# Effect of Transverse Pre-Rolling before Drawing on the Anti-Ridging Properties of 17%Cr Ultra-Purified Ferritic Stainless Steel

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**Abstract.** Cup-drawing test was performed to study the effect of transverse pre-rolling by 2%, 4% and 6% reduction on the surface anti-ridging properties during deep drawing of 17%Cr ultra-purified ferritic stainless steel cold-rolled annealed sheets. The shape and size of the grains in the tested sheets after transverse pre-rolling were analyzed by optical microscope (OM), and the evolution of textures and grain colonies in the tested sheet were analyzed by electron back-scatter diffraction (EBSD) and X-ray diffraction (XRD). The results show that transverse pre-rolling does harm to the anti-ridging properties of the experimental sheet, and the height of ridging increases with rising of rolling reduction. After transverse pre-rolling, $\gamma$-fiber texture grain colonies are not deflected and its width increases. The content of $\gamma$-fiber texture and $\alpha$-fiber texture increase and the texture strengths are more concentrated in the standard orientation of {111} line, which lead to the degradation of anti-ridging property.

## 1. Introduction

Ferritic stainless steels have advantages of low cost and outstanding sheet metal formability, therefore it can replace austenitic stainless steel under certain conditions [1, 2]. During deep forming, high plastic strain ratio and low earing rate are acquired, but the surface quality of drawing parts is unsatisfactory. A rather serious problem is that distribution of high and low undulating strip defects appears along the original rolling direction on the surface of sheet after deep drawing. It's so called ridging [2, 3]. The mechanisms of surface ridging of annealed ferritic stainless steel sheet during tensile or drawing were studied [4, 5]. Chao et al. [6] argued that ridging was caused by {111}//ND and {100}//ND textures with different plastic strain ratios. Takechi et al. [7] proposed that the shear deformation would be introduced by asymmetrical slippage between the RD//<110> texture components and the difference of shear deformation between the different components resulted in ridging when the plate is tensioned. However, Brochu et al. [8] found that the peaks and valleys were located in the same position in the top and bottom surface of ferritic stainless steel after tensile deformation, which is inconsistent with the deformed surface profiles measured by Chao [6].

In addition, many researches on improving ridging resistance have been reported. Gao et al. [9,10] proved that low temperature finish rolling contributes to reduce the ridging height of ferritic stainless steel. Huh et al. [11] found that the recrystallization texture was notably shifted towards {334}<483> and {554}<225> instead of forming the {111}//ND γ-fiber texture typical of recrystallized ferritic steel sheets when introducing intermediate annealing during cold rolling of 430 ferritic stainless steel.

We have reported transverse pre-stretching before deep drawing can improve the surface ridging resistance of ferritic stainless steel effectively [12]. In order to find a more efficient process than pre-stretching, the researches on transverse pre-rolling were performed. Microstructural evolution during pre-rolling and surface roughness after drawing were observed in this study.

## 2. Experimental

Table 1 lists the chemical composition of the 17%Cr ultra-purified ferritic stainless steel sheet. The sheets were rolled along the transverse direction by 2%, 4% and 6% reduction before drawing, which was named as transverse pre-rolling. The as-received sheet was marked as 0#, and the pre-rolled ones were marked as 1#, 2# and 3# corresponding to 2%, 4% and 6% reduction, respectively. Then the sheets were cut into disc specimens with the diameter of 78mm. The cup drawing test was carried out by the sheet metal forming machine BCS-30D with film lubrication. The surface ridging was tested by laser scanning confocal microscope LEXT OLS4000. Microstructural observations were performed by optical microscopy (OM, Leica DM2500). Macro-textures were tested by X-ray analysis (Bruker D8 X-ray diffractometer). Orientation distribution functions (ODF) were calculated from incomplete pole-figures measured in back-reflection. Micro-texture and spatial orientation distribution were measured by a ULTRA55 field emission scanning electron microscope equipped with an EBSD detector.

**Table 1.** Chemical composition of the studied steel.

| C | Si | Mn | S | P | Cr | N | Nb | Ti | Fe |
|------|------|------|-------|-------|-------|-------|-------|-------|------|
| 0.01 | 0.58 | 0.17 | 0.001 | 0.019 | 16.51 | 0.008 | 0.144 | 0.159 | Bal. |

## 3. Results

### 3.1. Surface ridging after drawing

Figure 1 shows the profile roughness curves of surface on the side wall of cups. It can be seen that the distance of curve peaks on sample 0#, 1#, 2# and 3# were 500, 600, 700 and 1000 μm, respectively. It indicated that transverse pre-rolling made the ridging becoming wide.

Table 2 lists the values of roughness with vertical pattern or U shape pattern on the side wall of the drawn cup. Here, Ra represents the arithmetic mean of the vertical distance between the profile and the center line in the evaluation length, while the Rz indicates the difference between the average value of the five highest contour peaks and the average value of the five deepest valleys. It indicated that the roughness of tested samples after transverse pre-rolling were bigger than those original annealed sheet.
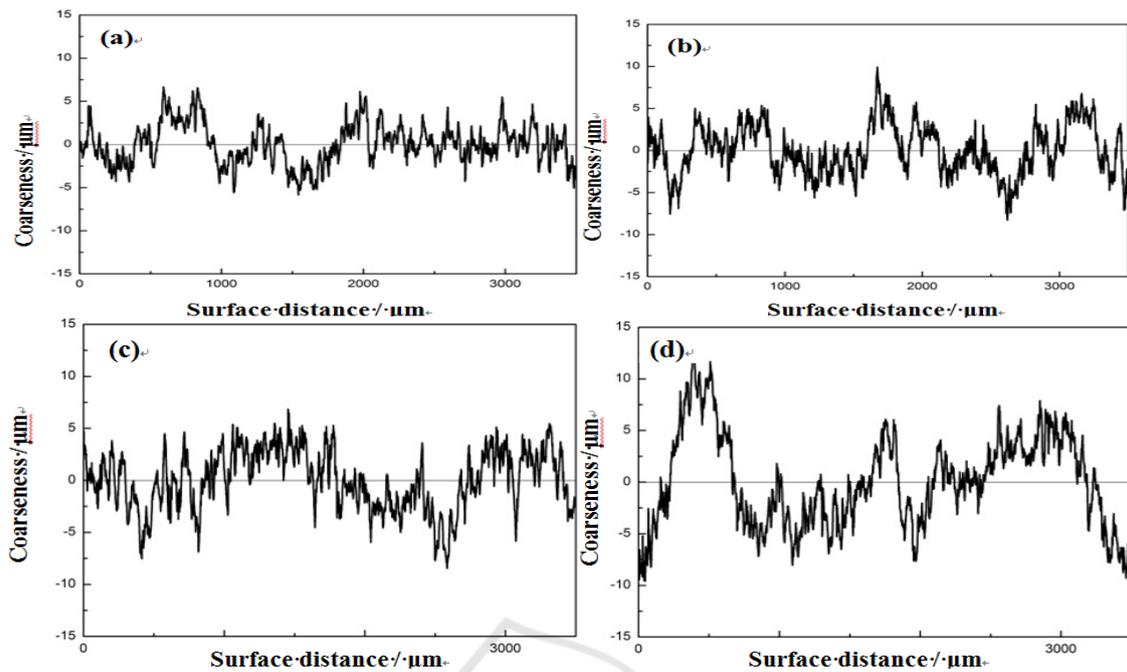
**Figure 1.** Roughness profiles of vertical pattern of deep drawing products for different transverse pre-rolling reductions: (a) annealed state, (b) 2%, (c) 4%, (d)6%

**Table 2.** Roughness values of deep drawing products for different transverse pre-rolling reductions.

|  |  | 0# | 1# | 2# | 3# |
|---|---|---|---|---|---|
| Vertical ridge | Rz | 3.533 | 3.983 | 4.142 | 4.179 |
|  | Ra | 0.676 | 0.755 | 0.748 | 0.830 |
| U shape ridge | Rz | 3.161 | 3.039 | 3.127 | 3.242 |
|  | Ra | 0.539 | 0.548 | 0.543 | 0.552 |

The above results revealed that transverse pre-rolling cannot improve the surface ridging resistance of ferritic stainless steel, which was contrary to our previous research on transverse pre-stretching [12]. The evolutions of microstructure and texture as below were studied to explain the distinct difference.

*3.2. Microstructures after transverse pre-rolling*

Figure 2 shows the microstructures of the sheets. It can be seen that the grains of annealed sheet were uniformly with the average size of 26 μm and the grains were just slightly elongated along the rolling direction after transverse pre-rolling.

The major difference of microstructures between samples with and without transverse rolling was the uniformity of grain size. The grain size on the surface and center layers were similar in annealed samples (Figure 3 a), However, the grain on the surface layer was greatly finer than that in the center when samples were transverse rolled for 2~6% reduction (Figures 3 b-d), which caused by the friction between the roller and sheet surface, and the shearing stress refined the grain in the surface layer [3, 9].
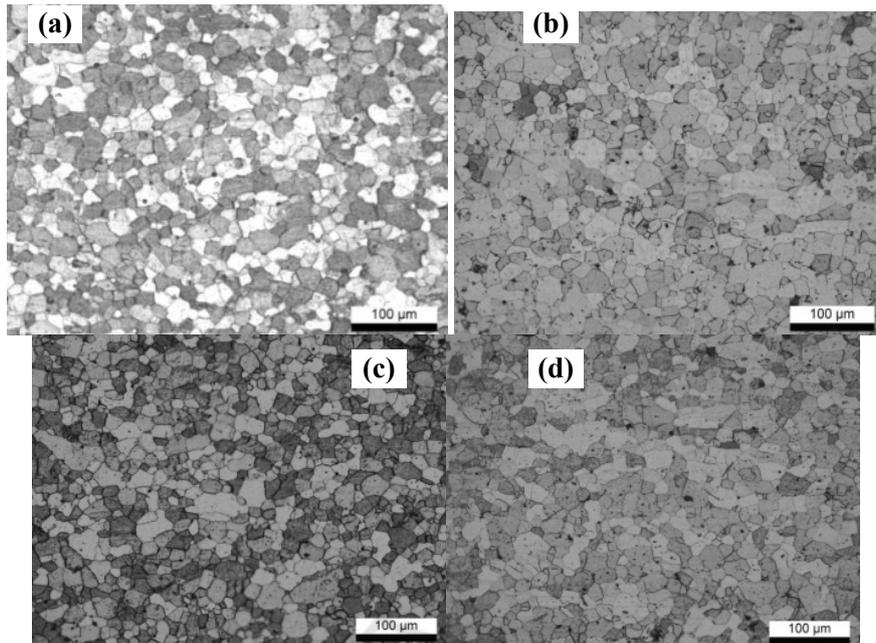
**Figure 2**. Microstructures of 17%Cr ultra-pure ferritic stainless steel sheet on transverse direction (ND) section after various transverse pre-rolling reductions: (a) annealed state, (b) 2%, (c) 4%, (d) 6%.
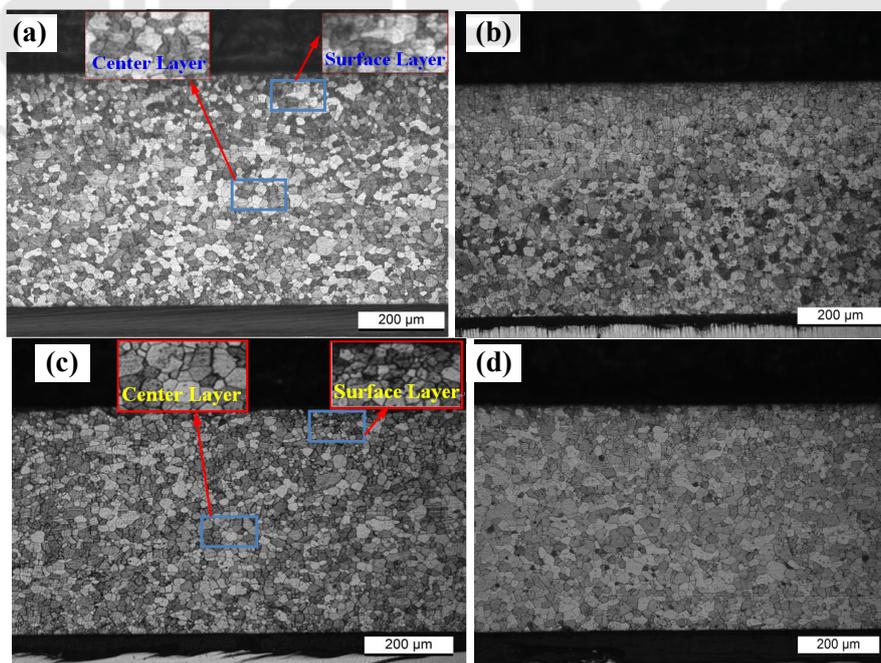


**Figure 3.** Microstructures of 17%Cr ultra-pure ferritic stainless steel sheet on transverse direction (TD) section after various transverse pre-rolling reductions: (a) annealed state, (b) 2%, (c) 4% and (d) 6%.

## 3.3. Grain clusters after transverse pre-rolling

Figure 4 shows the grain distribution of normal direction (ND) for the sheets under different transverse pre-rolling reductions. The blue, red and purple grains represent {111}ND, {001}ND and {112}ND, respectively. It indicated that all samples have very strong {111} texture, which formed clear grain colonies. The width of {111} grain clusters rises slightly with the increase of the deformation of transverse rolling. The grain clusters and profile curves of sample 2# are shown in Figure 5. It can be seen that the width of grain clusters and ridging on stamping surface was consistent, compared with the stamping surface profile as mentioned in Figure 1.

Grain clusters with same orientation were the decisive factor for the ridging of stamping surface, were widely used for explaining the ridging phenomenon on stamping of ferritic stainless steel sheets [6, 13]. Grain clusters were not narrowed greatly after transverse pre-rolling in this work. It indicated that there was no improvement in decreasing the ridging phenomenon by transverse pre-rolling.
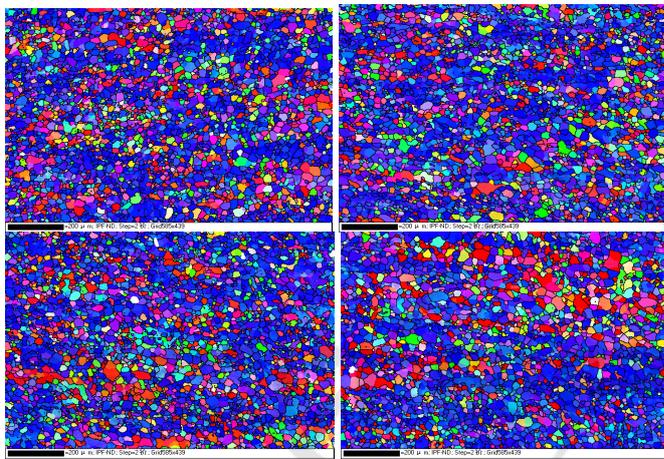


**Figure 4**. Grains distribution of normal direction (NT) for transverse pre-rolling reductions of (a)annealed state, (b)2%, (c)4% and (d)6%.
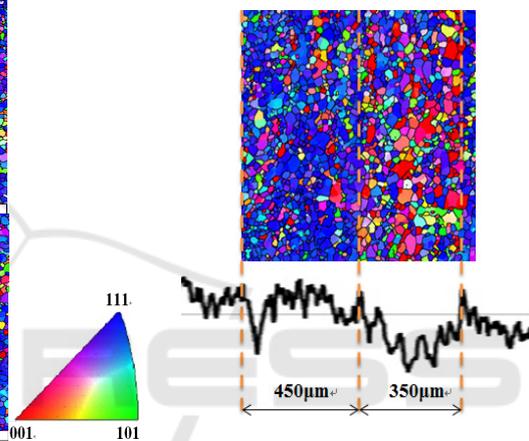
**Figure 5**. Grain clusters and profile curves of sample 2#.

## 3.4. Micro orientations of grains after transverse pre-rolling

The grain orientation and texture were regarded as the most important affect factors for ridging of ferritic stainless steel. Figure 6 shows the contents of various grain orientations in the tested steel sheet at as-received state and after transverse pre-rolling. It can be seen that {111} <uvw> was the primary orientation in all tested samples, which is the typical recrystallization texture for ferritic steel. It should be noted that the contents of all typical texture, {111}, {001} and <110> increased with the increasing of pre-rolling, which might lead to texture gradient and inhomogeneity of grain orientation.

Figure 7 shows the distributions of the specific oriented grains in the center layer of the sheets and in which the red zone represented grains with orientation of {001}//ND. The content of grains with {001}<uvw> was lower than 8% and cluster was not found in all the tested sheet. Thus, though Chao [6] and others believed that the difference of plastic strain ratio between {001}//ND texture and other textures components lead to the ridging phenomenon, the tested 17%Cr ultra-pure ferritic stainless steel sheet was not fit to Chao model because of little content of {001} texture and no texture cluster.
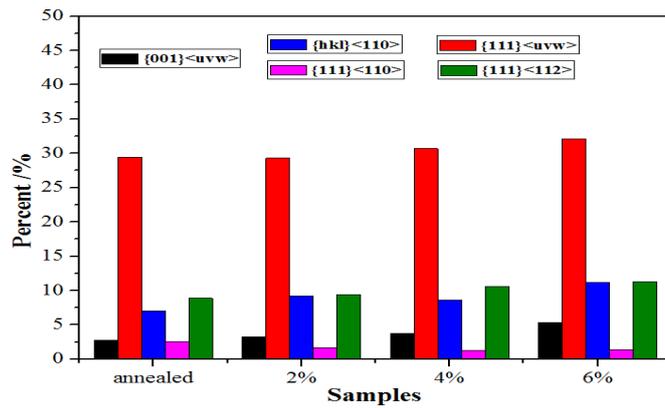
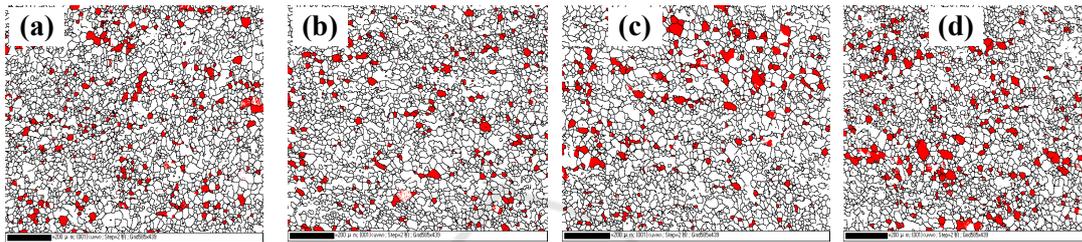**Figure 6.** Contents of typical grain orientation in tested sheets.



**Figure 7.** Grains distribution of {001}ND (normal direction) for different transverse pre-rolling reductions: (a) annealed state, (b) 2%, (c) 4%, (d) 6%.

## 3.5. Macro texture after transverse pre-rolling

Figure 8 shows ODF of the sheets with different transverse pre-rolling reductions. The annealed sheet formed strong γ fiber texture and the texture strengths slightly deviated from {111} line to orientation of (334)[4$\bar{8}$3] and (554)[$\bar{2}\bar{2}$5] with the orientation density of 6.4 due to high content of Cr. Meanwhile, α fiber texture and rotated cube texture (001) [1$\bar{1}$0] were relatively low, and the strength of α fiber texture was located in (111)[1$\bar{1}$0] with the orientation density of 2.2 (Figure 8. a). When the transverse rolling of deformation was applied, the grain orientation was rotated. There was no obvious change in texture and α fiber texture slightly moved to (445) [1$\bar{1}$0] for 2% rolling reduction (Figure 8. b). After rolling reduction of 4%, intensity of γ texture increased, α fiber texture continues move to (113)[1$\bar{1}$0] and the strength moved from (334)[4$\bar{8}$3] and (554)[$\bar{2}\bar{2}$5] to {111}<112>, with the orientation density of 7.1 (Figure 8. c). As the rolling reduction increased to 6%, intensity of γ texture continued to increase and the strengths moved to the position of {111} <112> with the orientation density of 7.7 (Figure 8. d).

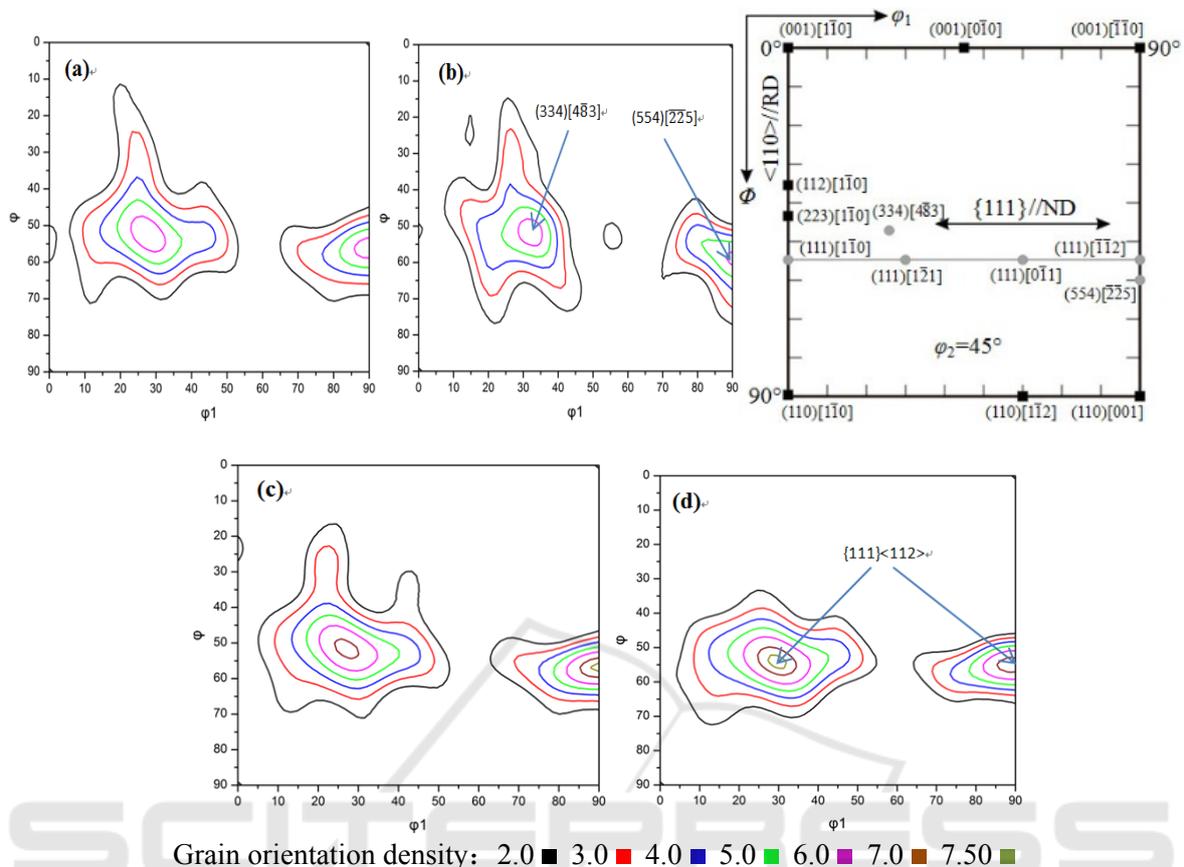Grain orientation density：2.0 ■ 3.0 ■ 4.0 ■ 5.0 ■ 6.0 ■ 7.0 ■ 7.50 ■

**Figure 8**. ODF of tested steel with different transverse pre-rolling reductions: (a) annealed state, (b) 2%, (c) 4%, (d) 6%.

The ODF maps of each sample were consistent with the results of grain orientation. γ fiber texture was gradually strengthened with the increase of rolling reduction, mainly lied in the increase of texture intensity of {111}<112>. The reason is that it formed {111}<110> rolling texture along the rolling direction, and the grain orientation performed as {111}<112> during the transverse rolling when it was observed along the original rolling direction. The conclusion that {hkl}<110> increased by a certain strength was not obvious. But it can be seen that although there was no obvious discipline of α peak changed, the texture distribution on α orientation line is more uniform with the increase of rolling reduction, and the amount of α texture increased. α texture is mainly caused by rolling. After transverse rolling, {001}<110> texture formed in the transverse direction, and it also performed as {001}<110> texture along the original rolling direction, thereby {001}<110> texture strengthened with the rolling reduction increased. The α texture downward extended along the orientation line, and the lower position was the larger deviation angle between the transverse direction and the original rolling direction was, until it move down to {111}<110>, the deviation angle reached 90°. {111}<110> as the main rolling texture increased along the rolling direction after cold rolling, but it performed as {111}<112> along the original rolling direction, so {111}<110> decreased in the original rolling direction, as shown in Table 2 by the measured results.

## 4. Discussions
In the stretching process, the grains of {hkl} <112> orientation along the stretch direction continuously turn to {hkl} <110> along the slip plane until the grains of {hkl} <112> absolutely turn

to {hkl} <110> orientation, and at this time it has reached the deformation limit that the grains can bear. Meanwhile, the content of {111} <uvw> oriented grains decreased gradually. Thus, in the transverse pre-stretching process [12], the content of {hkl}<110> and {hkl}<112>grains decreased and increased respectively along the rolling direction because the stretching and the cold rolling directions were perpendicular. Also, {111} <uvw> oriented grains were easily to slide and rotate continuously in the process of stretching, so the texture distributed wider and more uniformly, and the content of γ fiber decreased.

However, after rolling, both the intensity of α and γ fiber textures increases, that is, both the {hkl}<110> and the {111}<uvw> textures increases. In this experiment, after transverse rolling (the rolling direction perpendicular to the original cold rolling direction), the {111} <uvw> texture raised slightly, the {111} <112> texture raised significantly (caused by the increase of {hkl}<110> texture along transverse direction), and the {111}<110> texture decreased a little.

The quantities of {111} <uvw> oriented grains were measured by EBSD. When the deviation angle was 15°, no matter transverse stretching or transverse rolling, the quantities of the oriented grains were increased. When the deviation angle was 10°, the quantities of the grains were decreased and increased after transverse stretching and transverse rolling respectively, as shown in Figure 9. Transverse stretching make the distribution of the γ texture more uniform in ODF map, that is, the grains of γ fiber texture gradually shift to other orientations, so the typical {111} oriented grains decrease. With the increase of deformation, both the γ fiber texture and the deflection angle to the {111} orientation line changed obviously, the deflection range of main texture component increased along Φ in ODF map. On the contrary, transverse rolling made the γ texture distribute more compact along Φ in ODF map, it was more focused on the typical {111} orientation line. In the analysis of macro texture results by ODF, the texture strengths of 0# and 1# were located in {334}<483> and {554}<225>, and with the reduction of transverse rolling increased, the texture strengths of 3# had already moved to the standard position {111}<112> of γ fiber texture. Some studies [11, 14] have indicated that the two factors mentioned above would enhance the ridging phenomenon of ferritic stainless steel.

Therefore, it can be seen that the opposite influence on the ridging phenomenon of ferritic stainless steel by transverse stretching and transvers rolling, is due to that the intensity and strengths' position of α and γ fiber texture change differently after transverse stretching and transvers rolling.
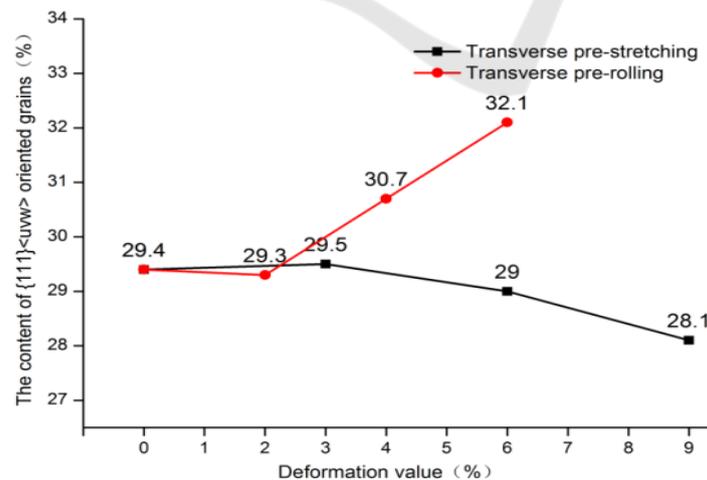


**Figure 9**. The content of {111}<uvw> oriented grains in the test site.

## 5. Conclusions

Transverse pre-rolling by 2~6% reduction before drawing will enhance the surface riding phenomenon of 17%Cr ultra-pure ferritic stainless steel, and deteriorate its anti-ridging property. The conclusions are summarized as follows:

1. The surface grains are refined by transverse pre-rolling, but the morphology of the central layer grains is less affected. Also, the increases of the width of <uvw> {111} grain clusters do not lead to deflection of the grain clusters by transverse pre-rolling.

2. EBSD and XRD analysis revealed that the content of α fiber texture and γ fiber texture were respectively increased slightly and obviously by transverse pre-rolling. Furthermore, the γ texture distribution, assembled along Φ in ODF map, is more focused on the typical {111} orientation line. Those results produced by transverse rolling is greatly different from transverse stretching process, which formed more dispersive γ texture and made the strengths of texture deviate from the typical {111} orientation line of γ texture. In conclusion, the anti-ridging property of the experimental plate was reduced under the united effect of these textures.

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