

Article

Deep Penetration of Shear Deformation in Ferritic Stainless Steel via Differential Speed Rolling Considering Contact Condition

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Featured Application: This study suggests a simple method to determine the active slip system in steel, which may be beneficial to improve effectiveness for industrial cold-rolling processes.

Abstract: In order to effectively process crystal-structured materials like metal, knowledge of the working slip system during plastic deformation is necessary. Rolling is a widely utilized industrial processing method, and understanding its inherent characteristics can optimize the process and help achieve the desired microstructure and texture. One key aspect worth investigating is how shear deformation penetrates through the material thickness, particularly in relation to contact conditions. Analyzing slip system activity provides valuable insights into the deep penetration of shear deformation. This is achieved by examining orientation gradients derived from inverse pole figure maps obtained through electron backscatter diffraction. The rotation axis is extracted and compared with that obtained from calculation using simple first-order self-consistent formulation. The analysis was carried out on grains with $\{001\} < 110 \rangle$, $\{001\} < \bar{1}10 \rangle$, $\{111\} < 110 \rangle$, $\{111\} < \bar{1}21 \rangle$, $\{111\} < 0\bar{1}1 \rangle$, and $\{111\} < \bar{1}12 \rangle$ to see the activity of slip systems of $\{112\} < 111 \rangle$ when plane strain or plane + shear mode is in operation. The rotation axis from the experiment is in agreement with that from the calculation, which confirmed the activity of the well-known $\{112\} < 111 \rangle$ slip systems. It was found that $\{112\} < 111 \rangle$ was active in solo in grain with $\{111\} // ND$ orientation along the γ -fiber during the early stage of differential speed rolling (DSR). Furthermore, it was revealed that the $\{112\} < 111 \rangle$ slip system was found active when shear deformation mode was in operation at the center of the sheet, which can only be found in the case of a sample with no lubrication. Conclusion: The current study shows that deep penetration was achieved under contact conditions where no lubrication was used during DSR by revealing the activity of the $\{112\} < 111 \rangle$ slip system under the shear mode of deformation.

Keywords: orientation gradient; shear; slip system; steel



Academic Editor: Paulo Santos

Received: 1 November 2024

Revised: 21 December 2024

Accepted: 25 December 2024

Published: 27 December 2024

Citation: Fatimah, S.; Bahanan, W.; Kang, J.-H.; Widianlara, I.P.; Ko, Y.G. Deep Penetration of Shear Deformation in Ferritic Stainless Steel via Differential Speed Rolling Considering Contact Condition. *Appl. Sci.* **2025**, *15*, 155. <https://doi.org/10.3390/app15010155>

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1. Introduction

In recent years, with the rapid advancements in aviation, space exploration, automotive, and related industries, the demand for improved the forming quality and extended service life of metal components has increased significantly. To meet these requirements, a thorough understanding of material and its forming behavior are essential [1]. The processing of metallic materials through rolling deformation has become a prominent and widely studied topic in recent times. Among the plastic deformation methods studied,

differential speed rolling (DSR) has shown substantial potential to influence both strain accumulation and plate-bending behavior. This process becomes particularly noteworthy due to its complex tribological interactions in the roll bite [2]. To enable industrial applications, optimizing key parameters of DSR and achieving a deep mechanistic understanding are essential [3]. One of the critical parameters is the contact condition, which is typically related to the application of lubrication. The primary objective of lubrication is to facilitate the penetration of shear across the sample thickness, thereby enhancing uniformity [4].

However, researchers are still working to determine the optimal method for confirming shear penetration [5]. One possible approach to investigating phenomena occurring in the plastic stage is through the activation of slip systems. As it is well established that activated slip systems significantly influence both the microstructure and texture of the material [6], this could provide a clearer understanding of the relationship between the characteristics of active slip systems and shear penetration.

Several methods have been documented for evaluating slip system activity. For example, Gibson et al. identified active slip systems by combining nanoindentation techniques with orientation measurements [7]. Similarly, Wang et al. investigated the relationship between texture variation and slip system activation in Ti-6Al-4V during machining [8]. In this study, slip system activity was derived from orientation gradients obtained through electron backscatter diffraction (EBSD), particularly those formed during the initial stages of plastic deformation, which subsequently provided the experimental rotation axis. These experimental findings were then combined with theoretical predictions from viscoplastic self-consistent (VPSC) simulations to correlate the activity of the single slip system $\{112\} < 111 >$ with its theoretical rotation axis. VPSC has been extensively utilized in simulating cold-rolling processes [9] and has also been reported to effectively model shear effects [10].

To align with the condition of interest, specifically the early stage of plastic deformation, the present analysis focuses exclusively on grains with $\{001\} // ND$ and $\{111\} // ND$ orientations [11,12]. To simplify the experimental analysis, specific conditions were chosen: high-grade ferritic steel with around 17% chromium content was selected for its low phase transformation tendency, ensuring a single-phase microstructure. The ferrite phase, being simpler, allows sole focus on processing effects. Meanwhile, the VPSC simulation provides an option to use first-order self-consistent formulation consisting of secant, tangent, and affine [13–15]. The second-order self-consistent approach is applicable when higher-order statistical information is required, such as in scenarios with strong directionality and significant variations in local properties, as observed in materials composed of highly anisotropic grains or multiphase polycrystals [16]. However, to replicate the conditions characteristic of the early stage of plastic deformation, the first-order self-consistent approach was utilized for the simulation.

The experimental rotation axis and theoretical rotation axis confirmed the activation of the $\{112\} < 111 >$ slip system. The current study proposed that the orientation gradient observed in early deformation can provide insights into the active slip system and the special case when it was under additional shear effect, which mostly found in the contact condition without lubrication. Investigation of this material offers potential for producing material with uniform, fine-grained microstructure to induce improved toughness [17].

2. Materials and Methods

2.1. Materials and Differential Speed Rolling

The material used in this study was ferritic stainless steel with a chemical composition of Fe–0.0065 wt% C–0.157 wt% Mn–0.0243 wt% P–0.0004 wt% S–16.93 wt% Cr–0.128 wt% Ni–0.2322 wt% Ti, which provided extra titanium as stabilizer. The sample underwent

homogenization at 950 °C for one hour, followed by furnace cooling to develop an equiaxed microstructure with random texture.

Deformation was applied using DSR with a speed ratio of 1:2, maintaining the lower roll speed at 3.45 m/min. The samples were subjected to 10 rolling passes, each with a reduction of 3.5%, chosen to prevent bending during DSR. Two conditions were tested: one where the sample was sprayed with lubricant (dominant plane strain) and another without lubrication (plane strain + shear), as illustrated in Figure 1. Here, ND, RD, and TD denote the sample's reference system, indicating the normal, rolling, and transverse directions, respectively. The deformed samples exhibited no visible deformation failures, such as cracking or excessive bending.

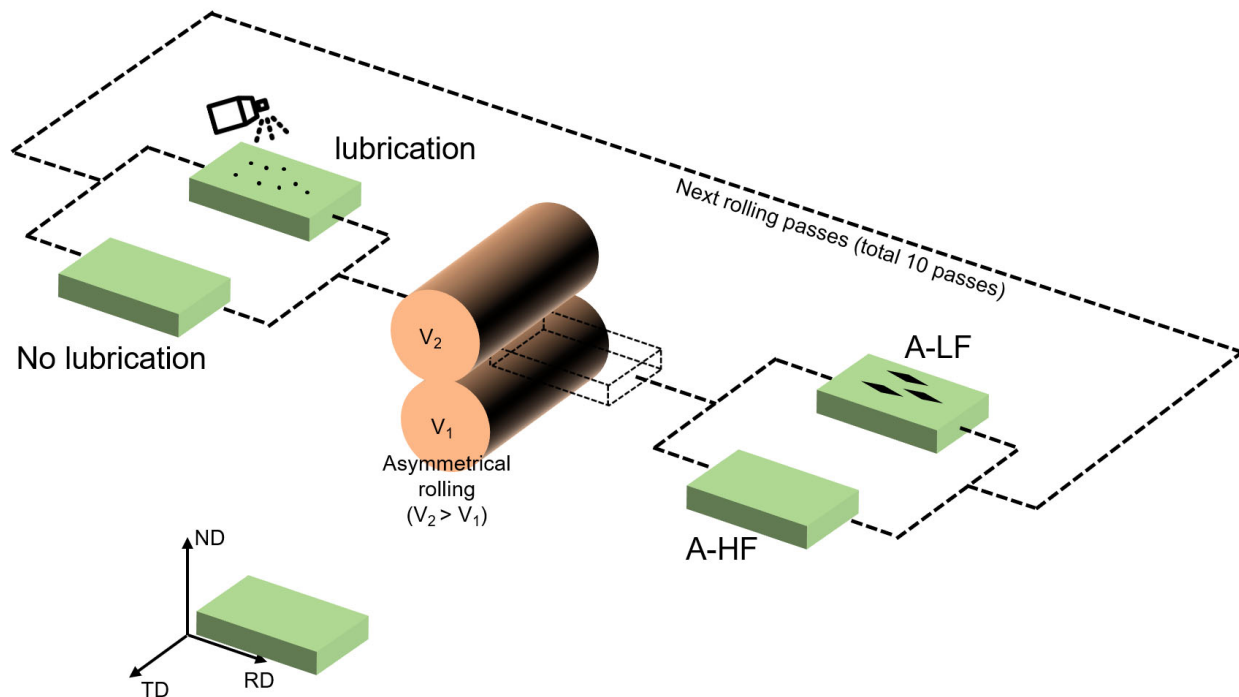


Figure 1. Schematic illustration of differential speed rolling for the case of sample with lubricant and with no lubricant. The sample's reference system of the rolled sample are shown.

2.2. Electron Backscatter Diffraction

Sample preparation for electron backscatter diffraction (EBSD) observation involved grinding and polishing. Sheets were cut from the TD plane of the fabricated samples for EBSD analysis. The TD plane was selected for observation, as it is commonly used for rolled samples. This plane enables examination of the microstructure through the thickness, providing insights into the role of shear deformation predominantly occurring at the top. The specimens were then mechanically polished and etched in a 2 wt% picric acid solution in ethanol. The microstructural and crystallographic characteristics of the steel samples were analyzed using EBSD in a field-emission scanning electron microscope (Hitachi S-4300 FESEM, Hitachi, Tokyo, Japan) using a working distance of 20 mm and a step size of 2.5 μm . EBSD data were cross-referenced with a ferrite phase database and further analyzed using the TSL-OIM software, 7.3.0.

2.3. Orientation Analysis

2.3.1. Crystal Adjustment

As the microstructure and texture was examined in the TD plane (Figure 1), it was necessary to rotate the crystal orientation to align the results of this study with the global orientation, especially when using the orientation distribution function (ODF) map. Figure 2

shows the crystal adjustment performed with Orientation Imaging Microscopy (OIM) version 7.3.0. This rotation enables users to view and analyze the data within a familiar reference frame. The color shift in the inverse pole figure (IPF) from unrotated to rotated leads to a corresponding change in the ODF. Notably, this crystal adjustment does not alter the sample's reference system (ND, RD, and TD); it only adjusts the lattice orientation to align with the global ODF maps, facilitating comparisons. The global ODF maps use φ_1 from 0 to 90°, Φ from 0 to 90°, and a constant φ_2 of 45°, which were chosen because they capture key textures relevant to rolling deformation.

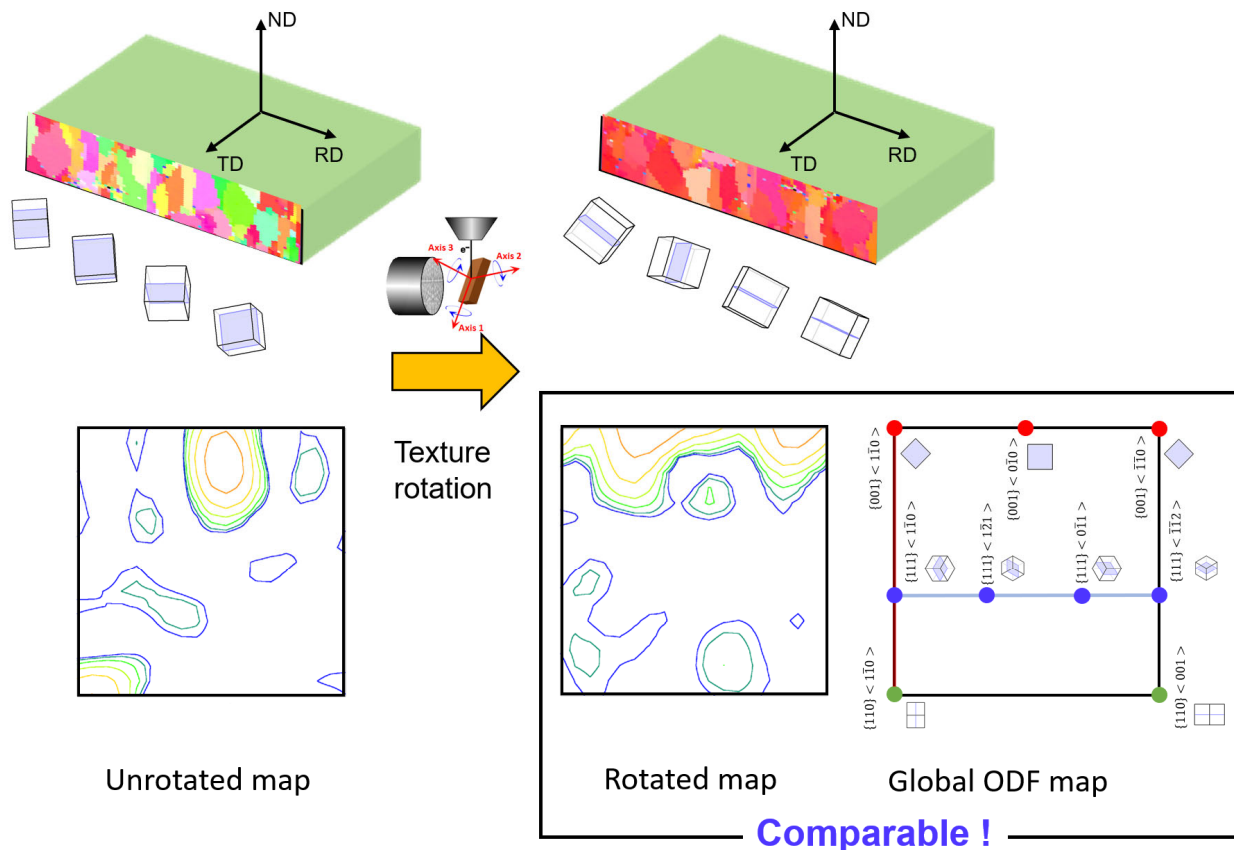


Figure 2. Orientation rotations of the EBSD data were carried out in order to match the global orientation. This is particularly important, especially for assessment using an ODF map.

2.3.2. Data Selection Among Pixels

The pixels selected for analysis in this study are displayed in deformed grain in Figure 3, which is roughly comprised of two parts: grain prior to rotation/primary orientation (light blue to lavender), which is termed as orientation 1, and grain after rotation/secondary orientation (light green to green color), which is termed as orientation 2. The selected pixels were located around the vicinity of orientation 1 and orientation 2 (squared region).

Misorientation profile analysis was conducted by indexing a series of pixel data across orientation 1 (lavender), orientation 2 (light green), and back to orientation 1 (lavender), with point-to-point misorientations calculated along the path. It can be seen that the misorientation angle values were below 15° or can be categorized as low angle boundaries.

In addition, each selected pixel needed to have a confidence index (CI) above 0.1. A series of data points were indexed within both orientation 1 and orientation 2, showing that each data point has a confidence index greater than 0.1.

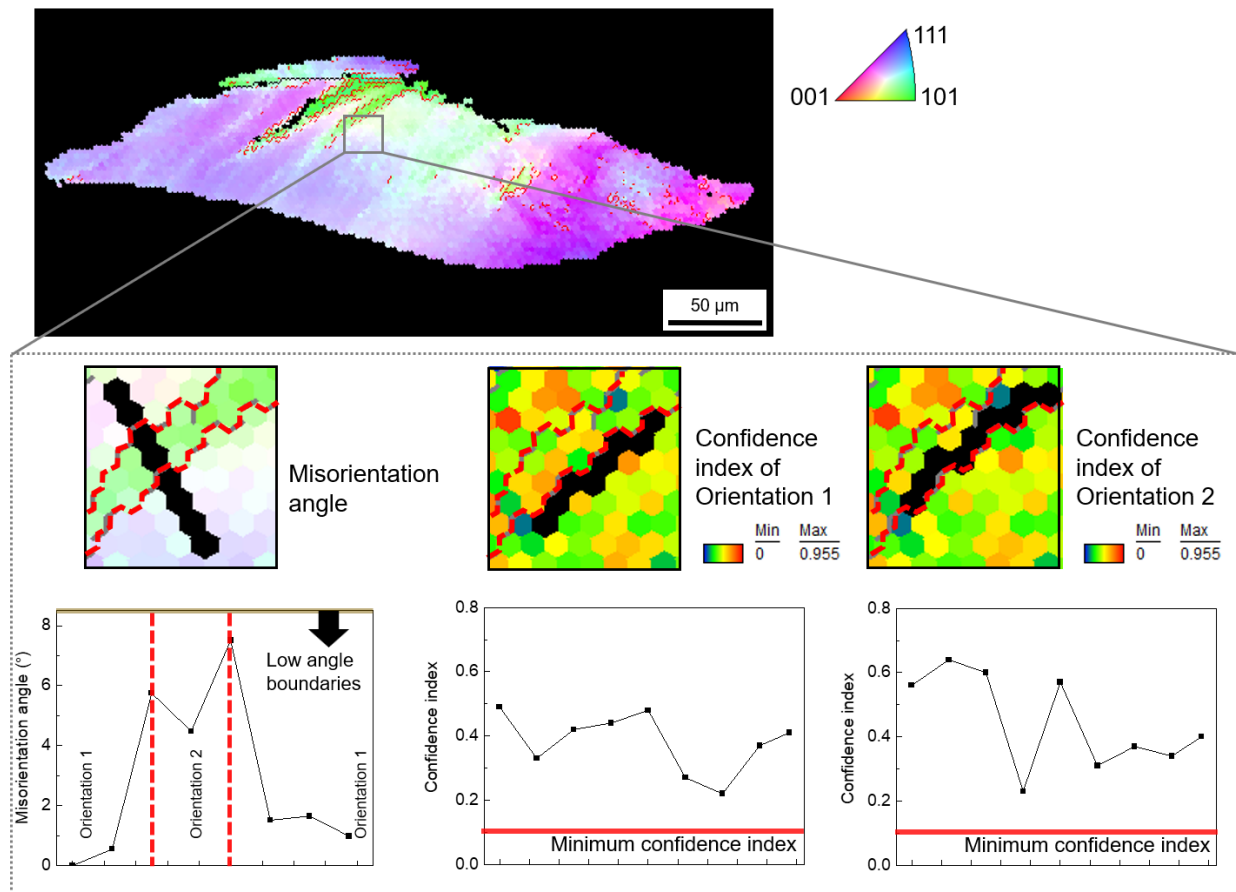


Figure 3. Pixel arrangement for orientation gradient analysis. The selected pixels have a minimum of 0.5 confidence index.

2.4. Viscoplastic Self-Consistent

The incompressible viscoplastic behavior at each material point was characterized using the following non-linear, rate-dependent equation:

$$\dot{\epsilon}(\bar{\mathbf{x}}) = \gamma_0 \sum_k m^k(\bar{\mathbf{x}}) \left(\frac{m^k(\bar{\mathbf{x}}) : \sigma(\bar{\mathbf{x}})}{\tau_0^s(\bar{\mathbf{x}})} \right)^n$$

$\dot{\epsilon}$ and σ are the deviatoric strain rate and stress. γ_0 is a normalization factor, and n is the rate-sensitivity exponent. τ_0^s and m^k are the threshold resolved shear stress and the symmetric Schmid tensor associated with the slip system (k).

Assuming a linear relationship between strain rate and stress within the statistically representative (SR) grains, the equation simplifies to the following:

$$\dot{\epsilon}(\bar{\mathbf{x}}) = M^{(r)} : \sigma(\bar{\mathbf{x}}) + \epsilon^{0(r)}$$

$M^{(r)}$ and $\epsilon^{0(r)}$ are, respectively, the viscoplastic compliance and the back-extrapolated term of SR grain (r). In this study, which adopted affine linearization, $M^{(r)}$ and $\epsilon^{0(r)}$ were chosen [18]:

$$M_{affine}^{(r)} = n\gamma_0 \sum_k \frac{m^{k(r)} \otimes m^{k(r)}}{\tau_0^{k(r)}} \left(\frac{m^{k(r)} : \sigma^{(r)}}{\tau_0^{k(r)}} \right)^{n-1}$$

$$\epsilon_{affine}^{0(r)} = (1-n)\gamma_0 \sum_k \left(\frac{m^{k(r)} : \sigma^{(r)}}{\tau_0^{k(r)}} \right)^n$$

In the experimental context, affine first-order self-consistent approximations are linearization schemes at the local level that make use of information on field averages only, disregarding higher-order statistical information inside the grains. The underlying physical significance of using affine simply lies in the fact that it was proven to work well for the case of polycrystalline materials (including the case where viscoplastic flow is highly non-linear) submitted to complex thermo-mechanical loading paths [15].

For the calculation to determine rotational axis, the active slip system here is the single $\{112\} \langle 111 \rangle$, which is known to be the most common slip system to be activated during cold rolling [19]. The $\{112\} \langle 111 \rangle$ family is detailed in Table 1.

Table 1. List of the family members of $\{112\} \langle 111 \rangle$ slip system.

Hkl	uvw
$\{21\bar{1}\}$	$\langle \bar{1}11 \rangle$
$\{12\bar{1}\}$	$\langle \bar{1}11 \rangle$
$\{112\}$	$\langle \bar{1}11 \rangle$
$\{2\bar{1}1\}$	$\langle \bar{1}11 \rangle$
$\{12\bar{1}\}$	$\langle \bar{1}11 \rangle$
$\{1\bar{1}2\}$	$\langle \bar{1}11 \rangle$
$\{21\bar{1}\}$	$\langle \bar{1}11 \rangle$
$\{\bar{1}21\}$	$\langle \bar{1}11 \rangle$
$\{\bar{1}12\}$	$\langle \bar{1}11 \rangle$
$\{21\bar{1}\}$	$\langle 111 \rangle$
$\{\bar{1}21\}$	$\langle 111 \rangle$
$\{\bar{1}12\}$	$\langle 111 \rangle$

Figure 4 summarizes the proposed method, with the central concept being the determination of the rotation axis from both experimental data and calculations. These rotation axes are then plotted on a pole figure to assess whether they are aligned parallel to each other.

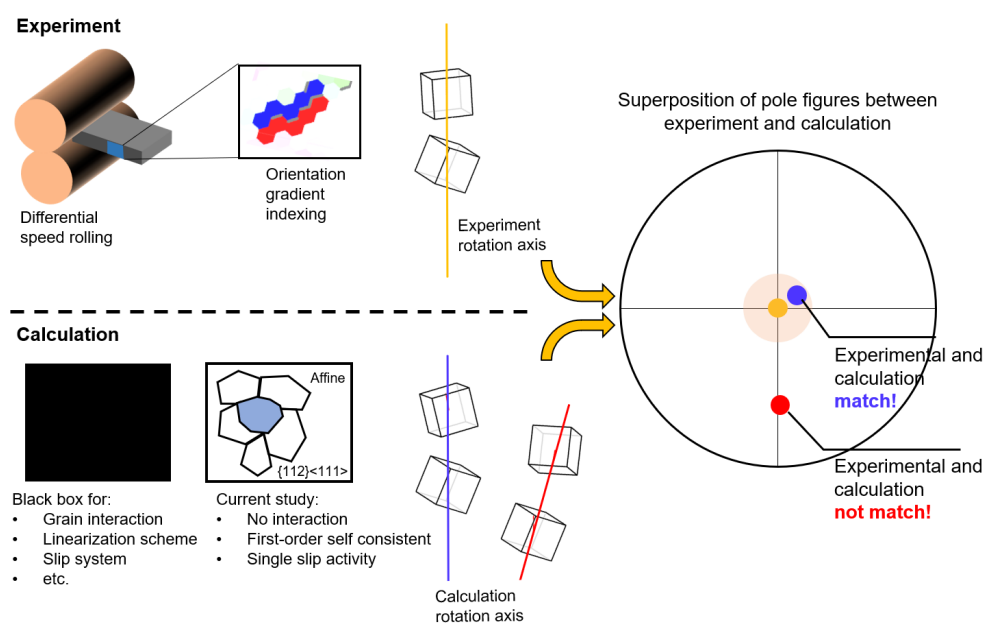


Figure 4. Schematic illustration of suggested method for single $\{112\} \langle 111 \rangle$ slip system activity.

Statistical analysis using analysis of variance (ANOVA) was conducted to examine the effect of position on the application of the current method, considering both top and center positions. A significance level of 0.05 was used, followed by a Tukey post hoc analysis to identify specific differences.

3. Results

3.1. Microstructure and Texture

To illustrate the microstructural characteristics, inverse pole figure (IPF) maps were generated from EBSD observations, with grain colors assigned according to the orientation triangle [20]. Figure 5 presents two maps, representing samples with lubrication (Figure 5a) and with no lubrication (Figure 5b). In these maps, red color-coded grains correspond to those where the normal direction of the (001) poles align with the ND axis (hereafter denoted as $\{001\}/\text{ND}$), while blue color-coded grains correspond to those with (111) poles aligned with ND (denoted as $\{111\}/\text{ND}$). In the lubricated sample, the microstructure is typical, with a predominant orientation of $\{111\}/\text{ND}$ grains, followed by $\{001\}/\text{ND}$ -oriented grains. For the non-lubricated sample, the fraction of $\{001\}/\text{ND}$ -oriented (red) grains is comparatively lower than in the lubricated sample. The $\{111\}$ pole figure (PF) maps revealed notable differences between the samples, particularly regarding the $\{111\}/\text{ND}$ texture. In the lubricated sample, the $\{111\}/\text{ND}$ orientation aligns with $\{111\} < 1\bar{1}0 >$ (following the black line trace), while in the non-lubricated sample, it aligns with $\{111\} < 1\bar{2}1 >$ (following the white line trace).

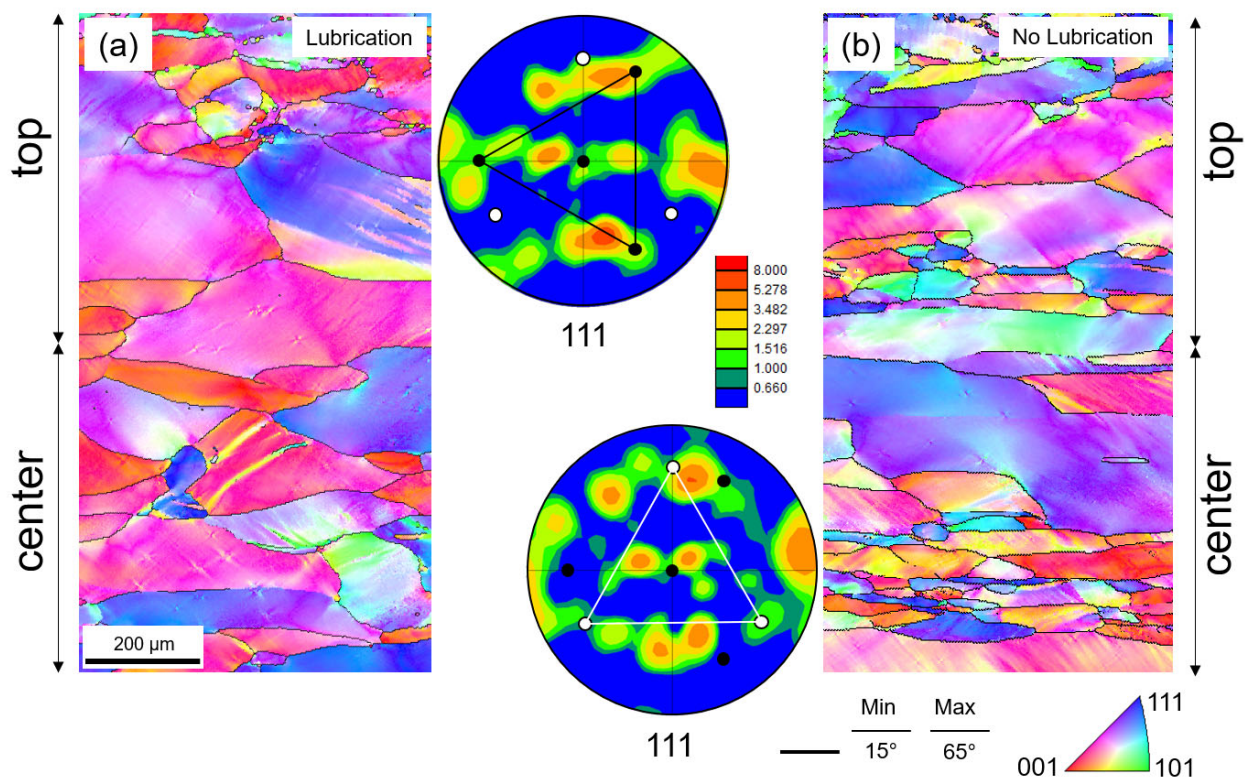


Figure 5. IPF maps imposed with grain boundary maps and $\{111\}$ PF maps of (a) lubricated and (b) non-lubricated sample.

To enhance visualization of the texture, orientation distribution function (ODF) maps were generated, as shown in Figure 6, covering a range of $\varphi_1 = 0\text{--}90^\circ$, $\phi = 0\text{--}90^\circ$, and $\varphi_2 = 45^\circ$. The differences in maximum intensity suggest that the non-lubricated sample (maximum intensity 14.85 ± 0.47 , Figure 6a) exhibits a more dispersed orientation distri-

bution compared to the lubricated sample (maximum intensity 24.68 ± 0.39 , Figure 6b). Regarding the ideal texture of red-coded grains (indicated by red dots), no significant difference is observed between the two samples. However, a clear distinction is evident in the blue-coded grains (indicated by blue dots). The orientations may not align precisely with ideal texture positions in ODF, especially following severe plastic deformation. Therefore, orientation assignments were based on the nearest ideal texture along the horizontal axis. For orientations along the γ -fiber (highlighted in light blue), orientation was assigned to the closest ideal texture either horizontally or along the γ -fiber. Under these criteria, the lubricated sample displays characteristics of $\{111\} \langle 1\bar{1}0 \rangle$, $\{111\} \langle 0\bar{1}1 \rangle$, and a minor fraction of $\{111\} \langle \bar{1}\bar{1}2 \rangle$, whereas the non-lubricated sample shows features of $\{111\} \langle 1\bar{2}1 \rangle$ and $\{111\} \langle 0\bar{1}1 \rangle$, aligning with the PF images in Figure 5.

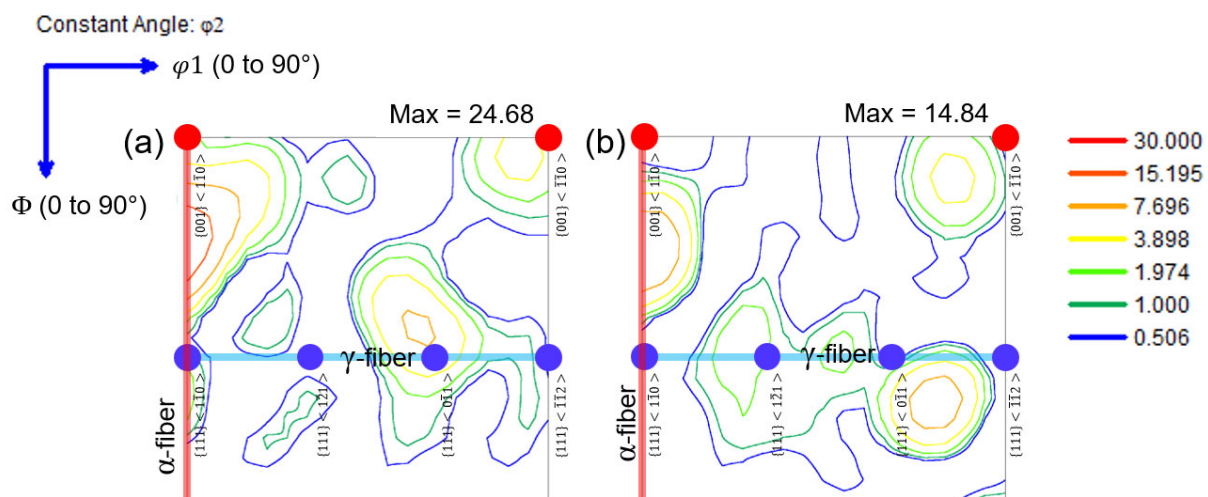


Figure 6. ODF maps (ϕ_1 (0 to 90°), Φ (0 to 90°), and a constant ϕ_2 of 45°) of (a) lubricated and (b) non-lubricated sample. The highlighted textures are those commonly found in a metal sheet after rolling deformation.

The microstructural analysis revealed a typical rolling deformation texture, with a dominant $\{111\}$ //ND grain orientation, followed by $\{001\}$ //ND-oriented grains, which is characteristic of post-rolling deformation textures. This orientation has been confirmed for cold-rolled steel through both experimental and simulation studies [21]. It has been suggested, with support from Taylor simulations, that most grains during rolling rotate into the α -fiber. Additionally, the Goss orientation is expected to rotate toward $\{001\} \langle 110 \rangle$ along the α -fiber and $\{111\} \langle 112 \rangle$ along the γ -fiber [22,23]. In the two samples studied, the majority of grains displayed orientations of $\{001\} \langle 1\bar{1}0 \rangle$ and $\{001\} \langle \bar{1}\bar{1}0 \rangle$ with red-like color coding and $\{111\} \langle 1\bar{1}0 \rangle$, $\{111\} \langle 1\bar{2}1 \rangle$, $\{111\} \langle 0\bar{1}1 \rangle$, and $\{111\} \langle \bar{1}\bar{1}2 \rangle$ with blue-like color coding. This study focuses specifically on these orientations for analysis of slip system activity.

3.2. Slip System Activity

Representative experimental data obtained using the DSR method are presented to provide an overview of the process leading to the final result, which is the confirmation of the activation of the $\{112\}\langle 111 \rangle$ slip system (Figure 7). The DSR method is known to involve differential rolling speeds, where the upper roll operates at a higher speed than the lower roll. This speed difference is expected to induce shear effects, making it plausible that the activation of the slip system under these conditions would occur, a configuration supported by VPSC simulations [10]. Additional experimental data include several cases where the active slip system predicted by calculations aligns precisely with experimental

observations. All these cases involve grains exhibiting shear texture, as identified by their positions in the ODF [24] and within individual grains.

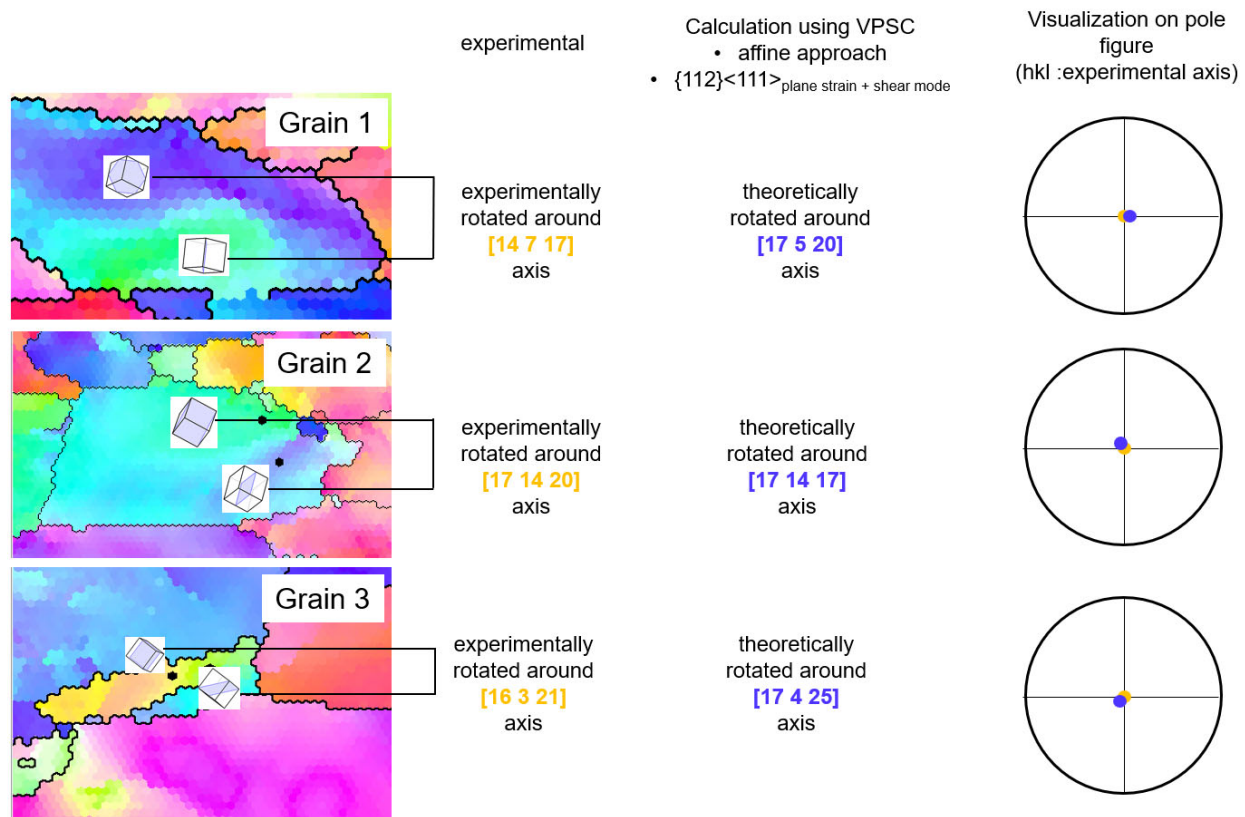


Figure 7. Three representative datasets providing an overview of the current method. Both experimental and theoretical rotation axes demonstrate the activation of the $\{112\}\langle 111 \rangle$ slip system under plane strain and shear conditions.

The slip system activity was statistically estimated for the following orientations: $\{001\} \langle 1\bar{1}0 \rangle$, $\{001\} \langle \bar{1}\bar{1}0 \rangle$, $\{111\} \langle 1\bar{1}0 \rangle$, $\{111\} \langle 1\bar{2}1 \rangle$, $\{111\} \langle 0\bar{1}1 \rangle$, and $\{111\} \langle \bar{1}\bar{1}2 \rangle$ and for grains with other orientations (referred to as “others”). All repeated observations (five repetitions for each condition) were averaged, and these averages were then compared. Figure 7 provides insights into the fraction of grains with these specified orientations and the proportion activating the $\{112\} \langle 111 \rangle$ slip system under plane strain or plane strain + shear strain conditions. Texture fraction was calculated as the ratio of each specific texture’s fraction to the total texture fraction within a single map. Several conclusions can be drawn from this analysis.

The first dataset, represented by the orange columns, indicates the fraction of grains with the orientation shown in the top left corner of each subfigure. Figure 8a,b illustrate that the fraction of red color-coded orientations is nearly identical between the two samples, as indicated by the similar mean values and consistent labels (all labeled “a”) from the Tukey post hoc test. In contrast, Figure 8c–f show that the dominant blue color-coded textures differ between the samples. Once again, it was confirmed statistically that the lubricated sample is primarily characterized by $\{111\} \langle 1\bar{1}0 \rangle$, $\{111\} \langle 0\bar{1}1 \rangle$, and a minor fraction of $\{111\} \langle \bar{1}\bar{1}2 \rangle$, whereas the non-lubricated sample is defined by $\{111\} \langle 1\bar{2}1 \rangle$ and $\{111\} \langle 0\bar{1}1 \rangle$. Additionally, the fraction of grains classified as “others” (Figure 8g) is higher in the non-lubricated sample than in the lubricated sample.

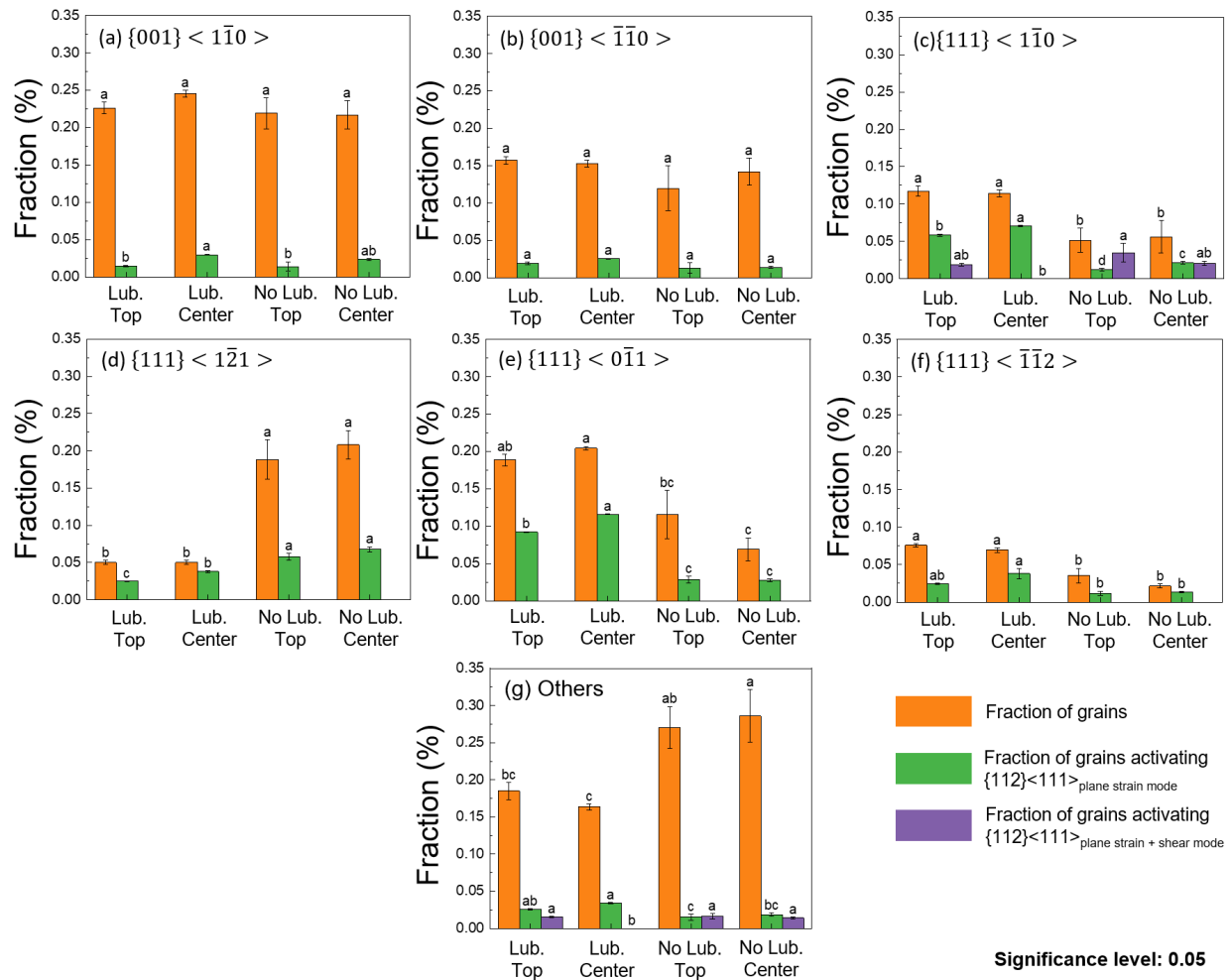


Figure 8. Statistic for the fraction (orange bar), fraction of grain with active {112} < 111 > aligned with calculated plane strain mode (green bar), and fraction of grain with active {112} < 111 > aligned with calculated plane strain and shear mode (blue bar) of grain with (a) {001} < 110 >, (b) {001} < 110 >, (c) {111} < 110 >, (d) {111} < 121 >, (e) {111} < 011 >, (f) {111} < 112 >, and (g) other orientations. The letters a, ab, b, bc, and c are added to summarize the results of the ANOVA.

The second dataset, represented by the green columns, shows the fraction of grains with the orientations indicated in the top left corner that activated the {112}<111> slip system under plane strain mode. Although the overall fraction of grains activating the slip system is small, activation is not strictly proportional to grain orientation. For instance, while grains classified as “others” appear in higher counts, they show close to the lowest fraction of grains activating the single {112}<111> slip system. Interestingly, grains with {111} // ND orientations activating the single {112}<111> slip system occur more frequently than those with {001} // ND orientations, indicating that {001} // ND grains are more likely to support multiple slip systems. In this framework, the method proves most effective for analyzing {111} // ND grains. Additionally, the center position consistently shows a higher fraction of slip system activation than the top, suggesting that the center’s increased likelihood for plane strain deformation favors single slip system activation.

The final dataset considers the combined effects of plane strain and shear strain modes of deformation, aimed at exploring grain rotation that relies on shear deformation. These cases are exclusively observed in Figure 8c,g. The fraction of active slip systems involving shear was highest at the top surface and found solely in grains with the {111} < 110 > orientation, indicating that this specific orientation is particularly prone

to rotation due to shear deformation. Thus, this can be used as an indication that, in the non-lubricated sample, the shear appears more likely to undergo deep penetration toward the center.

4. Discussion

Overall, the indexed active slip system was limited to a fraction of 50% or less, even for grains with $\{111\}/\text{ND}$ orientation. This limitation arises because the calculations in this study are based on a single slip system family; thus, if another slip system is active alongside the primary one being considered, the rotation axis from the experiment may not align with the calculated axis. Additionally, when deformation exceeds the “early deformation” stage, other phenomena, such as cross-slip, curved slip, diffuse slip, and/or intersecting slip, are likely to occur, significantly obstructing the rotation axis resulting from slip system activity [25,26]. Nevertheless, Figure 8d reveals an intriguing trend where the $\{111\} < 1\bar{2}1 >$ grain orientation exhibits the highest susceptibility to accommodate $\{112\} < 111 >$ single slip system activity based on its relatively high fraction of solo active slip systems compared to other $\{111\}/\text{ND}$ orientations, which exhibit nearly similar fractions. This indicates that the current method is sensitive to orientation, influencing slip system activity.

In this study, the proposed method proved most effective for $\{111\}/\text{ND}$ grains and primarily during the initial stage of plastic deformation. For other grain orientations, such as $\{001\}/\text{ND}$, the method can still be applied, but calculations of the rotation axis should incorporate additional active slip systems such as $\{110\} < 111 >$ and $\{123\} < 111 >$. Grains located at the center consistently showed higher statistical values compared to those at the top, likely due to the presence of additional shear strain at the top surface [27]. This shear strain induces a complex mixture of deformation modes, resulting in the activation of multiple slip systems. Consequently, the current method, which indexes single slip system activation, may not fully match the observed data in these cases. In such scenarios, slip systems may interact to collectively rotate the grain. Deeparekha et al. conducted simulations considering both single ($\{110\} < 111 >$) and dual ($\{110\} < 111 > + \{112\} < 111 >$) slip systems working in tandem [21].

Despite its limitations, the current method reveals several key insights. Figure 8c indicates that DSR without lubrication leads to greater uniformity in the activity of the $\{112\} < 111 >$ slip system across the surface and center under combined plane and shear strain or, in this case, termed as deep penetration of shear deformation. This aligns with findings that suggest DSR can enhance through-thickness equivalent plastic strain homogeneity [3]. Including shear mode in the calculations also corresponds well with the regions of the sample undergoing shear deformation. It is generally understood that shear promotes the activation of a broader range of slip systems compared to symmetrical rolling [28]. However, in this study, it was observed that shear primarily supports the activation of a single $\{112\} < 111 >$ slip system, especially in grains with the $\{111\} < 1\bar{1}0 >$ orientation.

The application of viscoplastic self-consistent formulation for assessing rotation axis presents considerable potential. Beyond its capability to identify which deformation modes drive texture changes and to evaluate the relative activities of multiple slip and twinning modes on texture evolution, it also allows for the inclusion of additional factors influencing orientation changes. In rotation axis analysis, incorporating grain incompatibilities could serve as input to permit each grain to adopt a unique strain value, potentially impacting neighboring grains [21]. Classic studies have highlighted the importance of grain shape effects on lattice rotation, though this has been traditionally limited to elastic interactions [29]. In this context, incorporating rate-controlling dislocation mechanisms may also be bene-

ficial [30]. Therefore, refining the current method to account for these factors is essential before broader application.

5. Conclusions

This study introduces a method to evaluate deep shear deformation penetration in ferritic stainless steel via DSR, taking contact conditions into account. The method integrates experimental (from EBSD analysis) and theoretical (VPSC analysis) rotation axes to identify the activity of the $\{112\} < 111 >$ slip system and determine whether it is activated under plane strain or a combination of plane strain and shear. To reflect the conditions of the early stage of plastic deformation, EBSD analysis was performed on regions with orientation gradients below 15° , and VPSC analysis was conducted using the affine approach within the first-order self-consistent framework. This study presents the first evidence of $\{112\} < 111 >$ slip system “solo” activity occurring under plane strain combined with shear, even in the central region of the non-lubricated sample. This activity is observed particularly in grains with a $\{111\} < \bar{1}10 >$ orientation, which are more prone to rotation from shear, supporting the phenomenon of deep shear penetration. Despite its limitations to the early stage of plastic deformation and grain with $\{111\}/\text{ND}$ orientation, this study effectively confirms that shear deformation contributes to uniformity in slip system activity by incorporating shear deformation mode. The study of this material presents the potential for developing a material with a uniform, fine-grained microstructure, leading to enhanced toughness.

Author Contributions: Conceptualization, S.F., W.B., J.-H.K., I.P.W. and Y.G.K.; Methodology, S.F., W.B., J.-H.K., I.P.W. and Y.G.K.; Software, S.F. and I.P.W.; Validation, S.F., W.B., J.-H.K., I.P.W. and Y.G.K.; Formal analysis, W.B.; Investigation, S.F. and W.B.; Resources, W.B.; Data curation, S.F., W.B. and I.P.W.; Writing—original draft, S.F. and W.B.; Writing—review & editing, S.F., W.B., J.-H.K., I.P.W. and Y.G.K.; Visualization, J.-H.K., I.P.W. and Y.G.K.; Supervision, J.-H.K., I.P.W. and Y.G.K.; Project administration, J.-H.K. and Y.G.K.; Funding acquisition, J.-H.K. and Y.G.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to their containing information that could compromise the privacy of research participants.

Conflicts of Interest: The authors declare no conflict of interest.

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