Microstructure, texture, and mechanical behaviour of warm-rolled and annealed standard duplex stainless steel

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Abstract. The microstructural evolution and mechanical behaviour of 2205-type duplex stainless steel were studied after plate warm rolling at 600 °C with 60% and 80% thickness reduction and subsequently annealed at 1050 °C for 300 s. With increasing thickness reduction level, ferrite-phase α-fibre became weaker and γ-fibre was developed. For the austenite phase, a weakening of Brass component and increases in Goss and Copper components was observed. A transition from bamboo type into a pearl structure from the 60% sample to the 80% warm-rolled annealed sample was observed. An average tensile strength of 794 MPa was assessed through tensile tests. Post deformation tests demonstrated an increase in microhardness toward the fractured areas and a deformation-induced martensitic transformation was observed in transmission electron microscope results in those regions for all conditions.

1. Introduction
The presence of approximately equal volume fractions of austenite (γ) and ferrite (α) phases results in good properties of duplex stainless steels (DSS). They are widely used in the pulp and paper, chemical, oil and gas, petrochemical, and energy industries [1,2].

Its conventional industrial processing consists of initial hot operation followed by solubilisation annealing, cold rolling, and a final annealing. Owing to the expensive thermal energy demanded from hot rolling, operating at a lower temperature (e.g. warm rolling) has been used as an alternative option. Thus, considering a large thickness reduction to the final application, cold rolling may be reduced or even eliminated and, in some cases, additional heat treatment may be avoided [3].

A significant investigation of the effects of warm rolling and annealing processes on the property evolution of an UNS S32205 duplex stainless steel is presented herein. Three conditions were analysed: as-received and 60% and 80% thickness reduction with annealing. They were characterised as microstructural, textural, and mechanically performing results such that the effect of the thermomechanical process on the phase morphology, its relationship with the properties, and the phase-transformation-induced plasticity in DSS can be understood.

2. Material and Methods
The as-received DSS used in the present study was an industrially produced hot-rolled and annealed 5.16 mm-thick sheet. The chemical composition of this alloy given by the manufacturer is shown in Table 1, which characterises it as UNS S32205 DSS.
Table 1. Chemical composition (wt.%) of UNS S32205 duplex stainless steel

| Element | C   | Mn  | Si  | Cr  | Ni  | Mo  | N   | P   | S   | Fe   |
|---------|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|
| Weight percent | 0.026 | 1.83 | 0.25 | 22.43 | 5.44 | 3.04 | 0.15 | 0.03 | 0.0002 | Balance |

Using the Thermo-Calc™ software and the composition listed in Table 1, it is found that degraded DSS properties can occur owing to deleterious phases, as sigma (σ) and chi (χ) [2]. Therefore, the temperature of 600 °C was carefully selected to avoid the precipitation of these secondary phases in thermomechanical processing [4].

The as-received DSS strips were warm rolled in along the previous rolling direction in a Fröhling rolling mill. A conventional muffle furnace was used to preheat the samples at 600 °C for 1800 s to achieve homogeneity. After each warm rolling pass a holding time of 900 s, the same temperature was applied to the slabs. The samples reached strains (ε) of ε = 0.60 (thickness reduction from 5.16 to 2.16 mm in nine passes) and ε = 0.80 (thickness reduction from 5.16 to 1.22 mm in 16 passes). After the last warm-rolling pass, the samples were air quenched until the room temperature.

Subsequently, the warm-rolled samples were isothermally annealed in a box-type furnace at 1050 °C for 300 s, and subsequently air quenched. The final annealing was applied to control the proportions of ferrite and austenite, achieving a nearly equal volume fraction of the two phases, and to dissolve any secondary phase.

The schematic diagram for the orientations corresponding to the rolled product is shown in figure 1 where ND, RD, TD are the normal, rolling, and transverse directions, respectively.

![Figure 1. Schematic illustration of orientations corresponding to the warm-rolled product.](image)

Microstructural characterisation was performed in the as-received and warm-rolled and annealed states. For the microstructural analysis, samples of ND-RD:RD plane were mechanically ground and polished with diamond paste according to the conventional metallographic procedure. Subsequently, an additional polishing with colloidal silica particles allowed for the investigation of the microstructure and microtexture in the electron backscatter diffraction system. The phase maps, orientation distribution function (ODF), and pole figure (PF) for each condition were determined using the data in the TSL-OIM™ software.

Thin foils from the RD-TD plane were prepared using the conventional metallographic procedure and a twin-jet polisher (solution of 5% perchloric acid and 95% methanol in –30 °C and –20 °C, tension of 20 V) for transmission electron microscopy (TEM) observation.

To evaluate the mechanical behaviour of the steel, tensile tests were performed under a strain rate of 10⁻³ s⁻¹ at room temperature, using a 5582-model Instron machine. The specimens were obtained from the RD-TD plane in the RD direction according to the dimensions of the ASTM A-370-15 subsize [5]. In addition, Vickers microhardness was measured using the Future Tech FM700 equipment. Each hardness result was determined from an average of 20 measurements with a 2.98-N indentation load and dwell time of 10 s, along the central regions of the ND-RD plane.

3. Results and Discussion
3.1. Texture Evolution

Figure 2 illustrates the microstructure using the phase map. The microstructure of the as-received sample is formed by the alternated lamellae of austenite and ferrite, with elongated morphology, parallel to the RD. The 60% warm-rolled and annealed (60% WRA) sample exhibited a still lamellar microstructure, similar to the as-received sample, but with a finer thickness. This morphology consisting of elongated grains is referred to as a bamboo-like structure. Meanwhile, the 80% warm-rolled and annealed (80% WRA) sample exhibited the microstructure constituted by the bamboo-like and pearl structures (more globular). The transition from bamboo-like to pearl structure can be observed in some regions, as indicated by the black arrows in figure 2.

The transition from bamboo structure to pearl structure occurs owing to the migration of interphase boundaries between both phases. The increase in deformation level reduced the lamellae thickness and enhanced the interface between both phases. Thus, it can be inferred that the driving force for nucleation of the 80% WRA sample was superior to that of the 60% WRA sample, thus resulting in the difference in the microstructure morphology [6].

![Figure 2. Phase maps of the samples (a) as-received condition, (b) 60% WRA, and (c) 80% WRA.](image)

The orientation distribution function (ODF) with a $\phi_2 = 45^\circ$ section for the ferrite is shown in figure 3. Its microtexture is primarily characterised by the $\alpha$-fibre ($<011>/RD$) in the as-received sample, and contributed to its stability after warm rolling, as shown in figure 4 (b,c). The thermomechanical process promoted a weakening of this fibre type and a moderate development of the $\gamma$-fibre ($<111>/ND$); these are slightly more intense in 80% WRA.

![Figure 3. ODF sections of ferrite phase for (a) as-received, (b) 60% WRA, and (c) 80% WRA conditions.](image)
Figure 4 shows the PF for the austenite phase. The as-received sample is constituted mainly by \{110\}<112> Brass and \{123\}<634> S components. After the warm rolling, the \{110\}<112> Brass component was weakened, while the \{110\}<001> Goss components became more intense. Furthermore, \{112\}<111> Copper was found after warm rolling.

![Figure 4. PF sections of austenite phase for (a) as-received, (b) 60% WRA, and (c) 80% WRA conditions.](image)

It is highly difficult to recrystallise grains with \(\alpha\)-fibre orientation because of the low energy stored; furthermore, they tend to be consumed during recrystallisation [7,8]. For the DSS, the as-received sample exhibited a high intensity of the \(\alpha\)-fibre. This condition and the warm-rolling process resulted in a low stored energy that favoured the recovery process and the remaining \(\alpha\)-fibre in the ferrite phase. Meanwhile, the austenite developed a \{110\}<001> Goss component after warm rolling. The presence of \{110\}<001> Goss and \{112\}<111> Copper after warm rolling and annealing, and a similar texture in the warm and cold rolled samples, were reported by the Odnobokova et al. [9] for 304L stainless steel processed at 300 °C.

### 3.2. Tensile and Hardness Tests

To evaluate the effects of warm rolling on the mechanical properties, tensile tests were conducted. The mechanical properties extracted from the stress–strain data are shown in Table 2, along with the stress–strain curve, indicating that the results of mechanical strength and ductility are similar for all the analysed conditions.

| Condition  | Yield Strength (0.2%) (MPa) | Tensile Strength (MPa) | Uniform Elongation (mm/mm) | Tensile strain at Break (mm/mm) |
|------------|-----------------------------|------------------------|-----------------------------|-------------------------------|
| As-received| 540                         | 781                    | 0.319                       | 0.483                         |
| 60% WRA    | 559                         | 794                    | 0.251                       | 0.340                         |
| 80% WRA    | 519                         | 806                    | 0.292                       | 0.410                         |

To evaluate the effect of plastic deformation on the mechanical properties, a microhardness profile was performed on the specimens after the tensile tests, as represented in figure 5. A gradual increase in microhardness occurred near the fractured region in all samples, yielding a value of approximately 400 HV. These results indicate, beyond strain hardening, the formation of martensite induced by plastic
deformation (TRIP effect), with a greater volume fraction for warm-rolled specimens because of their higher microhardness values [10].

![Figure 5. Evolution of microhardness profile as a function of distance from fracture after tensile tests.](image)

3.3. Microstructural Analysis

Figure 6 shows the microstructures obtained from TEM near the fracture from the tensile tests. In all conditions, martensite is observed, with laths varying from 11 to 223 nm that confirm the findings obtained from the Vickers microhardness tests shown in table 3.

The transformation of austenite into martensite during deformation is more likely to occur when the SFE is lower than 20 mJ/m². From this value until 50 mJ/m², mechanical twinning is the predominant mechanism and dislocation slip for values above 50 mJ/m² [11]. Using the chemical composition of the austenite phase obtained through Thermo-Calc™ and EDS, the values obtained for SFE were approximately 32 and 41 mJ/m² using Scharmm and Reed equations, respectively [12]. Although mechanical twinning had been reported as the predominant mechanism for this range of SFE, van Tol et al. [13] found a high SFE (50 ± 10 mJ/m²) for a Mn-based TWIP steel with strain-induced α’-martensite formation.

![Figure 6. Bright-field images near the fracture for (a) as-received, (b) 60% WRA, and (c) 80% WRA conditions.](image)

4. Conclusions

(i) The microstructure of as-received 2205 DSS demonstrated ferrite and austenite grains with elongated morphology parallel to the rolling direction. A more narrowed lamellar microstructure than
that in the as-received condition was observed in the 60% WRA sample. Meanwhile, bamboo-like and pearl structures were observed in 80% WRA.

(ii) The microtexture of the ferrite phase was primarily constituted by α-fibre (⟨011⟩//RD) for all samples, with a weakening of this fibre and a slight development of γ-fibre (⟨111⟩//ND) as the deformation level increased. The austenite phase, in the as-received condition, was mainly constituted by Brass (⟨110⟩⟨112⟩) and S (⟨123⟩⟨634⟩) components. For the warm-rolled samples, the Goss (⟨110⟩⟨001⟩) component became more intense as the Brass (⟨110⟩⟨112⟩) component weakened.

(iii) The stress–strain curve demonstrated a similar behaviour for all conditions. A gradual increase in microhardness was observed close to the fractured region after the tensile, thus proving the deformation-induced martensitic transformation (TRIP effect).

(iv) TEM analysis confirmed the formation of martensite laths near the fracture in all specimens, with the thickness varying from 11 to 223 nm.

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