Forming behaviour of stainless steel sheets at different material thicknesses

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Abstract. The austenitic stainless steel X5CrNiMo17-12-2 in thickness ranging from 0.2 mm to 1.0 mm was examined in regard to the mechanical properties and microstructure. The aim was to investigate the suitability of conventional test methods for thin material down to 0.2 mm. Within these investigations, all used thicknesses were characterized by conventional tensile tests and X-ray diffraction. The results were subsequently compared with each other. The material specific vertical anisotropy $r$ and forming limit curve showed a strong dependence on material thicknesses. The results of anisotropy pointed out different values depending on the test methods performed. In addition, the results of microstructure analysis show a decrease of grain size with lower material thickness caused by the formation of twins and probably heat treatments during the manufacturing process.

1. Introduction

Due to further discussions about lowering pollutant emission, new power unit systems are prioritized, because of global warming and shortage of fossil fuels. Especially the automotive industry drives for greener and lower-carbon energy industry. Therefore, increasing of knowledge regarding forming behavior of thin materials as presented in this paper becomes more important.

Basically during plastic deformation accruing dislocations and the increase of the number of grain boundaries result in smaller grain sizes. This material behavior implicates a higher strain hardening, since the dislocations block each other, and the individual atomic planes can no longer slide freely [1,2]. Through dislocation sliding the strength of the material can be reduced.

This work deals with the material characterization of stainless-steel material X5CrNiMo17-12-2 in thicknesses of 0.2 mm, 0.3 mm and 1.0 mm to determine the impact of thickness on material properties. The forming behavior is examined by forming limit diagram.

In addition, the structure of the material is analyzed to investigate the physical mechanisms. The applied material with a face-centered cubic structure shows formation of mechanical twins based on forming process [3]. Mechanical twinning occurs as a result of a compensation of stress in crystal lattices during plastic deformation. The mechanical twinning is characterized by the stacking fault energy which must be defeated by a crystal system. It also leads to smaller grain sizes and reduces the distortion in the crystal structure, allowing further plastic deformation [4-7].
2. Experimental methods
The material characterization of austenitic stainless steel X5CrNiMo17-12-2 was determined at the different material thicknesses of 0.2 mm, 0.3 mm and 1.0 mm.

2.1. Material
The material composition is shown in table 1.

|Composition of X5CrNiMo17-12-2.|
|Fe [wt%] | Cr [wt%] | Mn [wt%] | Ni [wt%] | Co [wt%] | C [wt%] |
|---|---|---|---|---|---|
|68,6 | 16,8 | 1,2 | 10,5 | 0,15 | 0,05 |

The material was hot rolled by the supplier from an initial thickness of 3.5 mm. Final thicknesses are reached by several cold rolling steps with a degree of deformation up to 86% [8]. There is no further information about the different rolling steps or probably heat treatments which have taken place between the individual rolling steps.

For microstructural investigations embedded specimens were etched after grinding and polishing with a V2A acid at 50°C. This enables the activation energy for chemical decomposition to be achieved. The etching time is 3 to 5 minutes and varies depending on the material thickness of the specimen. The V2A acid allows etching of stainless steel material homogeneously.

2.2. X-ray Diffraction
The texture of the stainless steel X5CrNiMo17-12-2 was examined by X-ray-diffraction. The angles of the diffraction peaks for particular specimen orientations were analyzed by theta-2-theta scans. Further measurements in smaller angular steps in the range of diffraction angles are carried out to determine orientations of individual crystallites, called polfigures. The polfigures of each material thickness were examined namely the reflections (100), (110) and (111). The orientation distribution function (ODF) was calculated using a series expansion, which allows to the calculation of texture and vertical anisotropy r [9].

2.3. Tensile Test
In tensile tests the deformation of the material was examined according to DIN EN ISO 6892-1:2009-12 with a loading cell of 100kN by using DIN 50125:2009-07 flat specimens with a gauge length of 50mm. The specimens were deformed with 0.0025 s⁻¹. The tensile strength and the fracture strain were determined by the stress-strain diagram. Furthermore, the vertical anisotropy r has been investigated by the tensile test to compare the results with other test methods. Therefore, the specimens have been coated with a stochastic pattern. This pattern allows to record the flow curve with the optical 3D digital image correlation (DIC) system ARAMIS from GOM GmbH, which is coupled with the tensile testing machine. With a frequency of 5Hz the DIC system measures the deformation of the pattern, which expands with the specimen. The strain values were determined with a subset distance of 16 pixel, corresponding to a reference length of 1.2 mm. The DIC system calculates the vertical anisotropy from the last measured strain state before fracture of specimen.

2.4. Nakajima Test
For investigation of forming limit behavior of steel, the forming test was carried out according to DIN EN ISO 12004-2 using the Nakajima test method. The material is clamped by a blank holder and was deformed with a hemispherical punch. Figure 1 shows the schematic experimental setup.
During the forming process, two shims made of a high-strength material were placed above and below the specimen, which is different to the conventional Nakajima test method. This optimization protects the specimen surface to prevent perforation of the specimen material and was already described in the work of Bade et al, who simulated deformation of low material thickness shims between material, blank holder and die [10]. The specimen width varies to be able to determine the forming limit curve according to DIN EN ISO 12004-2 and has been modified based on investigations by Hasek [11-14]. Thereby the specimen widths were 40 mm, 120 mm and 200 mm [7].

To determine the forming limit curve of the different material thicknesses, the optical 3D DIC system ARAMIS from GOM GmbH was used. Therefore, the specimens were coated with a stochastic pattern similar to the tensile test. This pattern enables the measuring of the strain with the DIC system, which is coupled to the testing machine. With a frequency of 15 Hz the DIC system measures the deformation of the pattern, which expands with the specimen. The strain values were determined with a subset distance of 16 pixel, corresponding to a reference length of 1.2 mm. The deformation of the specimen concurrently deforms the stochastic pattern whereby the major and minor strain can be calculated according to DIN EN ISO 12004-2 to construct the forming limit curve.

3. Experimental methods

In this work the mentioned methods were compared to investigate the suitability of the tensile test for low material thicknesses.

3.1. Microstructure Analysis

The results of the microstructural analysis for the different material thicknesses of X5CrNiMo17-12-2 are shown below. Figure 2 shows cross section analysis at 0° to rolling direction.

![Figure 1. Schematic experimental setup of optimized Nakajima test.](image)

![Figure 2. Microstructure analysis of stainless steel X5CrNiMo17-12-2.](image)
The different material thicknesses show a microstructure of different grain sizes and no clearly deformed grains can be recognized, which could indicate a preferred direction of the material. In addition, a high number of twin boundaries were indicated by etching process. This is particularly desirable because twin boundaries affect the grain size which is relevant for the forming process [1,2]. By decreasing the material thickness a decreased number of grains can be observed along sheet thickness. The average grain size was determined by orientation angles of the individual crystallites. The grains are reconstructed and their size is calculated by an evaluation software. Table 2 shows the determined average grain size in material thicknesses and the resulting average grain number in thickness direction.

| $d$ [mm] | average grain size $[\mu m^2]$ | average grain number [unit/$\mu m$] |
|---------|-------------------------------|----------------------------------|
| 0.2     | $14.3 \pm 5.7$                | approx. 17                       |
| 0.3     | $20.3 \pm 6.5$                | approx. 24                       |
| 1.0     | $28.6 \pm 6.6$                | approx. 70                       |

In the microstructure of each material thickness a high number of mechanical twins can be observed. The plastic deformation of the material leads to dislocations in the material. In this work, the two main mechanisms have been considered during plastic deformation in a cubic-face centered system, dislocation gliding and mechanical twinning [1,4]. Dislocations are sliding during the plastic deformation due to different number of cold-rolling steps. Since the crystal structure of the material aims a low energy level, the resulting lattice distortion within the crystallites is reduced by various mechanisms. Thus further plastic deformation is possible.

The divergence of the grain size in the microstructure analysis can be described by the twinning formation at different plastic deformation of individual material thicknesses. Moreover, the grain size decreases with decreasing material thickness motivated in several mechanisms. The twinning formation causes dislocations and grain boundaries, thus reducing the average grain size [4-6]. This material behavior is plausible due to estimated stacking fault energy of $31.2 \text{mJ/m}^2$, since this shows a low value and therefore twinning is preferred [15].

In addition, no further information about the number of heat treatment steps during the rolling process are given by the supplier, which can also affect the grain size and the equated shape of the grains.

### 3.2. Texture

X-ray diffraction is used to determine the texture of a sample, which allows the anisotropic parameters to be calculated. Basically, X-ray measurement of a multi-crystalline sample is based on the fact that each crystallite contributes to the reflexes in the diffraction spectrum and thus satisfies the Bragg condition at certain angles. These reflexes are characteristic of both the orientation and are proportional to the volume fraction of the respective crystallite. The reflexes can be used to determine pole figures. These represent the intensity of the 2D orientation of the individual crystallites for a lattice plane. Since the texture can only be determined from a 3D orientation distribution function (ODF), however, the pole figures in (100), (110) and (111) were determined for the present face-centered cubic structure. The diffraction theory yields a series development using the generalized spherical function (1) in dependence of the Euler angles $\varphi_1, \Phi$ and $\varphi_2$ [16,17]:

\[
f(\varphi_1, \Phi, \varphi_2) = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} \sum_{n=-l}^{l} C_{lmn}^{mm} T_l^{mm}(\varphi_1, \Phi, \varphi_2)
\]  

(1)
By integration, consideration of crystal symmetries and a limited degree of series development for cubic materials of $L=22$, the macroscopic material property of a multi-crystalline sample $\overline{P}(g)$ can be described as in equation (2) \cite{16,17}:

$$\overline{P}(g) = \sum_{I=0}^{L} \sum_{\mu=0}^{M(I)} \sum_{\nu=0}^{N(I)} \frac{1}{2l+1} P_l^{\mu\nu} C_{l}^{\mu\nu}$$

(2)

The calculation of the anisotropic plastic properties can be simply determined from the tensor 4th step as in equation (3) with series development of $L=4$ \cite{16,17}:

$$\overline{P}(g) = \frac{1}{9} (p_4^{11} C_4^{11} + p_4^{12} C_4^{12} + p_4^{13} C_4^{13})$$

(3)

The results of the vertical anisotropy $r$ of the X-ray-diffraction show significantly less scattering and a much more detailed course of the anisotropy, see figure 3. The results indicate a high level of anisotropic material behavior at 90° to rolling direction.

Figure 3. Vertical anisotropy $r$ examined by X-ray-diffraction.

Figure 4. Texture sharpness in dependence of material thickness.

Figure 4 shows the maximal signal intensity which indicates the maximum texture sharpness. The texture sharpness increases between 0.2 mm and 1.0 mm with decreasing material thickness. This behavior partly shows clear deviations between the individual orientations, which is caused by the increasing plastic deformation between the individual rolling steps during manufacturing process \cite{18}.

3.3. Flow Behaviour

For investigation of material characteristics dependent on different material thicknesses a conventional uniaxial tensile test was carried out to determine tensile strength and elongation. In figure 6 the stress strain-curves are shown.
After reaching the maximum tensile strength the flow behavior shows necking which indicates an unstable behavior of the material. The cross section of the specimen is reduced until the specimen fails. Thus, a further plastic deformation is only possible in a small part of the specimen. The results of the examined material indicate a small necking area where the elongation can be neglected.

The vertical anisotropy was examined by conventional tensile test as well as by X-ray-diffraction, see figure 6. The vertical anisotropy \( r \) by uniaxial tensile test observed large variances of the measured values and offer only results for three orientations of the material to the rolling direction. The values indicate a low anisotropic material behavior at different rolling directions.

Figures 7 and 8 show the results of tensile tests in dependence of different thicknesses. The results show fracture strains up to 62\% and tensile strength higher than 600 MPa, which basically indicates a good deformation behavior of materials. The material can be strongly deformed based on the results of elongation at fracture. This behavior is increasing lightly by decreasing the material thickness and can be explained by the increasing plastic deformation by the manufacturing process [1].

**Figure 5.** Stress-strain-diagram in rolling direction according to DIN EN ISO 6892-1:2009-12.

**Figure 6.** Vertical anisotropy \( r \) examined by conventional tensile test.

**Figure 7.** Results of tensile strength of X5CrNiMo17-12-2.

**Figure 8.** Results of fracture strain of X5CrNiMo17-12-2.
3.4. Forming Limit Diagram

To examine the forming behavior of the stainless steel materials, the forming limit curve was investigated. This describes the logarithmic deformations of a material and is determined by different specimen geometries.

Figure 9 shows exemplary cracked specimens of Nakajima test.

Figure 10. Forming limit diagram according to DIN EN ISO 12004-2.

The results in figure 10 show that the slopes are similar to the various forming limit curves, but the major strain value increases with increasing thickness in the field of biaxial stretching. This indicates that higher material thicknesses show a better forming behavior than lower ones.

4. Conclusions

The austenitic stainless steel X5CrNiMo17-12-2 in thickness ranging from 0.2 mm to 1.0 mm was examined. In this work the mentioned methods were compared to investigate the for low material thicknesses. The material was analyzed especially for material-specific properties and forming behavior. The mechanical material characteristics of the stainless steel were examined by conventional uniaxial tensile tests and X-ray diffraction. Both measuring methods are based on completely different physical principles, which should be considered in the interpretation of the results. In particular, vertical anisotropy $r$ is used as a parameter for material simulations, which serve to predict material failure. This parameter is usually determined by conventional uniaxial tensile test.
Compared to the X-ray diffraction, the results showed different characteristics. For different material thicknesses the X-ray diffraction indicated various results of vertical anisotropy which are mainly due to the manufacturing process. Furthermore, the uniaxial tensile test is a purely mechanical test method with diverse test influences and the X-ray-diffraction method is a measurement method based on the crystal structure. Thus, there may be test-related deviations in the tensile tests compared to X-ray-diffraction. These deviations have to be investigated in a further work.

In addition, the results of microstructure analysis show that the average grain size decreased with decreasing material thickness. This material behavior can be caused by the process of twinning formation. The formation of twins increases with increasing plastic deformation, resulting in dislocations and a decrease in the average grain size. In addition, twin formation enables further plastic deformation, as stresses in the crystal lattice can be relieved. Heat treatments were probably carried out between the individual cold rolling steps so that dislocations were reduced to enable further plastic deformation and thereby caused the equated shape of the grains. However, there is no further information available from the supplier concerning details about stages of heat treatments. The forming behavior of stainless steel X5CrNiMo17-12-2 was determined with an optimized Nakajima test method. The results showed a better forming behavior for larger material thicknesses.

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