Quantitative prediction of deformed austenite and transformed ferrite texture in hot-rolled steel sheet

To cite this article: Y Tanaka et al 2015 IOP Conf. Ser.: Mater. Sci. Eng. 82 012057

View the article online for updates and enhancements.

Related content
- A review of research and development on titanium microalloyed high strength steels
  Xiangdong Huo, Jinian Xia, Liejun Li et al.
- Development of Ti microalloyed high strength steel plate by controlling thermo-mechanical control process schedule
  Jinian Xia, Xiangdong Huo, Liejun Li et al.
- FE-based analysis for the prediction of inner microstructure in metal forming
  Jun Yanagimoto

Recent citations
- DAMASK – The Düsseldorf Advanced Material Simulation Kit for modeling multiphysics crystal plasticity, thermal, and damage phenomena from the single crystal up to the component scale
  F. Roters et al.
Quantitative prediction of deformed austenite and transformed ferrite texture in hot-rolled steel sheet

Y. Tanaka¹, T. Tomida² and V. Mohles³
¹Technival R&D Bureau, Nippon Steel and Sumitomo Metal Corp., Amagasaki, JP
²Amagasaki Unit, Nippon Steel and Sumikin Technology, Amagasaki, JP
³Institute of Physical Metallurgy and Metal Physics, RWTH Aachen, Germany
E-mail: yasuaki.km5.tanaka@jp.nssmc.com

Abstract. A model to quantitatively predict ferrite (α) textures in hot-rolled steel sheets has been developed. In this model, the crystal plasticity model, called "Grain Interaction model (GIA)", and the transformation texture model, called "Double K-S relation (DKS)", are linked together. The deformed austenite (γ) texture is predicted by GIA with taking not only the standard {111}<110> slip system but also non-octahedral slip systems into account. Then the transformed α texture is calculated by DKS, in which a nucleated α prefers to have orientation relationship near the Kurdjumov-Sachs relation with both of two neighboring γ grains. For validation, single pass hot-rolling tests on a C-Si-Mn steel were carried out. The comparison between the predicted and the experimental textures shows that the linked model (GIA & DKS) can lead to a remarkable reproduction of the texture of hot-rolled steel sheets.

1. Introduction
It is important to understand the texture development during hot-rolling processes because the texture strongly influences the material properties, and the texture of hot-rolled steel is known to largely influence (or inherited to) the texture even after cold-rolling and annealing. However, there is still much difficulty in predicting the texture development throughout the manufacturing process, since the influence of deformation and recrystallization of γ as well as phase transformation from γ to α on the texture evolution have not been thoroughly clarified. Among those phenomena, the texture development during deformation has been perhaps best understood. For instance it was reported that the Taylor-type crystal plasticity model, such as "Grain Interaction model (GIA) [1]" in which the interaction of the deformation of neighboring grains can be considered, could make a reasonably quantitative prediction for the deformation texture of cold-rolled fcc alloys [2]. Furthermore, recently, a new variant selection model called "the double K-S relationship (DKS)" has been proposed for the transformation texture simulation [3], which theoretically deals with an important issue in the phase transformation, which of the variants in the orientation relation (24 for K-S relation) are preferentially selected. DKS assumes that α nucleating on γ grain boundaries prefers to have orientation relationship near the Kurdjumov-Sachs relation with two neighboring γ grains at the same time. It was then reported that DKS could lead to an excellent reproduction of experimental transformation textures of low carbon steel [3]. In this research, GIA and DKS have been linked together to construct the through-process prediction model for hot-rolling processes in which deformed γ directly transforms to α without recrystallization, and the model has been experimentally examined.

2. Experiments
The hot-rolled steel sheets of 0.2%C-1.5%Si-1.45%Mn in chemistry (mass%) were prepared by single pass hot-rolling of 30 % or 50 % in reduction at 930°C as shown in Fig.1. The final thickness of hot-rolled samples was 3.4 mm. To avoid recrystallization of γ, the finish-rolled steel sheets were cooled immediately to 750°C at a rate of about 1000°C s⁻¹ to promote precipitation of α. Then they were kept at 400°C for 10 minutes to promote bainite transformation and stabilize the retained γ. Fig.2 shows the OIM image of 50% hot-rolled steel sheet. The sample consisted of the retained γ of around 8% in volume fraction, polygonal ferrite, bainite and a trace amount of martensite. The textures for fcc and bcc phase in the thickness center were examined via XRD, and ODF was calculated using incomplete pole figures and the harmonics method. In this study, the model validation has been made on the assumption that the retained γ has the equivalent textures to that of the whole γ.
3. Simulations

3.1. The deformation texture model “GIA” [1]

GIA has been established as a crystal plasticity model in which the interaction of the deformation of neighboring grains is taken into account [1]. In this model, a material is deformed as a statistically suitable set of aggregates comprised of 8 grains as shown in Fig. 3. Although the aggregates follow the sample strain path, each grain within an aggregate is allowed to perform individual relaxations. Accumulating incompatibilities between the grains and their surroundings are compensated by geometrically necessary dislocations (GND), and the active slip systems are chosen such that the total consumed power for dislocation slips and GND generation is minimized. To improve the agreement with the measured rolled textures, a macroscopic plane strain deformation with random shear components were applied [4]. The proposed strain rate tensor takes the form as Eq. (1) [4].

\[
\begin{align*}
\dot{\varepsilon}_{11} & = 1 \pm 0.1, \dot{\varepsilon}_{11} = -1 \pm 0.1, \dot{\varepsilon}_{22} = -\dot{\varepsilon}_{11} - \dot{\varepsilon}_{33}, \\
\dot{\varepsilon}_{13} & = 0 \pm 0.6 \ldots 0.75, \dot{\varepsilon}_{23} = 0 \pm 0.4, \dot{\varepsilon}_{12} = 0 \pm 0.3 \ldots 0.15
\end{align*}
\] (1)

The rolling simulation was conducted assuming the macroscopic plane strain deformation as above with standard \{111\}<110> as well as non-octahedral \{110\}<110> and \{112\}<110> slip systems activated. The non-octahedral slip systems have been reported to be activated due to deformation at elevated temperatures [5-7]. The preceding studies on Al alloys [5-7] have reported that the critical resolved shear stress (CRSS) of non-octahedral slip systems at the temperatures above 70% of their melting points are in the range from 0.75 to 1.4 as the ratio to that for standard \{111\} slips. Therefore, the CRSS’s of \{110\}<110> and \{112\}<110> slips were assumed to be equal to that of \{111\}<110> slip system in this study to better reproduce the development of Cu-orientation \{211\}<111> during hot-rolling as will be described later.

The hot-rolling texture was thus calculated from the random texture, and its ODF was expanded applying the spherical harmonic method for the next transformation texture calculation.

3.2. The variant selection model “Double K-S relation” [3]

The transformation textures have been simulated assuming that the variants of \(\alpha\) holding the K-S relation with two neighbor grains of \(\gamma\) are preferentially selected when \(\alpha\) nucleates on the high angle grain boundaries of \(\gamma\). This selection rule is called the double K-S relation: DKS [3]. Because the precise double K-S relation can be achieved only on the special grain boundaries, its probability in ordinary materials is negligibly small. In DKS, the tolerance angle of about 10° for the K-S relation on, at least, one side of the \(\gamma\) grain boundary is assumed, which would increase the probability of having double K-S relation on the general grain boundaries.

The variant selection function \(\rho(g)\) is expressed with the term due to DKS (the first term) and the one without selection (the second term) as given in Eq. (2). The value of the variant selection parameter \(\omega\) was determined from the comparison of the measured texture of \(\alpha\) and the simulated one based on the measured texture of \(\gamma\).

\[
\rho(g) = \frac{\omega}{N} \sum_k f(\Delta g^{-1} \cdot g_k^* \cdot \Delta g \cdot g) + \rho_c(g)
\] (2)

\(\Delta g\): crystal rotation of transformation, \(g_k^*\): rotational operators for the cubic symmetry group, \(N\): number of variants, \(\omega\): intensity of the variant selection.
The transformed texture of \( \alpha \) can be related to the parent texture of \( \gamma \) by Eq. (3) with using spherical harmonic series expansion and the variant selection function of Eq. (2) [8]. \( aC_{\lambda}^{\mu \nu} \) and \( \gamma_{GIA}^{\mu \nu} \) are the series expansion coefficients of the ODF’s of \( \alpha \) and \( \gamma \) respectively. \( \zeta_{\mu \nu}^{\alpha} \) and \( \zeta_{\mu \nu}^{\gamma} \) are the symmetrically invariant functions for cubic crystal symmetry and related coefficients [8], \( \{ \lambda_1 \lambda_2 m r | \alpha \} \) and \( \{ \lambda_1 \lambda_2 v_1 v_2 | \nu \} \) are Clebsh-Gordan coefficients and related coefficients defined by Bunge et al. [8] for the symmetrically invariant functions.

\[
aC_{\lambda}^{\mu \nu} = \sum_{\lambda_1=0}^{\infty} \sum_{\mu_1=1}^{N(\lambda_1)} \gamma_{C_{\lambda}^{\mu \nu \alpha}} \left[ \sum_{\lambda_2=0}^{\infty} \sum_{\nu_1=1}^{N(\lambda_2)} \sum_{\nu=1}^{+\lambda} \rho_{\lambda_2}^{\nu \nu_2} \zeta_{\lambda_1}^{\mu \nu_2} (\lambda_1 \lambda_2 m r | \alpha) (\lambda_1 \lambda_2 v_1 v_2 | \nu) \zeta_{\lambda_2}^{\mu \nu} (\Delta g) \right] \\
\quad s = m + r, |\alpha - \lambda_1| \leq \lambda \leq |\lambda_1 + \lambda_2|, s \leq \lambda
\]

(4)

\( \rho_{\lambda_2}^{\nu \nu_2} \) are the expansion coefficients of \( \rho (g) \) by the invariant function for crystal symmetry \( \zeta_{\lambda_2}^{\mu \nu} \), which can be given as Eq.(5). Thus, the \( \alpha \) texture \( aC_{\lambda}^{\mu \nu} \) can be calculated via Eq.(3) if \( \gamma_{GIA}^{\mu \nu} \), \( \Delta g \) and \( \rho (g) \) are given. For the linked prediction of GIA and DKS, the \( \gamma_{GIA}^{\mu \nu} \) were determined by GIA as aforementioned.

\[
\rho_{\lambda_2}^{\nu \nu_2} = \frac{\omega}{N} \sum_{\mu_2=1}^{M(\lambda_2)} \gamma_{C_{\lambda}^{\mu \nu \alpha}} \left[ \sum_{\nu=1}^{24} (\Delta g)^{-1} \cdot g_{C} \cdot \Delta g \right] - \frac{1}{24} \sum_{\lambda_2} \zeta_{\lambda_2}^{\mu \nu} (\Delta g^{-1} \cdot g_{C} \cdot \Delta g \cdot g_{C})
\]

(5)

4. Verification of the model

4.1. Deformation texture simulation

Figures 4 and 5 show the experimental ODF and \( \beta \) fiber intensity of retained \( \gamma \) and those predicted by GIA for hot-rolling. The measured texture of \( \gamma \) exhibits a rolling texture typical of cold-rolled pure Cu. It is also seen that the GIA has successfully reproduced the development of deformation textures in \( \gamma \) quantitatively. In particular, using both of the octahedral as well as non-octahedral slip systems, the agreement is excellent so that the predicted height of major texture components closely matches to the experimental ones. Without the non-octahedral slip being taken into account, a somewhat poorer agreement between the experimental and predicted textures has resulted as shown in Fig. 5.

Fig. 4 (a) Measured ODF of the retained \( \gamma \) hot-rolled by 30% in reduction and (b) the predicted textures with octahedral and non-octahedral slip system. (Levels: 2.0,2.5,3.0...)

4.2. The Linked simulation results

Figures 6 and 7 present the comparison of the measured \( \alpha \) textures and the simulated ones, which is calculated by the linked model of GIA and DKS. The measured texture has the typical transformation texture of \( \alpha \) that is arisen from the unrecrystallized deformed \( \gamma \). As
also seen in this figure, the calculated texture based on the deformation texture of $\gamma$ by GIA is in a surprisingly good agreement with the measured $\alpha$ texture. The deviation from the experimental texture in ODF is as small as 0.5 or less, while the parameter of variant selection, $\omega$, has been determined to be 0.8 to minimize the deviation. In Fig. 7 are shown the BCC $\alpha$ fiber plots, which compare the profiles of the major component in the experimental texture and the ones predicted with and without DKS. The simulation result without the variant selection rule is much weaker than the experimental one, while the adoption of DKS leads to a better reproduction of the experimental ones as abovementioned. Furthermore, the comparative simulation in which non-octahedral slips were not taken into account, has led inadequate prediction results also for the transformation texture. A disagreement that much higher intensity of $\{211\}<011>$ is predicted by the simulation without non-octahedral slip system seems to be caused by an improper prediction of $\gamma$ texture with a too strong copper component. Introducing of non-octahedral slips could avoid such an excessive development of the copper component. However the CRSS of $\{112\}<110>$ system has been reported to strongly affect the intensity of the copper component as well as that of the brass component [5]. For improving accuracy of prediction, the accurate values of CRSS for non-octahedral slips would be required. Since the strength of the variant selection according to DKS is determined by the parent $\gamma$ texture, further improvement in the deformation texture simulation in hot-rolling would naturally lead to more accurate prediction of the transformation texture of hot-rolled steel sheets.

5. Conclusions
The linked model of GIA and DKS could provide us with a remarkable reproduction or prediction of the transformed $\alpha$ texture in hot-rolled steel sheets in the case where the deformed $\gamma$ does not recrystallize before phase transformation. Incorporating non-octahedral slip system into the model of deformation texture development could lead to a better agreement between the measured and predicted textures in hot-rolled steel sheets. These results indicate the possibility of the through-process texture modeling of hot-rolling processes in steel, although further investigation is required, e.g., for the CRSS of non-octahedral slips as well as recrystallization texture development in $\gamma$.

References
[1] M. Crumbach, G. Pomana, P. Wagner, G. Gottstein 2001 Proc. 1st Rex&GG (Berlin), 1053
[2] P. Van Houtte, S. Li, M. Seefeldt and L. Delannay 2005 Int. Journal of Plasticity 21, 589
[3] T. Tomida, M. Wakita, M. Yoshida and N. Imai 2008 Proc. 15th ICOTOM (Pittsburg),325
[4] O. Engler, 2002 Advanced Engineering Materials 4, 181
[5] B. BACROIX and J. J. JONAS 1988 Textures and Microstructures, Vols. 8 & 9, 267
[6] Cl. MAURICE and J. H. DRIVER 1997 Acta mate., Vol. 45, No. 11, 4639
[7] F. Perocheau and J.H. Driver 2002 Int. Journal of Plasticity, 18, 185.
[8] H. J. Bunge, M. Humbert and P. I. Welch 1984 Textures and Microstructures, Vol. 6, 81.