Texture and microstructure evolution of 321 austenitic stainless steel ultra-thin strip during asynchronous rolling

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Abstract. This paper studied the evolution of texture and microstructure of 321 austenitic stainless steel ultra-thin strip during asynchronous rolling. Experimental results show that during the process of asynchronous rolling, the martensitic structure mainly forms such kinds of texture, as {111} <110> Z texture, {111} <112> Y texture, {001} <110> R-CubeND texture, {112} <110> Cu texture, and {110} <110> Goss texture. With the increase of deformation, the strengths of {111} <112> Y texture, {001} <110> R-CubeND texture, {112} <110> Cu texture, and {110} <110> Goss texture increase first and then decrease. In the early stage of rolling, dislocation slip is the main plastic deformation, followed by deformation twins in the high strain region, which prevents further dislocation slip. When the rolling pressure rate is greater than 50%, the deformation induces rapid growth in the content of the martensite, with the continued nucleation and growth of the deformation twins.

1. Introduction
Due to its good strength and toughness, resistance to high-temperature oxidation [1], high forming performance [2], good creep strength [3, 4] and good corrosion resistance [5], the stainless steel ultra-thin strip plays an important role in electronic products and various kinds of precision instruments and equipment. Many scholars have studied the mechanism of martensite transformation in austenitic stainless steel and its influencing factors.

The susceptibility of AISI 321 steel to the formation of adiabatic shear band increases with a decrease in grain size [6]. Ghazani [7] proposed a simple combined phenomenological method which can be used for precise prediction of the flow stress of AISI 321 steel during the occurrence of dynamic recrystallization.

The influence of factors including chemical elements, strain rate, stress state and deformation temperature on the transformation process of martensite was discussed. The microstructure and texture of austenitic stainless steel play a crucial role in the choice of material forming process and the performance of the final product. It is of great theoretical and engineering significance to study the microstructure and texture evolution of austenitic stainless steel during cold rolling.

In recent years, asymmetric rolling technology has aroused great interest of engineers in the field of metal material processing. The reason is that the magnitude of the normal force and productivity can be increased relatively simply during rolling. Fu et al. [8] produced nanograined TWIP steel with high strength-ductility via asymmetric cryorolling. The yield strength and ultimate tensile strength of the
TWIP steel increases, significantly. Mallick et al. [9] investigated the influence of deformation up to 40% by cold rolling and cryorolling processes on the properties of 304 austenitic stainless steel. They found that 40% cold rolling at 0 °C results in 936 MPa yield strength, 1225 MPa ultimate tensile strength, and 13% total elongation, while 20% deformation at −196 °C leads to 1463 MPa yield strength, 1589 MPa ultimate tensile strength, and 9% total elongation. These extraordinary results were owing to increasing the volume fraction of strain-induced martensite. While many researches focused on the technical aspects of the augmented reality process, and some features of the process still poorly understood.

The anisotropy of ultrathin strip closely relates to microstructure and crystal texture. This study involves the evolution of the crystal structure and texture of the 321 stainless steel extremely thin strip formed during the AR process.

2. Experimental procedure
The chemical composition of 321 stainless steel is show in Table 1. The material with the initial thickness of 100 μm was subjected to asymmetric rolling to a final thickness of 65 μm, 40 μm and 20 μm with a thickness reduction of 35%, 60%, and 80%. The macroscopic texture was measured in a Schulz back reflection method on a semiautomatic texture measuring table by X Pert Pro X ray diffraction (PANalytical B.V., Almelo, The Netherlands) at 35 kV. The transmission electron microscope (TEM) study was carried out using a Tecnai G220 (FEI Technologies Inc., Hillsboro, OR, USA) at 200 kV.

| Table 1. Chemical composition of 321 stainless steel | wt% |
|-----------------------------------------------|-----|
| C                                            | 0.045 |
| Cr                                           | 18.4 |
| Ni                                           | 10.1 |
| Si                                           | 0.611 |
| Mn                                           | 1.49 |
| S                                            | 0.014 |
| P                                            | 0.027 |
| Ti                                           | 0.156 |
| Fe                                           | Bal. |

3. Results and discussion

3.1. Texture evolution
In order to study the process of transformation of metastable austenite to martensite in 321 stainless steel during asynchronous rolling, martensite texture testing was performed on samples with different reduction. Figure 1 presents ODF diagram of martensite texture of cold-rolled samples of different reduction. As shown in Figure 1a, the texture in the raw material is mainly the annealing texture left in the previous process, which is mainly composed of the following types, such as {001} <100> Cube, {110} <112> Brass, {110} <111> Goss, {123} <634> S, and {112} <110> R-Cu. In the process of strain-induced martensite, the martensitic structure mainly formed {111} <110> Z texture, {111} <112> Y texture, {001} <110> R-CubeND texture, {112} <110> Cu texture, and {110} <110> Goss texture.

Figure 2 shows the martensite texture γ-orientation lines and α-orientation lines of samples with different reduction. As the reduction ratio increases from 35% to 80%, the {111}-Z texture gradually increases with the increase of rolling reduction. While the {111} <112> Y texture appears to decrease first and then increase as reduction increases. As the {112} <110> Cu texture increases, the orientation strength increases first and then decreases. The orientation of {112} <110> Cu is unstable, and it rotates to the Goss orientation through a plastic deformation mechanism. With the increase of the reduction, it was found that {110} <110> increased first and then decreased. As a whole, there are two main reasons for the texture enhancement in the <110> direction: one is the rolling texture of the body-centered cubic martensite rotates to <110> direction during rolling; and the other is the K-S orientation relationship is inherited from the original austenite tissue.
3. Microstructure evaluation

Figure 3, 4 and 5 are the microstructures of cold rolled samples at 35%, 60% and 80% reductions, respectively. As shown in Figure 3a and 3b, at the reduction rate of 35%, deformation twins began to appear in the experimental steel. When the amount of deformation is small, the plastic deformation of austenitic stainless steel is mainly achieved by the dislocation slip. As seen in Figure 3c that a wide lath martensite structure has appeared. The newly generated lath martensite separates the...
untransformed austenite, and due to the obstacle effect of the martensite boundary on the dislocation movement, many dislocations accumulated in the lath martensite. As can be seen in Figure 3d, the deformed twins form nucleate inside the austenite grains and grow further into wider deformed twins. At the same time, a number of dislocations gathered at the austenite grain boundaries. These dislocations continue to intertwine to generate dislocation boundaries or subgrain boundaries, and gradually refine the untransformed austenite grains. J.E. Wittig [10] and others studied the effect of deformation temperature on the deformation mechanism of austenitic stainless steel and found that at room temperature, dislocation slip in austenite undertook most of the deformation, except for the TRIP mechanism. Although the contribution of mechanical twins to total deformation was small at room temperature, some deformation-induced twins could still be observed.

Figure 3. Microstructure of cold-rolled specimen with reduction of 35%. (a) deformed twins, (b) lath martensite, (c) wider lath martensite with a large number of dislocations and (d) deformed twins in the austenite grains.

When the reduction increased to 60%, more lath martensite formed in the experimental steel and the size and distribution are more uniform, as shown in Figure 4a and Figure 4c. At this time, the TWIP effect still plays a role in the plastic deformation of the experimental steel. As shown in Figure 4b, a large number of deformation twins still exist in the microstructure of the experimental steel. During the further nucleation and growth of the deformed twins, twin or sub-grain boundaries continuously formed, and the untransformed austenite grains are continuously refined. During this process, the grain boundary density is greatly increased. By continuously refining the grains, the strength of the experimental steel is continuously improved. In the untransformed austenite grains, as shown in Figure 4d, due to the obstruction of dislocations at the grain boundaries, dislocations entangled inside the untransformed austenite grains, making the dislocation density of austenite grains greatly increased, which further intensifies the process of hardening.

With the rolling process, when the reduction ratio is increased to 80%, as shown in Figure 5a, as the reduction ratio increases, dislocations accumulated inside the lath martensite, which further improves the its strength. At the same time, as seen in Figure 5c and Figure 5d that the newly generated narrower lath martensite has a lower dislocation density. While the lath martensite separates the untransformed austenite, untransformed austenite internal dislocations constantly tangled during
the deformation process, and a large number of dislocations can be observed in the lath martensite spacing. Due to the obstruction of the lath martensite boundary, it forms high dislocation density regions at the lath martensite spacing. Within these regions, further tangle of dislocations gradually form dislocation cell-like structure.

Figure 4. Microstructure of cold-rolled specimen with reduction of 65%. (a) lath martensite, (b) deformed twins, (c) even distribution of lath martensite and (d) austenite grains with high dislocation density.

Figure 5. Microstructure of cold-rolled specimen with reduction of 80%. (a) lath martensite and deformed twins, (b) dislocation cell, (c) lath martensite and (d) high dislocation density microstructure.
In the process of cold deformation, shear bands composed of slip bands or deformed twins were formed first, and then the deformation-induced martensite starts to nucleate at the shear band crossing. With the increase of cold rolling reduction, martensite nucleates on shear bands and gradually replaced the position of the shear zone, which eventually caused shear bands to disappear. At the same time, with the increase of the amount of cold rolling reduction, the generated martensite lath was crushed and twisted and mixed with unconverted austenite to form dislocation cell martensite. Compared with deformation-induced martensite, this martensite had a higher dislocation density and is stronger than lath martensite.

4. Conclusions
(1) In the asynchronous rolling of 321 stainless steel strip, the martensitic structure mainly formed \{111\} <110> Z texture, \{111\} <112> Y texture, \{001\} <110> R-CubeND texture, \{112\} <110> Cu texture, and \{110\} <110> Goss texture;
(2) As a whole, there are two main reasons for the texture enhancement in the <110> direction: one is the rolling texture of the body-centered cubic martensite rotates to <110> direction during rolling; and the other is the K-S orientation relationship is inherited from the original austenite tissue;
(3) In the initial stage of asynchronous rolling, the plastic deformation mechanism of 321 stainless steel is mainly dislocation slip. When the reduction ratio is greater than 50%, the plastic deformation is mainly deformation-induced martensite.

Reference
[1] Ohmi T, Nakagawa Y, Nakamura M 1996 Formation of chromium oxide on 316L austenitic stainless steel Journal of Vacuum Science and Technology A 14 2505
[2] Gonzalez BM, Castro CSB, Buono VTL 2003 The influence of copper addition on the formability of AISI 304 stainless steel Materials Science and Engineering: A 343 51
[3] Yamamoto Y, Brady MP, Santella ML 2011 Overview of strategies for high-temperature creep and oxidation resistance of alumina-forming austenitic stainless steels Metallurgical And Materials Transactions A-Physical Metallurgy And Materials Science 42 922
[4] Laha K, Kyono J, Sasaki T 2005 Improved creep strength and creep ductility of type 347 austenitic stainless steel through the self-healing effect of boron for creep cavitation Metallurgical and Materials Transactions A 36 399
[5] Pardo A, Merino MC, Coy AE 2008 Effect of Mo and Mn additions on the corrosion behaviour of AISI 304 and 316 stainless steels in H2SO4 Corrosion Science 50 794
[6] Tiamiyu AA, Szpunar JA, Odeshi AG 2019 Strain rate sensitivity and activation volume of AISI 321 stainless steel under dynamic impact loading: Grain size effect Materials Characterization 154 7
[7] Ghazani MS, Eghbali B 2019 Modeling the flow behavior of AISI 321 austenitic stainless steel using a simple combined phenomenological method Mechanics of Materials 137 103
[8] B Fu, L Fu, S Liu, H R Wang, W Wang, A Shan 2018 High strength-ductility nanostructured high manganese steel produced by cryogenic asymmetry-rolling Journal of Materials Science Technology 34 695
[9] P Mallick, N K Tewary, S K Ghosh, P P Chattopadhyay 2017 Effect of cryogenic deformation on microstructure and mechanical properties of 304 austenitic stainless steel Materials Characterization 133 77
[10] Wittig JE, Pozuelo M, Jiménez JA 2010 Temperature dependent deformation mechanisms of a high nitrogen-manganese austenitic stainless steel Steel Research International 80 66