Advances in the Optimization of Thin Strip Cast Austenitic 304 Stainless Steel

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This study is about the latest advances in the optimization of the microstructure and properties of thin strip cast austenitic stainless steel (AISI 304, 1.4301). Concerning the processing steps the relevance of different thin strip casting parameters, in-line forming operations, and heat treatments for optimizing microstructure and properties have been studied. The microstructures obtained from the different processing strategies were analysed with respect to phase and grain structures including the grain boundary character distributions via EBSD microtexture measurements, the evolution of deformation-induced martensite, the relationship between delta ferrite and martensite formation in austenite, and the texture evolution during in-line deformation. It is observed that different process parameters lead to markedly different microstructures and profound differences in strip homogeneity. It is demonstrated that the properties of strip cast and in-line hot rolled austenitic stainless steels are competitive to those obtained by conventional continuous casting and hot rolling. This means that the thin strip casting technique is not only competitive to conventional routes with respect to the properties of the material but also represents the most environmentally friendly, flexible, energy-saving, and modern industrial technique to produce stainless steel strips.

Keywords: Austenitic stainless steel, ecological processing, energy-saving, 304, 4301, thin strip casting, martensite, deformation, dendrite, delta ferrite, hot rolling, twin roll strip casting, recrystallization, texture.

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Introduction

Stainless steel strips are conventionally manufactured by continuous casting, slab reheating, hot rolling, hot strip annealing, and pickling.

Thin strip steel casters offer a competitive efficient alternative to industrially produce such steels when compared to the conventional thick-slab production lines. Today's advanced twin roll thin strip casters for the production of stainless steels combine the two operations of casting liquid metal between two rolls and subsequently imposing in-line hot deformation steps to produce hot rolled thin strips that are directly coilable [1-5] (**Figure 1**). Twin roll thin strip casting of steels thus eliminates major steps required in conventional production, for instance slab handling, slab reheating, hot strip roughening / break-down reversing rolling, and hot rolling in a conventional hot rolling mill (set of 5-7 four-high stands) (**Figure 2**). Both thin strip cast material and conventionally produced hot strips can be further cold rolled and recrystallization annealed, depending on the desired final thickness and properties.

Thin strip casting of stainless austenitic steel (AISI 304 / 1.4301 in this work) provides a number of significant advantages in comparison to the conventional slab processing method. First, the thin strip casting method permits the entire continuous conventional hot rolling process to be bypassed. The thin strip casting method is even capable of producing strips with a smaller thickness than conventional production routes. At the same time it allows one to produce steel strips which are difficult to be cast or hot rolled by conventional methods, such as for instance some complex highly alloyed austenitic grades. Second, it offers a significantly higher solidification rate, which leads to microstructures with reduced dendrite arm spacing, reduced microsegregation, and smaller inclusion sizes when compared to conventional slabs. Third, the thin strip route allows exploiting higher and locally different heat fluxes which may lead to alternative solidification modes with respect to the primary γ / δ phase ratio close to

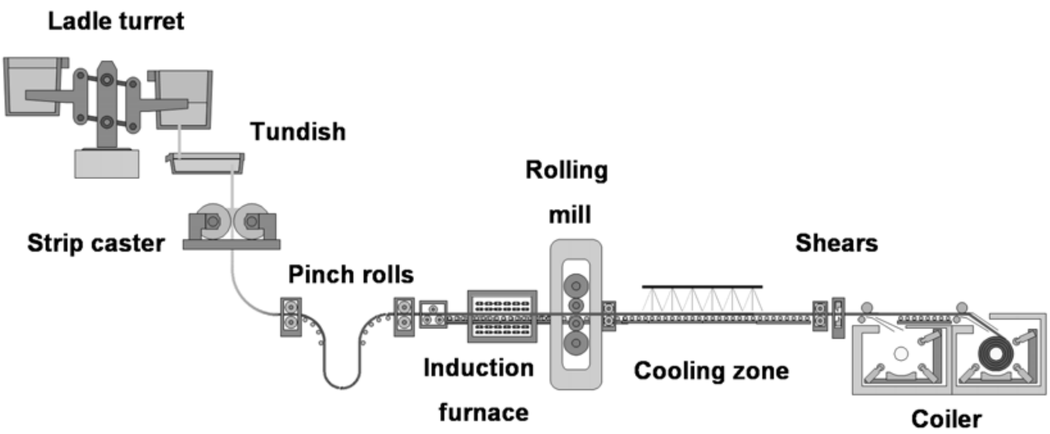

Figure 1. Schematic presentation of the thin strip casting plant of ThyssenKrupp Nirosta in Krefeld, Germany, which was used in this work.

	Slab casting	Thin strip casting
Casting speed (m/min)	0,9 - 2,2	40 -100
Solidification rate (mm/s)	0,1	5
Heat flux density (MW/m²)	1,0 - 2,5	5 -14
Solidification time (s)	10³	<0,5
Solidification structure (AISI 304)		

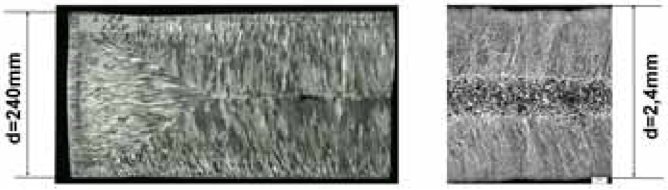

Figure 2. Most relevant process parameters of the thin strip casting route compared to the conventional hot strip route.

the strip of the surface. Fourth, the weak crystallographic texture and low through-thickness texture gradients of strip cast steels, which predetermine the forming properties and strength of the final strip, result in reduced anisotropy when compared to conventional hot strip material [6-13].

Fifth, the microstructure and properties of strip cast austenitic 304 stainless steels are equivalent to those obtained by conventional processing. Also, strip cast austenitic stainless steels often reveal a more homogeneous microstructure through the strip thickness than conventional hot rolled material. This means that the scatter in the mechanical properties may be even lower than in the case of conventionally produced stainless steels that are known to reveal through-thickness gradients of their texture and microstructure [14-19]. Finally, the strip casting route is the most environmentally friendly, energy saving, and CO_2-sensitive way to produce steel strips.

In this study we present the latest advances in the optimization of the microstructure and properties of strip cast austenitic stainless steels (AISI 304, 1.4301). We discuss in part the influence of some of the relevant process parameters (e.g. coiling temperature, in-line hot rolling temperature, lubrication, in-line rolling speed, heat treatments) for optimizing the microstructure and properties of the final strips.

Experimental

We investigated austenitic stainless steel with commercial analysis (~18 wt.% Cr and ~8.5 wt.% Ni according to AISI 304, 1.4301). The strips were cast on an industrial twin roll thin strip caster at the ThyssenKrupp Nirosta stainless steel plant in Krefeld, Germany (Figure 1).

The method consists of casting liquid steel into a preheated tundish, where the liquid steel contacs two rotating rolls which have symmetrical position and size. The steel solidifies as thin film on the roll surfaces. In the gap the films impinge and are compressed to a strip. The thickness of the thin strip samples typically lies between 1.5 and 3.5 mm. Subsequent deformation steps were conducted using a single in-line hot rolling stand (Figure 1).

Specimens for microstructure characterization were cut as longitudinal sections for metallography, HR-SEM (high resolution scanning electron microscopy), EDX (energy dispersive X-ray spectrometry), and HR-EBSD (high resolution electron back scatter diffraction). The measurements were conducted on a JSM-6500F field emission scanning electron microscope at an accelerating voltage of 15kV and an emission current of around 100nA. Crystallographic orientation mappings were taken using step sizes of 50nm-500nm, depending on the resolution desired. The EBSD data were used to determine crystallographic texture, interface character, crystal size distribution, and area fractions of the coexisting phases. Details on the EBSD technique are given in [20-23].

Results and Discussion

As-cast thin strip microstructure. The longitudinal section of an as-cast sample, analysed by optical metallography, reveals a microstructure which consists of uniformly oriented blocks of austenitic dendrites, see **Figure 3**. The primary dendrite extension along the normal direction is in part up to 1 mm. In the surface region (~100μm from the surface) of the thin cast strips the microstructure is finer than below this zone. This observation indicates that growth selection takes place at the beginning of the solidification process.

Figure 4 shows a magnified part of a longitudinal section of an as-cast thin strip specimen as measured by

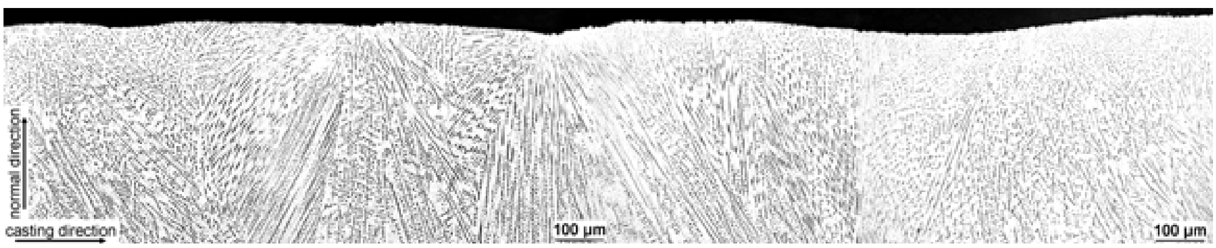

Figure 3. Longitudinal section of an as-cast 304 stainless steel sample, analyzed by optical metallography.

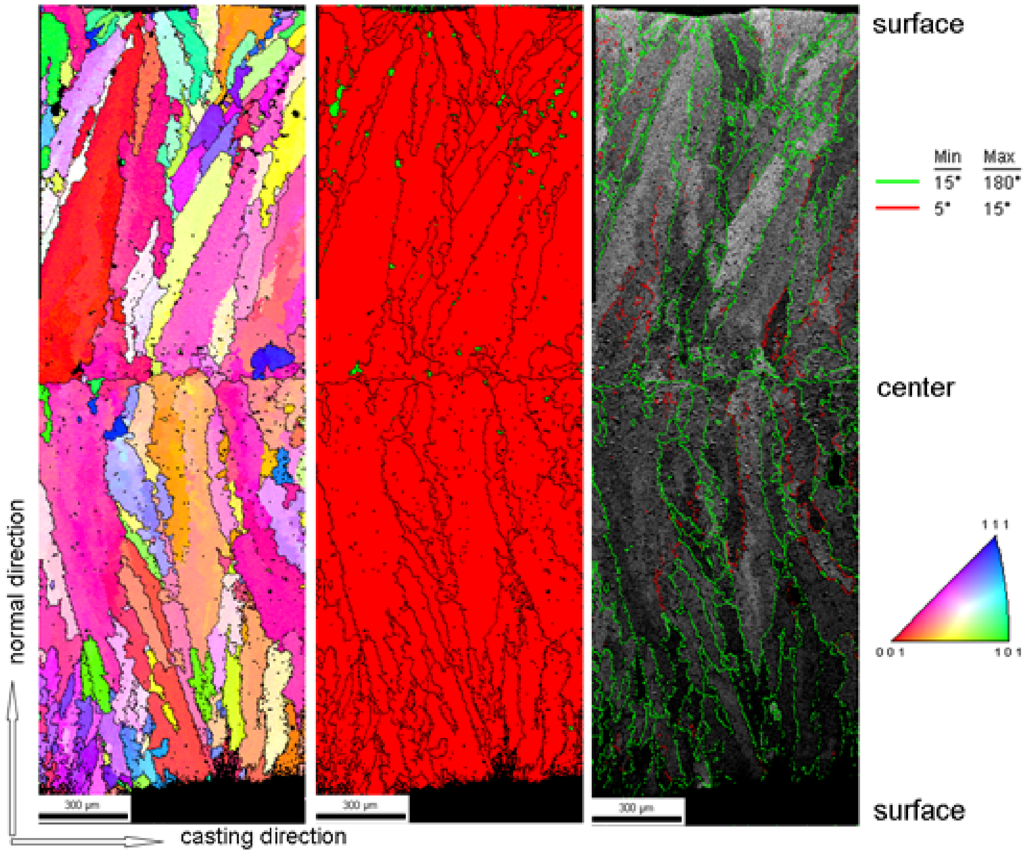

Figure 4. Longitudinal section of an as-cast thin strip specimen as measured by HR-EBSD. Left: crystal orientations in terms of their respective Miller index, {hkl}, parallel to the strip surface; Centre: distribution of the two main phases, namely of the γ austentic face centered cubic (FCC) majority phase and the finely dispersed body centered cubic (BCC) δ minority phase. Right: distribution of the grain boundary character in the same metallographic section.

HR-EBSD. The first image (left hand side) indicates the crystals in terms of their respective Miller index, {hkl}, parallel to the strip surface. The texture reveals a slightly inclined weak orientation fibre close to {001}<uvw> [8,9,11,24]. It must be noted though that the HR-EBSD data set presented in Figure 4 does not display a statistical texture analysis. Previous work on thin strip steel textures that was conducted using X-ray Bragg diffraction methods [6-12,24] had shown before the occurrence of a weak {001}<uvw> fibre texture. The deviation from an exact {001}<uvw> fibre texture can be attributed to the shape inclination of the grains. The EBSD data also reveal, as qualitatively observed already in Figure 3, that the region close to the surface of the as-cast material consists of smaller grains than the regions below, indicating growth selection. Also, differences in the ratio between the δ and the γ phase content and in the dispersion of the δ phase between the surface and centre layer regions may play a role for the observed differences in the crystal size and morphology.

The image in the middle of Figure 4 reveals the distribution of the two main phases, namely of the γ austenitic face centered cubic (FCC) majority phase and the finely dispersed body centered cubic (BCC) δ minority phase. The image on the right hand side of Figure 4 shows the distribution of the grain boundary character in the same metallographic section. The figure elucidates that most of the interfaces are high angle grain boundaries.

Microstructure after in-line hot rolling and recrystallization annealing. The investigation of the in-line hot deformation parameters imposed after casting is essential for the optimization of the microstructure and the resulting mechanical properties of the final strip. **Figure 5** shows the microstructure as obtained from HR-EBSD measurements, taken in longitudinal sections, for three different in-line hot rolling strategies. The image at the bottom below these three microstructures shows a magnified part of the grain structure of the sample on the right hand side.

All hot rolling processes were conducted on an industrial in-line mill (cf. Figure 1). The left hand side of Figure 5a shows a microstructure with only weak shape changes of the grains after hot rolling. Recrystallization cannot be observed. Figure 5b exhibits larger shape distortions of the grains. Close to the bottom of the micrograph some recrystallization can be found. The micrograph in Figure 5c also shows distorted grain shapes which indicate strong shear deformation particularly close to the surface. It is important to note that this sample reveals a larger volume fraction of finely recrystallized material, particularly close to the surface portion where the accumulated plastic strain is usually larger than in the centre regions.

Figure 6 shows the microstructure of three mappings obtained from HR-EBSD measurements (longitudinal sections). The micrograph on the left hand side is a conventionally produced hot strip. The other two micrographs show

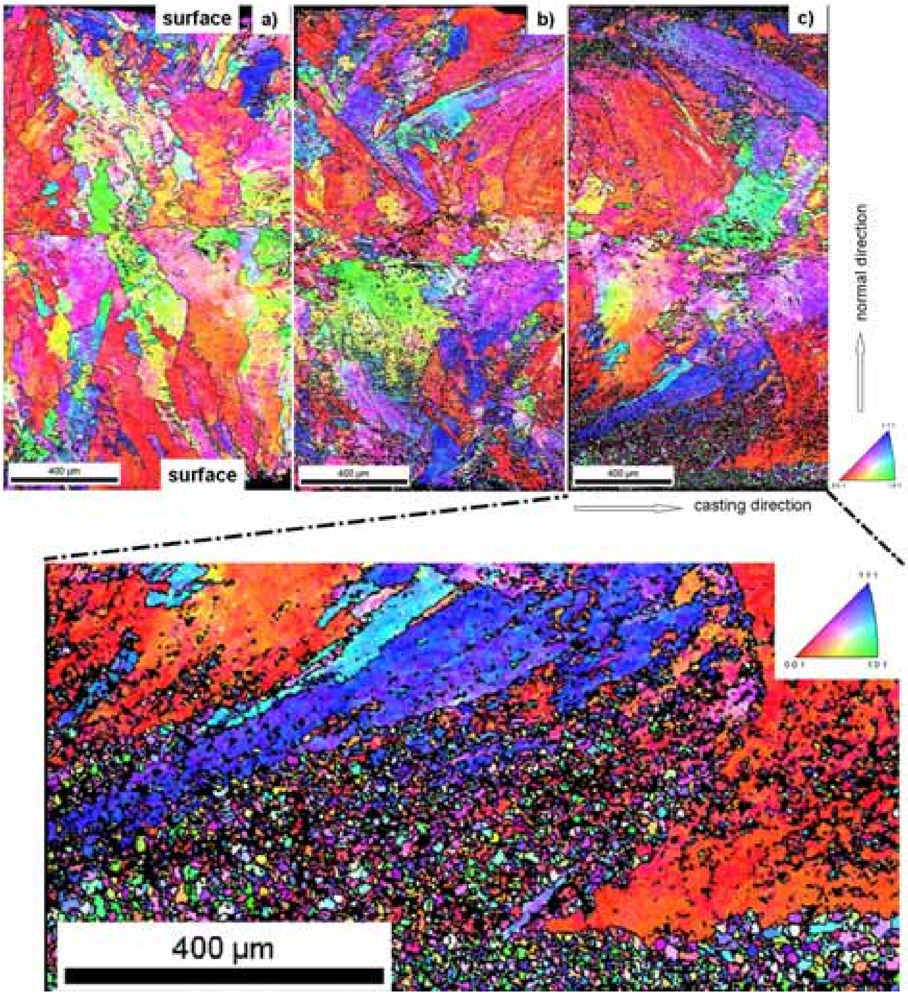

Figure 5. Microstructure mapping obtained from HR-EBSD measurements (longitudinal sections) for three different in-line hot rolling strategies. The bottom figure is a magnification revealing recrystallization. The colour code indicates the crystallographic direction which is parallel to the surface in terms of Miller indices {hkl}.

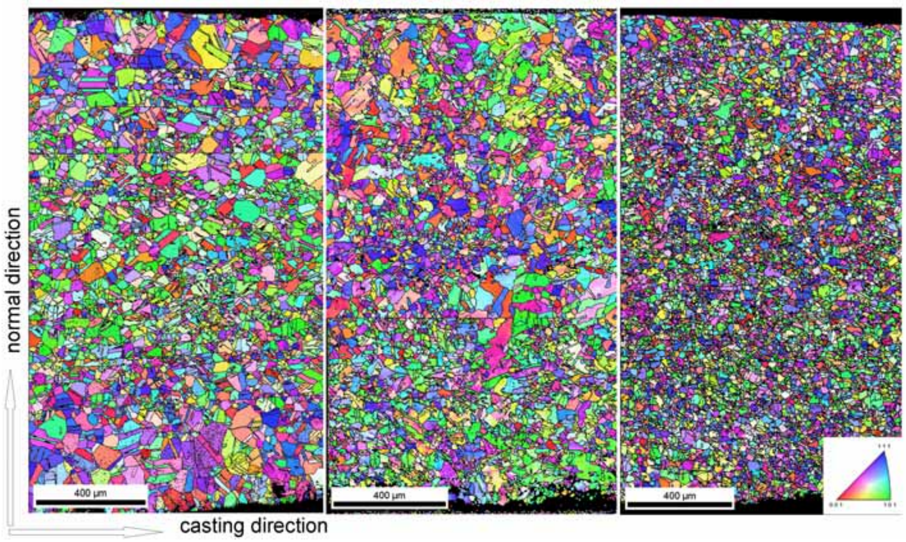

Figure 6. Microstructure mapping and grain size distribution obtained from HR-EBSD measurements (longitudinal sections) for a 304 sample produced via the conventional hot strip route (left) and two 304 thin strip samples after different in-line hot rolling and subsequent recrystallization treatment (centre and right). The colour code indicates the crystallographic direction which is parallel to the surface in terms of Miller indices {hkl}.

microstructures obtained form two different in-line hot rolled strips after final recrystallization treat-ment. The EBSD maps show a fine and homogeneously dis-tributed grain size for the two heat treated thin cast and in-line rolled strips. The strip cast material is characterized by a very homogeneous micro-structure through the strip thick-ness which suggests that the mechanical properties show only small scatter.

Conventionally cast and subsequently hot rolled speci-mens, in contrast, typically reveal stronger microstructure gradients between the near-surface and the centre layer regions owing to the large shears imposed during conventional hot rolling [15-19,24]. Moreover, the crystallographic textures are similar in the near surface and centre layer regions for the thin cast strips. This fact also indicates a relatively homo-geneous deformation history when compared to conven-tionally hot rolled material.

Mechanical properties of cast, hot rolled, recrystallized strips. Figure 7 shows the mechanical properties of two samples of a strip after thin strip casting, hot rolling and recrystallization. Two samples from different positions were taken to probe the heterogeneity of the material with respect to the stress-strain behaviour. The EBSD maps show the corresponding distribu-tion of the δ-phase plus the deformation-induced α' marten-site (bright) and of the austentite (dark) for the two samples. The δ-phase has BCC crystal structure and the deformation induced α' martensite has slightly tetragonal near BCC structure. This means that both phases can jointly be differen-tiated from the FCC austenite. The volume increase of the deformation induced α' mar-tensite upon plastic straining is a well known phenomenon in these steels [8]. It is related to the low thermodynamic stability of the austenitic phase in this steel grade. Deformation also leads to a very small volume fraction of the deformation induced hexagonal ε phase, but the α' martensite is generally the dominant deformation induced transformation phase. Depending on the thermodynamic and microstructure details such as the Cr/Ni equivalent ratio and the grain size, up to 45 vol.% deformation induced α' martensite can be formed in these steels. The exact location, arrangement and volume fraction of the α' martensite is of relevance for the forming properties. Among the different methods of quantifying the α' phase (magnetism, metallography, hardness, EBSD) the EBSD method is considered the most reliable one.

The mechanical properties presented in Figure 7 are comparable to those obtained for samples that are manufactured via the conventional continuous casting and hot rolling route.

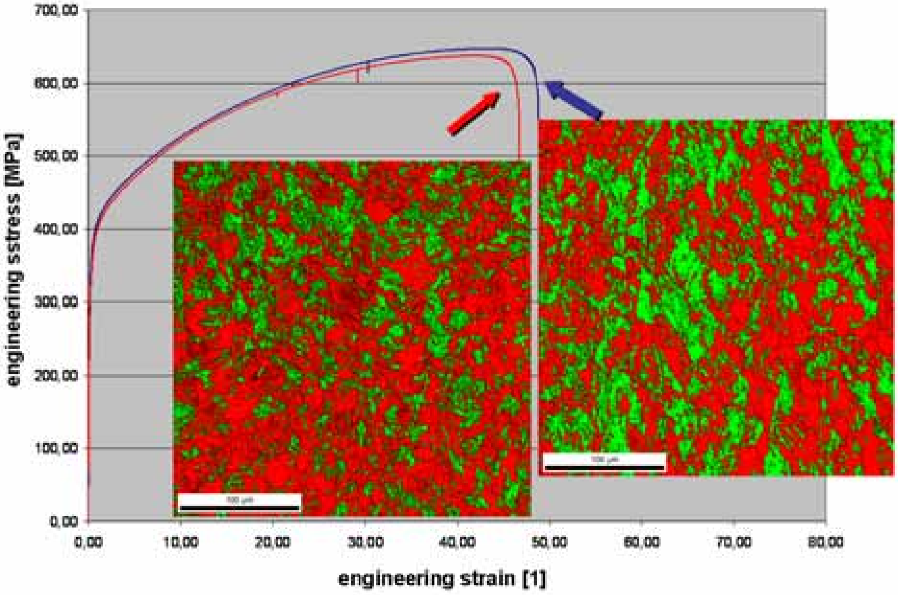

Figure 7. Stress-strain curves of two samples of a thin strip cast, hot rolled, and recrystallized strip. Two samples from different regions were taken to probe the homogeneity of the material. The EBSD maps show the corresponding distribution of the delta-phase plus the deformation-induced α' martensite (bright) and of the austentite (dark) for the two samples.

Conclusions

This paper presents recent advances in the optimization of the microstructure and properties of thin strip cast austenitic (AISI 304, 1.4301) stainless steel. The main conclusions are:

Austenitic 304 stainless steels can be produced by thin strip casting, in-line hot rolling, and subsequent heat treatment with equivalent mechanical properties and even better microstructure homogeneity than steels produced by the conventional thick slab processing route.

The formation of deformation induced α' martensite in austenitic stainless steels produced by the thin strip casting route is similar as in conventionally produced 304 steels.

Precise characterization of the different phases, interfaces, and crystallographic textures can be conducted by using a high resolution EBSD method.

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