INFLUENCE OF TEXTURE AND ANISOTROPY
ON MICROSTRESSES AND FLOW BEHAVIOR IN A
DUPLEX STAINLESS STEEL DURING LOADING

J. Johansson Moverare and M. Odén
Division of Engineering Materials, Department of Mechanical Engineering
Linköping University, S-581 83 Linköping, Sweden

ABSTRACT
The load partitioning between the two phases in a cold rolled duplex stainless steel sheet have been experimentally studied in situ during loading, via X-ray diffraction, for different loading directions. The microstresses in the two phases were found to decrease when loading in the transverse direction, while they increase during loading in the rolling and 45°-direction. Due to strong crystallographic texture in the ferritic phase the material is anisotropic with a higher stiffness and yield strength in the transverse direction compared to the rolling direction. The texture have been measured and used as input to theoretical predictions of both elastic and plastic anisotropy. The predicted anisotropic material properties have then been used in finite element simulations to study the flow behaviour of the material in different directions. The predicted flow behaviour was found to be in good agreement with the experimentally observed load partitioning between the phases for loading in the rolling and transverse direction. However, the yield strength of the ferritic phase during loading in the 45°-direction was found to be lower than what can be predicted by the crystallographic texture.

INTRODUCTION
Duplex stainless steels possess microstructures containing comparable volume fractions of austenite and ferrite. Due to the difference in coefficient of thermal expansion, residual tensile stresses are formed in the austenitic phase during cooling from the solution annealing temperature. These stresses are balanced by compressive stresses in the ferritic phase. Since the two phases also have different elastic and plastic properties, the microstresses between the two phases may change during deformation. The interactions between the two phases thus give rise to a complex flow behaviour. In many of the reported studies that include modelling work on the deformation behaviour of duplex stainless steels, the ferritic phase has been considered as the strong phase and austenite the softer and more ductile phase [1-4]. However, experimental studies on duplex stainless steels show the opposite behaviour, i.e. the austenitic phase is the stronger phase [5-8]. The reason for this is that modern duplex stainless steels are alloyed with nitrogen in order to increase the strength of the material, and to balance the phase contents. Nitrogen is mainly increasing the strength of the austenitic phase. Other factors contributing to a complex load partitioning are that, as a result of hot or cold rolling, duplex stainless steel exhibit anisotropic material properties, with values of yield and tensile strength that are higher in the transverse direction (TD) than in the rolling direction (RD) [7].

This study emphasises determination of the plastic properties of the constituent phases in a duplex stainless steel and the influence of texture and anisotropy on load partitioning, flow behaviour and evolution of microstresses during uniaxial loading in different directions.
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EXPERIMENTAL DETAILS

Material

The studied material is a duplex stainless steel SAF 2304, manufactured by Avesta Sheffield, with the chemical composition: Fe-22.8Cr-4.9Ni-0.3Mo-0.1N (wt.%). The material was hot and cold rolled, down to a thickness of 1.5 mm, before a final solution treatment at 1050°C. More details about the microstructure and mechanical properties of the studied material can be found in ref. [7, 9].

Texture analysis

The crystallographic texture of both phases was determined from X-ray diffraction measurements on a Seifert PTS 3000 diffractometer using CoKα radiation. Reflections used were 110, 200, 211 and 220 for ferrite, and 111, 200, 220 and 311 for austenite. The texture was investigated in greater detail using orientation distribution functions (ODF’s) calculated by the series expansion method [10]. The samples were prepared by grinding with a 1200-grit SiC paper followed by 4000-grit paper and 3 µm diamond paste. After mechanical surface treatment all specimens were electropolished and the total material removal were approximately 30 µm.

In order to assess the effect of crystallographic texture on mechanical properties the method of Taylor and of Bishop and Hill (TBH-model) as described by Hosford [11] has been used. The Taylor factor M, which express the flow stress of the material relative to the critical shear stress necessary to move a dislocation in a single crystal, are calculated for a single texture component as a function of the width to longitudinal strain ratio \( q = \frac{-\Delta e_w}{\Delta e_l} \). To get the Taylor factor for mixed textures the M versus q curves were averaged over all components described by the ODF and weighted with the volume fraction of each component. It was then assumed that the material will select the strain state which correspond to the minimum flow stress. The strain ratio q can also be converted to the more commonly used width to thickness strain ratio \( r = \frac{-\Delta e_w}{\Delta e_t} = q/(1-q) \) often referred to as the r-value. For both phases octahedral slip was assumed, i.e. \{111\}{110} for the austenite and \{110\}{111} for the ferrite. Pencil glide \{hk1\}{111} is sometime assumed for BCC metals but are not considered in this study. Predictions based on pencil glide generally give the same form of anisotropy, but with reduced magnitude of variation, compared to octahedral glide [12-14].

X-ray stress measurements

An Ω-diffractometer with Cr Kα radiation was used to measure the interplanar spacing of the {211} planes in the ferritic phase and of the {220} planes in the austenitic phase. In order to make three-dimensional stress analysis possible, lattice displacements were determined in 3 φ-directions (0°, 60° and 120°) for 11 ψ-angles between ±50° for the ferrite and between ±42° for the austenite. For a definition of the above angles, see reference [15]. The locations of the diffracted peaks were determined by a least squares fit of a pseudo-Voigt function to the data. The unstressed lattice parameters \( a_0 \) for each phase in the investigated material were determined previously to be 3.59694±0.00020 Å for austenite and 2.87355±0.00018 Å for ferrite [7]. The stress tensor was determined in each phase by a least-squares procedure [16], where the Hill average of the single crystal values given by Inal et. al [17] was used as the X-ray elastic constants. The phase stress tensors were than separated into macro- and microstress tensors for each phase [18]. Macrostresses are by definition the same in both phases of a two-phase material, while the microstresses is the difference between the phase stress and the macro stress.
Finite element analysis

The load partitioning between austenite and ferrite during plastic deformation was simulated using the ABAQUS finite element program [19]. A three-dimensional unit cell containing one irregular austenitic rod in a ferritic matrix was modelled with solid 8-node linear brick elements. Periodic kinematic boundary conditions corresponding to an average strain $\bar{\varepsilon}_{ij}$ was applied to the unit cell by introducing a constraining equation to all boundary nodes. This procedure, which is described in ref [20], makes it possible to load the unit cell with an uniaxial stress or strain in an arbitrary direction without change of geometry or boundary condition. Both phases were assumed to have anisotropic elastic behaviour, and the 9 elastic constants, $D_{1111}$, $D_{1122}$ etc necessary for describing generally elastic anisotropy in an orthotropic material were calculated by a crystallographic method based on the Voigt-Reuss-Hill assumption [21] using the measured texture data and the single crystal elastic constants given in [17]. The plastic response of both phases when loaded in RD were chosen according to earlier investigations [7]. Plastic anisotropy were than applied by using Hill's anisotropic plasticity potential were the anisotropic yield stress ratios are defined as $R_{ij} = \sigma_{ij}/\sigma_0$ [19], where $\sigma_0$ was defined for loading in RD and thus $R_{11} = 1$.

The other 5 stress ratios were calculated from texture data using the TBH-model as described earlier. The initial thermal stresses present in the unloaded material due the different coefficients of thermal expansion between the two phases was achieved by simulating cooling from 300° down to room temperature [7]. After the cooling a uniaxial tensile test was simulated and the average phases stresses were calculated.

RESULTS AND DISCUSSION

The texture in the ferritic phase was dominated by orientations near the rotated cube component $\{001\}$ / $\langle110\rangle$. This component has an intensity of 5.5×random. A second strong component in the ferritic phase is spread along the $\varepsilon$-fibre axis, extending from the $\{111\} / \langle112\rangle$ orientation ($\phi=55^\circ$) towards the $\{110\} / \langle001\rangle$ Goss orientation ($\phi=90^\circ$), see Figure 1(a, $\phi_2=45^\circ$). The preferred crystallographic orientations were found to be lower in the austenitic phase compared to the ferritic phase, see Figure 1(b). By using the method described in the previous section the anisotropic elastic and plastic properties of the two-phases were calculated taking the crystallographic texture into account. Figure 2 shows the variation in mechanical properties as a function of the angle from RD. As one can expect from the texture data, the ferritic phase shows a more pronounced anisotropic behaviour compared to the austenitic phase.

The complete total stress tensor in the ferritic and the austenitic phase were measured with X-ray diffraction in situ during uniaxial loading. In Figure 3 the total stress in the loading direction for both phases are plotted as a function of the applied strain. One can notice a considerable difference in the stress response for the different directions. As a consequence of the difference in coefficient of thermal expansion between the two phases, tensile stresses are found in the austenite and compressive stresses in the ferrite. However the magnitude of the residual thermal stresses are different in different directions. The highest microstresses are found in TD and the lowest microstresses in RD. During uniaxial loading the difference in stress between the two phases remains and shows only small variations when loaded in RD, see Figure 3(a,d). However when loaded in the $45^\circ$-direction the difference in stress between the two are increasing, see Figure 3(b,e), while loading in TD leads to a decreased difference in stress between the two phases, see Figure 3(c,f).
Figure 1: Orientation distribution function (ODF) describing the surface texture in a cold rolled duplex stainless steel SAF 2304 (a) Ferritic phase (b) Austenitic phase.

Figure 2: Anisotropic mechanical behavior due to crystallographic texture.
The evolution of microstresses indicates that for loading in RD, both phases deforms plastically to the same degree, while the ferrite deforms plastically to a larger extent than the austenite during loading in the 45°-direction. However for loading in TD more plastic deformation occurs in the austenitic phase. This is also confirmed when the increase in peak width is considered. For loading in RD the relative increase is similar in both phases, while it is bigger in the ferrite for loading in the 45°-direction, and bigger in the austenite for loading in TD.

**Figure 3**: Measured versus predicted stress. (a) LD//RD, phase stress (b) LD//RD, microstress (c) LD//45, phase stress (d) LD//45, microstress (e) LD//TD, phase stress (f) LD//TD, microstress.

The results from the finite element simulations are also included in Figure 3. The FEM simulations predict similar thermal microstress in both the rolling and TD when cooling from an elevated stress free temperature is simulated. The measurements, however, show that the initial stress in TD is almost two times higher than the microstress in RD. For loading in RD, Figure 3(a,d) one can therefore see that the initial microstresses are overestimated by the FEM simulations. This overestimation remains in the elastic region, but when plastic deformation occurs, the FEM simulations predict the correct microstresses, and the predicted yield stress for
loading in RD seems therefore to be correct for both phases. For loading in the 45°-direction, see Figure 3(b,e), the yield strength of the ferritic phase is highly overestimated and the predicted microstresses show therefore poor agreement with the measured microstresses. This means that during loading in the 45°-direction the plastic anisotropy of the ferritic phase must have other sources than crystallographic texture, for instance phase boundary sliding. However, when the material is loaded in TD, see Figure 3(c,f), a very good agreement is found between experimental and predicted microstresses. Thus, the anisotropic plastic properties for loading in RD and TD can be explained by the crystallographic texture.

SUMMARY

Cold rolled duplex stainless steel shows highly anisotropic behaviour leading to different load partitioning for loading in different directions. The plastic deformation is similar in both phases for loading in the rolling direction, while the plastic deformation is higher in the ferrite for loading in the 45°-direction, and higher in the austenite for loading in the transverse direction. This anisotropy can only partly be explained by the crystallographic texture. Especially for loading in the 45°-direction other mechanism must be involved which decrease the strength of the ferritic phase.

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REFERENCES