Texture-tensile properties correlation of 304 austenitic stainless steel rolled with the change in rolling direction

Matruprasad Rout
School of Mechanical Engineering, KIIT Deemed to be University, Bhubaneswar 751 024, India
Department of Mechanical Engineering, Indian Institute of Technology Kharagpur, 721302, India
E-mail: matruprasadrout87@gmail.com
Keywords: rolling, texture, tensile, rolling direction, EBSD

Abstract
Rolling, at elevated temperature, with a change in the rolling direction (RD) have been conducted on 304 austenitic stainless steel. Two different sequences of change in RD, after each pass, have been followed viz., change in RD by 90°; designated as cross rolling (CR) and change in RD by 180°; designated as reverse rolling (RR). Effect of this change in RD on texture and tensile properties has been studied through Electron backscattered diffraction (EBSD) and uniaxial tensile test, respectively. In addition, tensile tests have been performed to study the anisotropy in tensile properties. The result shows a significant effect on the texture component formation. RR develops strong Cu and S components whereas CR forms strong Brass component. However, both the rolling sequence produces moderate Goss orientation. The observed tensile properties are correlated with the texture developed by both the processes.

1. Introduction

The application of austenitic stainless steel is wide, ranging from houseware goods to nuclear, fertilizer and petro-chemical industries [1]. This is due to its excellent corrosion resistance and high strength at elevated temperatures [2]. The wide-ranging applications leads to a lot of research on the hot rolling and subsequent metallurgical characterizations of these steels. In the field of material characterization, study on the crystallographic preferred orientation or texture evolution has rapidly grown in last few decades. During rolling the strain developed along the thickness direction of the workpiece is not homogeneous. The presence of friction at the roll-workpiece interface produces shear strain at the surface of the workpiece whereas the mid-thickness experiences a plane strain condition. So, rolling of metallic materials, depending upon the deformation conditions, may produce rolling texture and/or shear texture [3]. In hot rolling, as the rolling is performed at high temperature, in addition to deformation texture, recrystallization texture can also be developed. In austenitic stainless steel, near to the top surface of the rolled samples i.e. in severely sheared region {112} {110}, {111} {110} and {001} {110} texture components are developed. On the other hand the texture component at the mid-thickness is mainly contributed by {110} {112} [4]. In addition to {001} {110} and {112} {110} components, γ fiber also develops near to the top surface, and β fiber with cube component at the center [5]. In texture development during hot rolling process, the amount of reduction and the temperature of the last pass have a greater impact on the final texture [6]. It has been reported that with increase in the rolling temperature the texture for 304 austenitic stainless steel can be changed to copper type from brass type [7]. In another work [8], Raabe found the through thickness hot rolling texture for 304 austenitic stainless steel to be dependent on the shear strain distribution along the thickness. At the center of the hot band and at the sub-surfaces random texture was observed whereas, at the top surface and at the intermediate layer i.e. between the center and the top surface, {001} {110}, {111} {211} and {211} {100} orientations were observed. These orientations are the shear texture components, which led the author to conclude that the hot rolled texture is dependent on the through thickness shear strain distribution. Other significant work [9–12] on texture evolution during rolling of austenitic stainless steel are based on cold rolling process.
The preferred orientation or texture developed during the rolling process can be altered by controlling the thermo-mechanical process. Rolling with change in rolling direction (RD) by 90° about normal direction (termed as cross rolling, CR) is one such way of changing the texture development in the rolled samples. However, the effect of this change in RD is governed by the amount of reduction per pass, the total number of passes and most importantly the sequence of change in RD. In past, the effect of change RD has been studied for the austenitic stainless steel material [7, 13, 14] however they are mainly for cold rolling followed by annealing process. Literature [6] also suggest that the texture developed by the cold rolling process is dependent on the texture of the input material which is usually the hot rolled band. So a change in texture of the initial hot rolled material by CR process may subsequent affect the texture developed by cold rolling process. At the same time, it can also affect the mechanical properties of the material [15–17]. Hence, the current work is based on the hot rolling with change in RD and its effect on the tensile properties and plastic anisotropy of the rolled samples.

2. Experimental details

2.1. Processing

The hot rolling experiments on 304 austenitic stainless steel (C-0.035, Cr-18.29, Ni-8.04, Mn-1.5, Si-0.384 wt%) samples were carried out on a 2-high reversing rolling mill with 320 mm diameter rolls. These experiments were performed with two different modes of rolling viz. reverse rolling (RR) and cross rolling (CR). For the first one, the rolling direction (RD) is changed by 180° and this has been achieved by the reversing action of the rolls. In the second mode, the RD has been changed by 90° and this has been achieved by rotating the sample by 90° on the rolling plane. During CR, the rolls were also reversed. The two different modes, used in the present study, is schematically shown in figure 1. A total of 70% reduction in thickness was obtained in seven passes and the amount of reduction in each pass was kept as 2 mm. The experiments were performed at a roll speed of 10 rpm and the initial temperature and thickness of the samples were 1100 °C and 20 mm, respectively. After rolling, the samples were left for air cooling.

2.2. Characterization

For microstructure and texture analysis small sample volume was taken from the rolled material. The RD-ND (rolling direction-normal direction) plane of the sample was subjected to manual polishing followed by electropolishing and the characterization was done on the polished surface through electron back scattered diffraction technique (EBSD). The EBSD scan with a step size of 1 μm was performed on FIB-SEM (Focused Ion Beam Scanning Electron Microscope, ZEISS AURIGA Compact) operated at 25 kV. The scan was performed at the mid-thickness. The obtained scan data were cleaned with standard grain dilation cleanup procedure and the cleanup was performed for single iteration. For the texture analysis, the RD of the last pass is considered. Texture developed in the material is represented in the form of pole figure and orientation distribution function (ODF). Only the important ODF sections i.e. $\varphi_2 = 0^\circ$, 45° and 65° are shown.

Tensile specimens with ASTM sub-size dimensions (25 mm gauge length, figure 2(a)) were cut from the rolled sample. Two sets (I and II) of three tensile specimens with the longitudinal axis aligned to RD (0°), TD (90°) and 45° to RD were cut (figure 2(b)). One set of tensile specimen (set I) was used for the study of tensile behavior whereas, the other set of specimen (set II) was used for the determination of anisotropy parameter. The tensile tests were performed on a universal testing machine (INSTRON 8862) with a cross head velocity of 1 mm min$^{-1}$. It can be noted that the room temperature tensile test of austenitic stainless steel results in the strain-induced martensitic transformation during testing [18, 19]. However, this has not been studied in the present work. For the determination of anisotropy parameter, the tensile tests were interrupted at the 70% of total elongation and the anisotropy parameters were determined using the following standard formulas [20].

\[
\begin{align*}
\varphi_2 & = 0^\circ, 45^\circ \text{ and } 65^\circ
\end{align*}
\]
where, $\bar{R}$ is the average plastic strain ratio and $D_R$ is the coefficient of planar anisotropy. $R_{RD}$, $R_{45}$ and $R_{TD}$ are the plastic anisotropy ratio determined from the specimen tested along RD, 45° to RD and TD, respectively. The plastic anisotropy ratio is defined by the ratio of the strain in width direction ($\varepsilon_w$) to the strain in thickness direction ($\varepsilon_t$).

3. Result and discussions

3.1. Texture evolution

Texture (in the form of $\varphi_2$ ODF sections) developed in the rolled materials shown in figures 3(a) and (b) can be characterized by the ideal components like Goss, Brass, S and Cu. Comparatively high fraction of Cube component can be observed for CR. Also for CR, the texture intensity spreads from Goss to Cube component ($\varphi_2 = 0^\circ$ section). On the other hand, RR develops a higher Goss component and with the change in RD (i.e. in CR) higher Brass component is formed. Higher intense Cu and S components can be observed for the RR sample. Moreover, it can be said that RR develops strong $\tau$ fiber than CR.

3.2. Tensile test

3.2.1. Stress-strain behavior

The engineering stress-strain behavior of the rolled material tested along the three directions is shown in figure 4. As expected, the stress value increases with the increase in strain, attains a maximum value i.e. the ultimate tensile stress (UTS) and then starts decreasing which is due to the localized deformation causing necking in the specimen. In both the cases, higher UTS value is obtained on the specimen tested along RD. However, the difference in the value from the other two directions (TD and 45° to RD) is more in case of RR. Similarly, the RR sample shows the maximum total elongation (TE) along the RD whereas for CR it is maximum along 45° to RD. To get the yield stress (YS), 0.2% offset method was used. The value for UTS, YS, TE and UE (uniform elongation) is summarized in figure 5.

The difference between the highest and lowest YS value for RR sample is $\sim 21\%$ whereas it is $\sim 16\%$ for CR sample. Similarly, the difference between the highest and lowest UTS value is $\sim 9\%$ and $\sim 5\%$ for RR and CR samples, respectively. On the other hand, the difference in TE is $\sim 19\%$ and $\sim 14\%$ for RR and CR sample whereas for UE, the values are $\sim 38\%$ and $\sim 26\%$ for RR and CR samples, respectively. Form this it can be concluded that rolling with change in RD can reduce the anisotropy of tensile behavior of the 304 austenitic stainless steel.

3.2.2. Correlation between texture and anisotropic behavior of tensile properties

It is well known that texture can significantly affect the tensile properties. So, in the present work the observations of anisotropy in tensile properties is correlated with the texture development in the material. This has been studied through the Taylor factor and the inverse pole figure (IPF) analysis.
Figure 6 shows the IPF of the rolled samples in four different directions viz. ND, TD, RD and 45° to RD. The distribution of texture intensity along ND is same in both the sample. The (001) and (111) directions are parallel to ND. Apart from this, distribution of texture intensities in between these two directions can also be seen. However, the texture intensities are almost same (maximum MRD ~2.7). But, the distributions along the other three directions are quite different. In RR sample texture intensities along TD can be observed near (101) and (111) whereas CR makes (001) directions to align with TD instead of (101). A slight increase in texture intensity can also be observed for the CR sample (maximum MRD ~1.9). Similarly, in RD IPF of RR sample along with (101) the texture intensities also spreads towards the (112) and the maximum intensity is observed near (101) (maximum MRD ~2.7). But the change in RD aligns more (101) directions towards RD and the texture.
intensity gets enhanced (maximum MRD ∼4.5). In 45° to RD IPF maximum intensity is observed near (001) for RR sample whereas for CR sample the intensity get shifted towards (102) and (212).

Now these texture intensity distributions, which indicates the orientation of different crystallographic planes with respect to the tensile axes, can be correlated to the tensile behavior by analyzing the number of slip systems activated. Figure 7 shows the stereographic triangle indicating number of slip systems activated in FCC material. The IPF in the direction of 45° to RD of CR sample shows the intensity distribution towards (102) and (212) which indicates the
activation of four more slip systems. This may be possible reason for observing a higher elongation along 45° to RD for CR sample. The same can be observed for the directions along RD of RR sample where texture intensity can be observed near (112) which allows two more slip system to activate due to which a higher elongation is achieved.

The Taylor factor distribution along the three different directions is shown in the figure 8 and the average Taylor factor value along with YS value is presented in table 1. The Taylor factor has been calculated for the \{111\} \{110\} slip system. Anisotropy of the YS can be correlated to the corresponding Taylor factor value. Higher YS value corresponding to higher Taylor factor value can be seen. Specimen tested along TD of RR sample exhibit higher Taylor factor (∼3.2) and also the higher YS value (∼518 MPa). Interestingly for the directions TD and 45° to RD of CR sample, the Taylor factor values are nearly (∼3.07) same which results in same YS value (432 MPa and 431 MPa, respectively). However an exception has been observed in case of 45 to RD of RR sample where moderate YS value (442 MPa) has been obtained with a lower Taylor factor (∼3.015).

### 3.2.3. Plastic anisotropy

Table 2 shows the values of \( \bar{R} \) and \( \Delta R \) obtained from the tensile tests. One important effect of these parameters is observed during the deep drawing of sheet metals. For higher deep draw-ability \( \bar{R} \) value close to one and \( \Delta R \) value close to zero is preferred. A higher \( \bar{R} \) indicates high resistance to thinning. This will be helpful in reducing the formation of local deformation and hence necking during deep drawing. Similarly, \( \Delta R \) value close to zero indicates that the material is more isotropic and this will reduce the chance of ear formation in deep drawing process. In the present case, for both the parameters, cross rolled sample shows higher values. The change in RD increases the \( \bar{R} \) value to 0.85. Similarly, \( \Delta R \) becomes much closer to zero (∼0.069). In short, CR produces material with lesser anisotropy.

### 4. Conclusions

Hot rolling of 304 austenitic stainless steel have been done with two different mode. Effect of change in RD on microstructure and texture have been studied through EBSD. In addition the tensile properties of the rolled
material, along three different directions, were also studied. The effect of texture on the anisotropy behavior of tensile properties were analyzed. The above work can be summarized as follows:

i. The effect of change in RD is observed on the final texture of the rolled samples. Development of strong Cu and S component leads to the formation of a strong $\gamma$ fiber in RR sample. On the other hand formation of strong rotated Bass texture results in development of strong $\alpha$ fiber CR sample. In addition, as compared to RR, CR develops moderate Cube component.

ii. Activation of higher number of slip system leads to higher elongation in the direction of RD and 45 to RD for samples rolled by RR and CR, respectively.

iii. Higher Taylor factor causes higher YS value along TD and RD for samples rolled by RR and CR, respectively.

iv. With the present processing conditions plastic anisotropy improves with the change in RD for the considered 304 stainless steel material.

Acknowledgments

The author acknowledges the facilities provided by Indian Institute of Technology Kharagpur to carry out the above research work.

ORCID iDs

Matruprasad Rout @ https://orcid.org/0000-0002-4111-7075

References

[1] Chowdhury S G, Das S and De P K 2005 Cold rolling behaviour and textural evolution in AISI 316L austenitic stainless steel Acta Mater. 53 3951–9
[2] Fang X, Zhang K, Guo H, Wang W and Zhou B 2008 Twin-induced grain boundary engineering in 304 stainless steel Mater. Sci. Eng. A 487 7–13
[3] Singh C D, Ramaswarny V and Suryanarayana C 1991 Texture evolution in a hot rolled austenitic stainless steel Textures Microstruct. 13 227–41
[4] Sakai B T, Saito Y and Kato K 1987 Recrystallization and texture formation in high speed hot rolling of austenitic stainless steel Trans. Iron Steel Inst. Japan 27 520–5
[5] Raabe D 1995 Inhomogeneity of the crystallographic texture in a hot-rolled austenitic stainless steel J. Mater. Sci. 30 47–52
[6] Jeong W C 2008 Effect of hot-rolling temperature on microstructure and texture of an ultra-low carbon Ti-interstitial-free steel Mater. Lett. 62 91–4
[7] Hu H and Cline R S 1988 On the mechanism of texture transition in face centered cubic metals Textures Microstruct. 8 191–206
[8] Raabe D 1997 Texture and microstructure evolution during cold rolling of a strip cast and of a hot rolled austenitic stainless steel Acta Mater. 45 1137–51
[9] Chowdhury S G 2005 Development of texture during cold rolling in AA5182 alloy Scr. Mater. 52 99–105
[10] Ravi Kumar B, Singh A K, Das S and Bhattacharya D K 2004 Cold rolling texture in AISI 304 stainless steel Mater. Sci. Eng. A 364 132–9
[11] Morikawa T and Higashida K 2010 Deformation microstructure and texture in a cold-rolled austenitic steel with low stacking-fault energy Mater. Trans. 51 620–4
[12] Kurc-Lisiecka A, Ogowicz W, Ratuszek W and Chrusciel K 2012 Texture and structure evolution during cold rolling of austenitic stainless steel J. Achiev. Mater. Manuf. Eng 52 22–30
[13] Wasnik W N, Gopalakrishnan I K, Yakhmi J V, Kain V and Samajdar I 2003 Cold rolled texture and microstructure in types 304 and 316L austenitic steels ISIJ Int. 43 1581–9
[14] Nezakat M, Akhiani H, Hoseini M and Szpunar J 2014 Effect of thermo-mechanical processing on texture evolution in austenitic stainless steel 316L Mater. Charact. 98 10–7
[15] Xiong J, Chen Z, Yi L, Hu S, Chen T and Liu C 2014 Microstructure and mechanical properties of annealed Mg–0.6 wt% Zr sheets by unidirectional and cross rolling Mater. Sci. Eng. A 590 60–5
[16] Mondal C, Singh A K, Mukhopadhyay A K and Chattopadhyay K 2013 Tensile flow and work hardening behavior of hot cross-rolled AA7010 aluminum alloy sheets Mater. Sci. Eng. A 577 87–100
[17] Song J H, Hong K J, Ha T K and Jeong H T 2007 The effect of hot rolling condition on the anisotropy of mechanical properties in Ti-6Al-4V alloy Mater. Sci. Eng. A 449–451 144–4
[18] Esko A, Misra R D K, Talonen I and Karjalainen I P 2013 The influence of grain size on the strain-induced martensite formation in tensile straining of an austenitic 15Cr-9Mn-Ni-Cu stainless steel Mater. Sci. Eng. A 578 408–16
[19] Bak S H, Abro M A and Lee D B 2016 Effect of hydrogen and strain-induced martensite on mechanical properties of AISI 304 stainless steel Metals 6 1691–98
[20] Tang W, Huang S, Li D and Peng Y 2015 Mechanical anisotropy and deep drawing behaviors of AZ31 magnesium alloy sheets produced by unidirectional and cross rolling J. Mater. Process. Technol. 215 520–6
[21] Rout M, Pal S K and Singh S B 2015 Cross rolling: a metal forming process Modern Manufacturing Engineering, Materials Forming, Machining and Tribology ed J P Davim (Switzerland: Springer International Publishing) pp 41–64