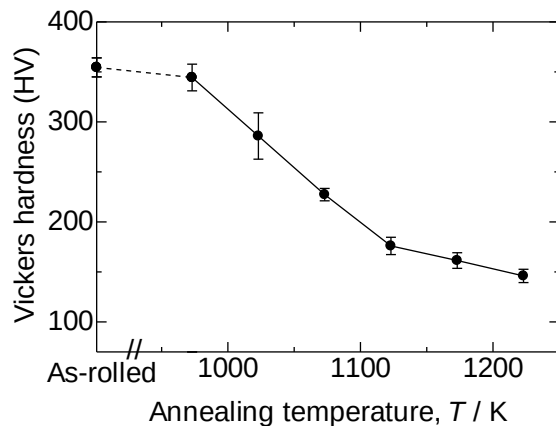


Fig. 1 Variation of hardness during isochronal annealing for 1800 s of cold rolled and asymmetrically warm rolled samples.

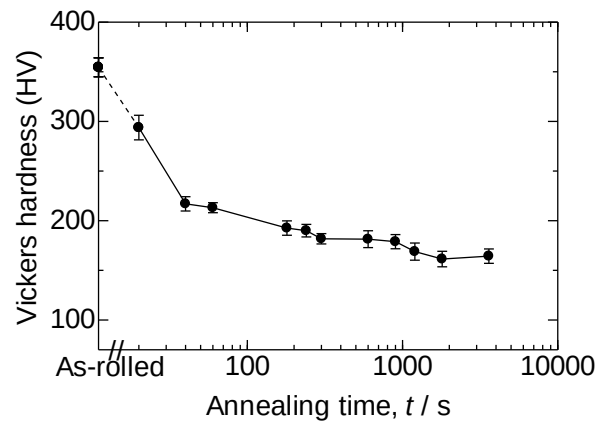


Fig. 2 Variation of hardness during isothermal annealing at 1173 K of cold rolled and asymmetrically warm rolled samples.

hardness became constant. As a result of microstructural observation, recrystallization was finished after annealing of 1800 s. Thus an annealing condition for recrystallization in the combined rolled sample was determined to 1173 K-1800 s. Figure 3 shows microstructures of (a) a cold rolled sample, (b) a cold rolled and asymmetrically warm rolled sample and (c) a cold rolled, asymmetrically warm rolled and annealed sample. Figure 3a exhibited elongated grains and no definite shear bands. Figure 3b showed large shear bands inclined by about 30° counterclockwise from RD indicated by white arrows and micro shear bands within grains inclined by about 30° clockwise from RD indicated by black arrows. Figure 3c showed equiaxed recrystallized grains with an average grain size of $4.2 \mu\text{m}$ and an aspect ratio of 1.1, including annealing twins.

3.2. Rolling texture

Figure 4 shows $\{111\}$ and $\{110\}$ pole figures measured in mid-thickness of samples. These pole figures were viewed from the side of a roll with larger diameter for a 70% cold rolled sample, and for 20% or 40% asymmetrically warm rolled samples after the cold rolling. As Nezakat et al.⁵⁾ reported, the cold rolled sample had an alloy-type rolling texture composed of α -fiber ($\langle 011 \rangle // \text{ND}$) with $(111)[\bar{1}\bar{1}0]$ and $(111)[\bar{1}\bar{1}2]$ orientations as weak components. In the cold rolled and 40% asymmetrically warm rolled sample, rolling

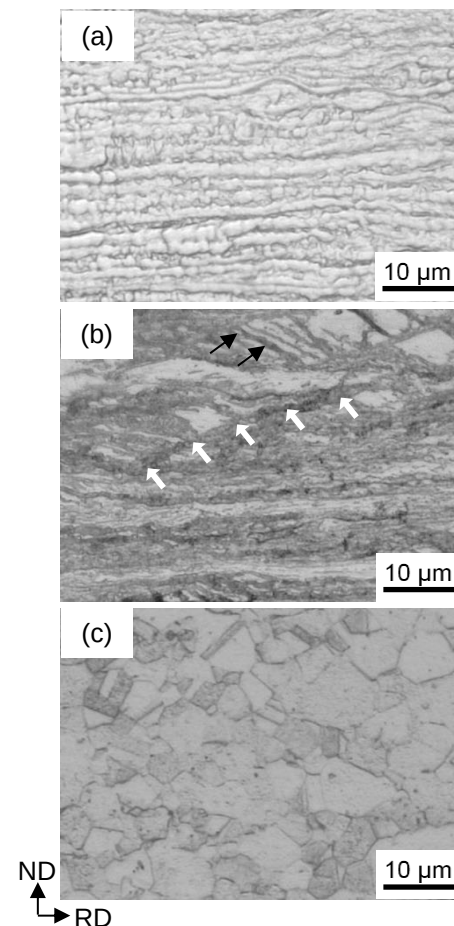


Fig. 3 Microstructures of (a) cold rolled sample, (b) cold rolled and asymmetrically warm rolled sample, and (c) annealed sample at 1173 K for 1800 s after the combined rolling. White arrows indicate shear band and black arrows indicate micro-shear bands within grains in (b).

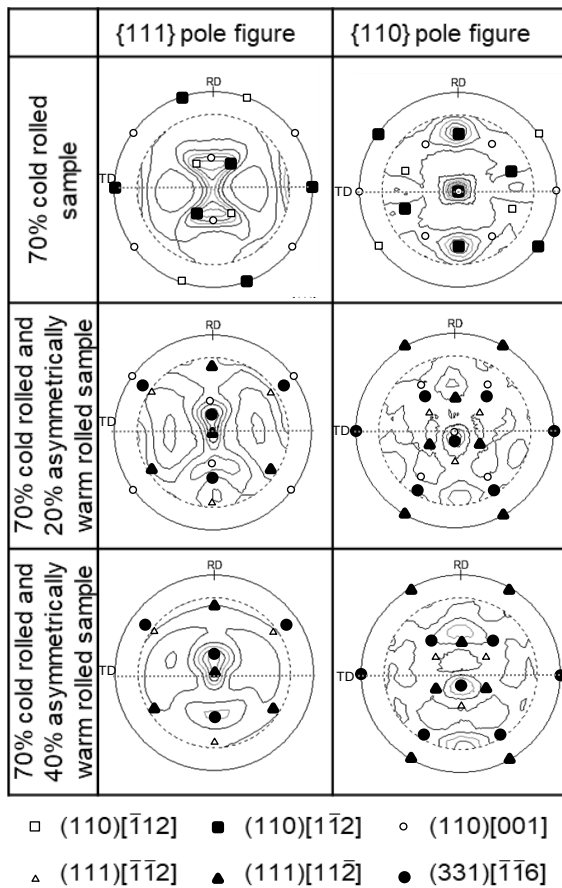
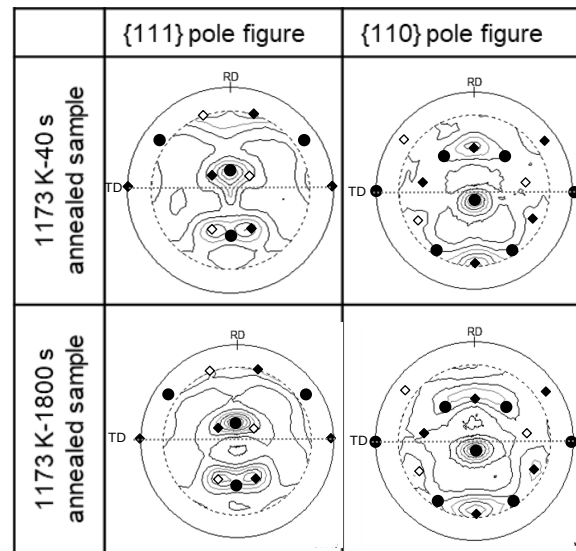


Fig. 4 {111} and {110} pole figures of 70% cold rolled sample (top), and 70% cold rolled and 20% (middle) or 40% (bottom) asymmetrically warm rolled samples. Contour levels are 0.5 to 5.0 at a step of 0.5.

texture of (331)[$\bar{1}\bar{1}6$]- (111)[$\bar{1}\bar{1}2$] orientation group asymmetrical on the TD axis was recognized. The (331)[$\bar{1}\bar{1}6$] orientation corresponds to the orientation that {110}<001> was rotated by about 13° around the TD axis. In the cold rolled and 20% asymmetrically warm rolled sample, rolling texture had an intermediate texture of the cold rolled sample and the additionally 40% asymmetrically warm rolled sample. The pole density at the center of {111} pole figure indicating the existence of {111}<uvw> components increased from 2.2 to 3.2 due to additional 40% asymmetric warm rolling. In addition, the pole density at the center of {110} pole figure decreased considerably from 5.1 to 1.3 by adding 40% asymmetric warm rolling.

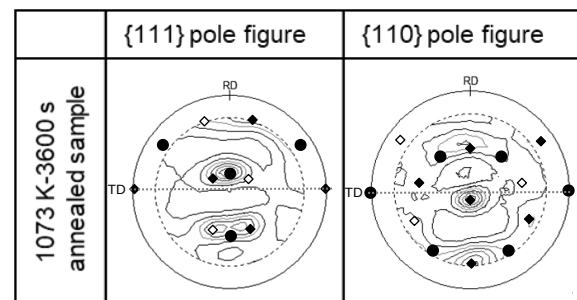
3.3. Recrystallization texture

Figure 5 shows {111} and {110} pole figures of samples annealed at 1173 K after cold rolling and 40% asymmetric warm rolling. Formation of the (341)[$\bar{5}27$]- (331)[$\bar{1}\bar{1}6$]- (431)[$2\bar{5}7$] orientation group is recognized in the pole figures of a sample annealed under a condition of 1173 K-1800 s. The pole density at the center of the {111} pole figure was 0.8. The pole density at the center of the {110} pole figure was 2.0. The {111}<112> orientation decreased considerably and the {431}<257> orientation was



◇ (341)[$\bar{5}27$] ◆ (431)[$2\bar{5}7$] ● (331)[$\bar{1}\bar{1}6$]

Fig. 5 {111} and {110} pole figures of annealed samples at 1173 K after 70% cold rolling and 40% asymmetrically warm rolling. Contour levels are 0.5 to 4.0 at a step of 0.5.



◇ (341)[$\bar{5}27$] ◆ (431)[$2\bar{5}7$] ● (331)[$\bar{1}\bar{1}6$]

Fig. 6 {111} and {110} pole figures of 70% cold rolled, 40% asymmetrically warm rolled and 1073 K-3600 s annealed sample. Contour levels are 0.5 to 4.0 at a step of 0.5.

formed by annealing for 40 s. After annealing of 40 s, the orientation group from the $\{331\}\langle 116 \rangle$ to the $\{431\}\langle 257 \rangle$ orientation exhibited an annular spread around the $\langle 110 \rangle$ axis inclined by about 10° from ND to the opposite direction of RD.

The rolling texture of the cold rolled and 40% asymmetrically warm rolled sample had a preferred orientation close to $\{111\}\langle 112 \rangle$. In order to retain the $\{111\}\langle 112 \rangle$ orientation in recrystallization texture as well as in rolling texture, in-situ recrystallization can be expected. The annealing condition for recrystallization completion was decided as 1073 K-3600 s under which the embrittlement due to sigma phase⁹⁾ hardly occurred. Figure 6 shows $\{111\}$ and $\{100\}$ pole figures of the 1073 K-3600 s annealed sample. The center of $\{111\}$ pole figure had pole density of 1.0, which slightly increased compared to 1173 K-1800 s. However, the main orientation of this recrystallization texture was basically the same as that of the 1173 K-1800 s annealed sample. Figure 7 shows $\{111\}$ and $\{110\}$ pole figures of an annealed sample at a lower heating rate. The pole density at the center of $\{111\}$ pole figure was 0.5. The orientation group from the $\{331\}\langle 116 \rangle$ to the $\{431\}\langle 257 \rangle$ orientation developed more strongly than that of the 1173 K-1800 s annealed sample.

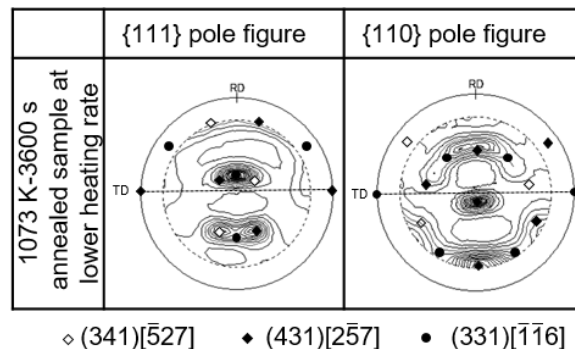


Fig. 7 $\{111\}$ and $\{110\}$ pole figures of 70% cold rolled, 40% asymmetrically warm rolled and 1073 K-3600 s annealed sample at a lower heating rate. Contour levels are 0.5 to 7.0 at a step of 0.5.

4. Discussion

4.1. Rolling texture evolution

In general, shear bands formed by cold rolling appear not in one direction but in symmetric two directions with respect to RD. Additional asymmetric warm rolling formed large-scale shear bands in one direction, although the shear bands were not seen after cold rolling. It is thought that strain was stored, although it was recovered in a furnace during the warm rolling process. Morii et al.⁴⁾, in the case of brass, described crystallographic rotation that causes the $\{111\}$ twin planes to be parallel to the sheet surface with shear banding in twin-deformed grains. The large-scale shear bands generated by the twin-deformed grains reduce twin regions and oriented grains parallel to the sheet surface rapidly increases on the $\{011\}$ face. The unidirectional large-scale shear bands had little influence on the decrease of the $\{111\}$ twin plane, and it is considered that the $\{111\}$ twin plane increased with the activity of shear bands generated in twin-deformed grains. In addition, it is thought that shear texture⁶⁾ such as $\{111\}\langle 112 \rangle$ and $\{111\}\langle 011 \rangle$ orientations was formed by additional shear deformation during asymmetric warm rolling.

Shear bands within the grains were formed in a direction crossing the large-scale shear bands in one direction in the microstructure. Noda¹¹⁾ reported that $\{110\}\langle 001 \rangle$ orientation was formed by shear bands in cold rolling. Formation of asymmetric texture on TD was also observed in cold rolled and asymmetrically warm rolled Al-Mg-Si alloy sheets²⁾. Deformation by asymmetrically warm rolling consists of plane strain compression and additional shear deformation. It is thought that $(331)[\bar{1}\bar{1}6]$ orientation was formed due to rotation of the $\{110\}\langle 001 \rangle$ orientation around the TD axis by plane strain compression and additional shear deformation.

4.2. Recrystallization texture evolution

For alloy type metals, $\{236\}\langle 385 \rangle$ or $\{113\}\langle 121 \rangle$ orientation is formed³⁾. Chowdhury et al.¹²⁾ reported that there was a twin relationship between the $\{236\}\langle 385 \rangle$ orientation and the $\{110\}\langle 001 \rangle$ orientation, and that the $\{236\}\langle 385 \rangle$ orientation had a rotation relation of 40° around the common $\langle 111 \rangle$ axis with the $\{110\}\langle 112 \rangle$ ($40^\circ \langle 111 \rangle$ relationship). In addition, the $60^\circ \langle 111 \rangle$ twinning can be

described as $70.5^\circ \langle 110 \rangle^{13}$. The $(331)[\bar{1}\bar{1}6]$ orientation and $(341)[\bar{5}27]$ or $(431)[\bar{2}\bar{5}7]$ orientation had $\pm 35^\circ \langle 110 \rangle$ relationship. However, since an approximately $70^\circ \langle 110 \rangle$ relationship was satisfied between $(341)[\bar{5}27]$ and $(431)[\bar{2}\bar{5}7]$ orientations, the formation of these two variants would result from annealing twins.

Sumitomo¹⁴) reported about SUS304 austenitic stainless steel that recrystallized nuclei of $\{211\}$ and $\{311\}$ having higher stored energy than $\{110\}$, which were generated at a lower temperature, encroached on the recrystallized nuclei of $\{110\}$. In this study, grains having a $\{331\}\langle 116 \rangle$ - $\{431\}\langle 257 \rangle$ orientation group relatively close to $\{110\}$ developed as a main component of recrystallization texture. It is thought that stored energy was changed due to additional shear deformation and recovery in asymmetric warm rolling. It is possible that release of stored energy was performed earlier at the $\{331\}\langle 116 \rangle$ - $\{431\}\langle 257 \rangle$ orientation group because the $\{331\}\langle 116 \rangle$ - $\{431\}\langle 257 \rangle$ orientation group was strongly formed by low-speed annealing. In order to clarify the mechanism of evolution of recrystallization texture consisting of the $\{331\}\langle 116 \rangle$ - $\{431\}\langle 257 \rangle$ orientation group close to $\{110\}$, research on stored energy may be required in the future.

Amane et al.¹⁵) reported that for cold rolled, asymmetrically warm rolled and subsequently annealed Al-Mg-Si alloy sheets, $\{111\}$ oriented grains formed and grew at the early stage of annealing. Combined rolling consisting of cold rolling and asymmetric warm rolling was effective for metals with high SFE. Goodman and Hu¹⁶) reported that the rolling texture of austenitic stainless steel changed depending on rolling temperature, and a pure metal type rolling texture similar to that of high SFE metals developed when rolled at high temperature. From these facts, asymmetric rolling at a temperature higher than 873 K might have a possibility of $\{111\}$ recrystallization texture evolution like Al-Mg-Si alloy having a pure metal type rolling texture.

5. Conclusions

SUS 316L austenitic stainless steel was 40% asymmetric rolled at 873 K after 70% cold rolling, and subsequently annealed for recrystallization. The main results are as follows:

(1) Rolling texture with near- $\{111\}\langle 112 \rangle$ orientation was obtained in cold rolled and asymmetrically warm rolled austenitic stainless steel sheets.

(2) Recrystallization texture changed to near- $\{110\}\langle 112 \rangle$ orientation as a main component. The preferred orientation group exhibited an annular spread around the $\langle 110 \rangle$ axis inclined by about 10° from ND to the opposite direction of RD.

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