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Microstructure and texture evolution of duplex stainless steels with different molybdenum contents

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ABSTRACT

The microstructure and texture evolution of duplex stainless steels with different molybdenum contents were studied. For this purpose, hot-rolled 2205 and 2304 samples were solution-annealed at 1100 °C for 1800 s and then cold-rolled to a 75% thickness reduction. This was followed by an isothermal annealing at 900 and 1100 °C for 180 s. The EBSD technique was used to determine the phase ratio, crystallographic texture, and microstructural characteristics. The hot-rolled steel had a work hardened microstructure and the samples submitted to intermediate annealing presented mainly deformation-free grains. Cold rolling resulted in a substantial reduction in the phase spacing with the formation of the strain-induced α'-martensite (SIM) from the metastable austenite. After annealing at 900 °C, the ferrite grains retained the elongated shape of the cold-rolled condition and the primary recrystallization progressed in the austenite phase. Increasing the Mo content increased the resistance to strain-induced martensitic transformation and inhibited the grain growth of austenite phase during annealing at 900 °C. Increasing annealing temperature to 1100 °C promoted the coarsening of both bcc and fcc structures with the formation of annealing twins in the austenitic grains. The recrystallization kinetics and subsequent grain growth occur earlier in ferrite than in austenite phase. Differences in Mo content did not significantly alter the evolution of austenite texture, whereas in the ferrite phase the increase in Mo content suppressed the γ-fiber development. Oriented nucleation was the predominant mechanism observed during the recrystallization of ferritic grains in the 2205 samples. The development of $\Sigma 19a$ boundaries was associated with the selected growth of $\{554\}\langle 225\rangle_\alpha$ grains in the annealed 2304 samples. Annealing twins were associated with the formation of $\Sigma 3$ boundaries after the heat treatments. Grain coarsening resulted in a larger fraction of the special boundaries in ferrite phase but inhibited the CSL formation in the austenite phase.

1. Introduction

Duplex stainless steels are a category of high-alloyed steels characterized by a biphasic austenitic-ferritic microstructure [1–5]. Chemical composition is usually adjusted to achieve the optimum phase ratio of approximately 1:1, which provides an attractive combination of mechanical properties and corrosion resistance [6–11].

Duplex stainless steels, based on their chromium, nickel, and molybdenum content, can be sub-divided into standard duplex, super duplex, hyper duplex, 25 Cr duplex, and lean duplex stainless steels grades. Lean duplex stainless steels have been developed to minimize cost fluctuations by reducing expensive elements like Ni and Mo [6,8,12–14]. Because of its lower Ni and Mo contents than standard 2205 grades, 2304 steels are less sensitive to precipitation of intermetallic compounds, which may seriously deteriorate the corrosion and mechanical properties of such alloys [15–17]. As a ferrite former, molybdenum increases the yield strength of duplex stainless steels but decreases their ultimate tensile stress (UTS) [18,19]. Molybdenum additions are responsible also by improving the stability of the passive film and the resistance of duplex stainless steels to chloride-induced corrosion (pitting, crevice corrosion, and stress-corrosion cracking), in aqueous environments particularly [20–22].

The morphology and repartition of austenitic and ferritic phases, as well as conditions of plastic working and annealing treatment, are important factors which are known to control the final properties of duplex alloys [23]. The presence of α/γ interfaces affects considerably the deformation mechanisms of these materials, due to strain incompatibilities at phase boundaries and to crystallographic slip in the bcc and fcc structures [24–27]. Apart from the mechanism of slip or twinning within the γ-phase and the multiple slips within the α-phase, plastic deformation can proceed by strain induced $\gamma \rightarrow \alpha$ transformation. Such transformation can be described by favored orientation

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relationships (OR's) between specific planes and directions of the phases, which allows the best fit of their interfaces [28]. The OR models were firstly investigated by Bain [29], Kurdjumov and Sachs (K–S) [30], Nishiyama and Wasserman (N–W) [31,32], Greninger and Troiano (G–T) [33], and Pitsch [34], and recently by Headley and Brooks (H–B) [35].

Since for most end applications duplex structures are manufactured from hot-rolled and annealed sheets, their crystallographic texture results from the deformation, recrystallization and phase transformation phenomena occurring in austenite and ferrite phases [23,36]. Recrystallization of deformed metals gives rise to changes in the distribution of crystallographic orientations by nucleation of new non-deformed grains and their subsequent growth into the deformed matrix [28,37]. The evolution of the recrystallization texture during annealing of duplex stainless steels has been the subject of several research studies [23,36,38–44]. In this sense, oriented nucleation (ON) and selected growth (SG) theories were associated with the preferential formation of specific orientations owing to either a frequency (ON) or size advantage (SG) [45–49]. According to Lee and Han [50], the Goss grains that persisted after rolling of fcc alloys seem to act as nuclei during the recrystallization and develop at the expense of surrounding brass grains. In the case of bcc alloys, the lower stored energy of the ⟨110⟩ components compared to those of the γ-fibers leads to a favored nucleation of {111} grains [49,51,52].

Annealing textures of bcc and fcc materials have been reasonably explained by the correlation between the SG theory and the CSL type-boundaries. It was established that certain misorientations, namely ~40° ⟨111⟩ in fcc and 26.5° ⟨110⟩ in bcc, resulted in high mobility interfaces that growth preferentially during the recrystallization [50,53–55]. The superior mobility of Σ7 CSL boundaries, misoriented in 38.2° about ⟨111⟩, is central to the SG model of fcc recrystallization texture and seems to be associated with the replacement of deformed S-grains by recrystallized cube grains [53]. With respect to bcc steels, Malta et al. [56] observed that during annealing the {554}⟨225⟩ components formed at the expense of {112}⟨110⟩ under a 26.5° ⟨110⟩ misorientation relationship, the same of Σ19a CSL boundaries.

The aim of present work was to evaluate the effect of molybdenum content and annealing temperature on microstructure and texture evolution by comparing the results obtained for a standard 2205 alloy and a lean 2304 alloy. To understand more deeply the morphological and crystallographic changes of annealed duplex steels, it is essential to study all the mechanisms involved in their recrystallization kinetics. Therefore, grain nucleation and growth, as well as the distribution of phases were evaluated from the initial processing condition.

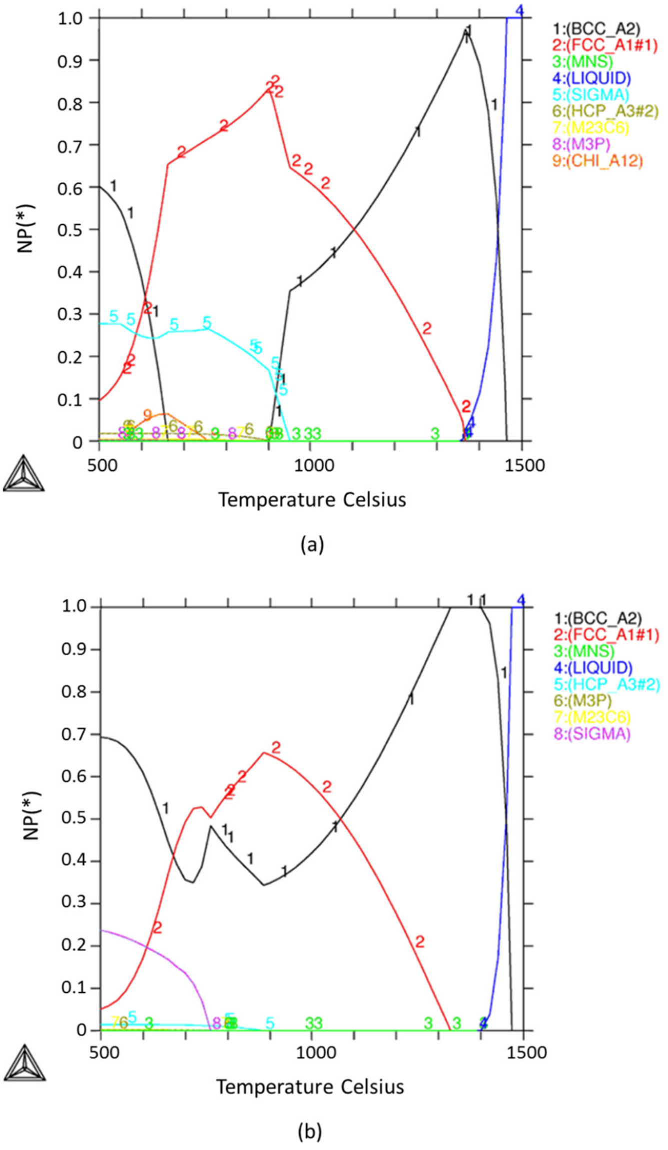

Fig. 1. Phase fraction as a function of temperature calculated by using the Thermo-Calc software for the (a) 2205 and (b) 2304 duplex stainless steels used in the present work.

2. Materials and Methods

The duplex stainless steels investigated in the present work, designated as 2205 and 2304 alloys, were received in the form of hot-rolled sheets of 4 mm thick. The chemical compositions of the standard and lean grades are given in Table 1.

The industrial sequence for obtaining duplex stainless steels by rolling includes two annealing steps: one intermediate after the hot rolling, and the final one after the cold rolling. In the present work, the parameters, i.e. temperatures and times, of both annealing treatments are selected to avoid the formation of precipitates. Furthermore, in the case of the intermediate annealing, the temperature was higher and soaking time longer to dissolve the precipitates which may have appeared during the last hot rolling passes.

The phase fraction as a function of temperature was calculated by using the Thermo-Calc software for the steels studied in this work, as shown in Fig. 1. Due to the high number of alloying elements, both steels showed a rather complex precipitation behavior. In duplex stainless steels, the precipitation of intermetallic phases is of greater interest since they seriously deteriorate the corrosion and mechanical properties of such alloys [15,16]. The χ-phase was observed only in 2205 alloy at a temperature range of 550–750 °C, while the σ-phase was formed in both 2205 (500–950 °C) and 2304 (500–750 °C) grades. Specimens aged between 500 and 900 °C were subjected to the precipitation of hexagonal nitrides (Cr_2N), which could lead to a possible

Table 1
Chemical composition of 2205 and 2304 duplex stainless steels (in wt%).

	C	Cr	Ni	Mo	Mn	Si	P	Cu	S	N	Fe
Standard 2205	0.023	22.43	5.44	3.046	1.82	0.249	0.03	0.191	0.0002	0.169	Bal.
Lean 2304	0.011	22.87	4.20	0.275	1.45	0.201	0.02	0.453	0.0004	0.101	Bal.