



Hot deformation characteristics of 2205 duplex stainless steel based on the behavior of constituent phases

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ABSTRACT

High temperature behavior of 2205 duplex stainless steel was studied by considering behavior of each constituent phase. The specimens were subjected to hot compression tests at temperatures of 800–1100 °C and strain rates ranging from 0.001 to 1 s⁻¹ at intervals of an order of magnitude. The flow stress analysis showed that hot working empirical constants are different at low and high temperatures. The strain rate sensitivity *m* was determined and found to change from 0.12 to 0.21 for a temperature rise from 800 °C to 1100 °C. The apparent activation energy *Q* was calculated as 554 and 310 kJ/mol for low and high temperature, respectively. The validity of constitutive equation of hyperbolic sine function was studied and stress exponent, *n*, was assessed to be 4.2. Assuming the hyperbolic sine function for determination of strain rate and application of the rule of mixture, the interaction coefficients of δ -ferrite, *P*, and austenite, *R*, were estimated at different hot working regimes. It was found that the interaction coefficients are functions of Zener–Hollomon parameter *Z* and obey the formulas $P = 1.4Z^{-0.08}$ and $R = 0.76Z^{0.005}$. Therefore, it was concluded that at low *Z* values δ -ferrite almost accommodates strain and dynamic recovery is the prominent restoration process which may even inhibit dynamic recrystallization in austenite. Otherwise, at high *Z*, austenite controls the deformation mechanism of material and dynamic recrystallization leads in finer microstructure.

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1. Introduction

The need for high corrosion resistance as well as desired strength characteristics has made duplex stainless steels (DSS) deserving alternatives to single phase austenitic and ferritic grades and good choices for different industries [1–3]. Deformation behavior of each constituent phase, austenite or ferrite, in the duplex structure is considerably affected by the presence of the other phase. As the austenite is significantly stronger than the ferrite in the hot working temperature range, it will affect the load transfer and thereby strain transfer characteristic between the constituents in a DSS [4–7].

Many researchers have investigated the hot working behavior of duplex stainless steels from different aspects [8–10] but some controversy over the restoration processes dominant in constituents have still remained. It has been well established that hot workability of δ -ferrite is better than that of the austenite. This advantage arises from the high stacking fault energy (SFE) of δ -ferrite and its ability to undergo dynamic recovery (DRV) [11–18]. On

the other hand, austenite, having a low SFE, undergoes only limited DRV [19] and when the dislocation density reaches a critical value dynamic recrystallization (DRX) takes place [7,17,18,20].

In duplex stainless steels, δ -ferrite and austenite make a composite material consisted of almost comparable amounts of these phases. The dynamic restoration behavior of both phases seems to be rather similar to their restoration behavior in the single-phase materials, where δ -ferrite softens by DRV and austenite by DRX. Coexistence of hard austenite and soft δ -ferrite at high temperatures is found to result in a strain partitioning at the early stages of deformation, when strain is mostly accommodated by the δ -ferrite phase [21,22]. At higher strains load is transferred from δ -ferrite to austenite leading to increment of dislocation density in the latter till triggering of DRX. Consequently, since strain energy is the driving force for softening to occur, the restoration process in ferrite is found to be far in advance of that in austenite [21].

Modeling of strain partitioning has been attempted by several researchers [23,24]. The relation between the hot working behavior of DSS, volume fraction of the constituents and the values of stress and strain partitioned in each phase has described by the law of mixture [23,25]. Several variants of this rule have been proposed for modeling the stress and strain distribution in the constituent phases.

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Table 1
Chemical composition of the DSS studied (wt%).

C	Cr	Ni	Mo	si	Mn	S	P	V	Cu	W	Co	Al	α/γ
0.025	22.8	5.2	2.6	0.3	1.5	0.001	0.025	0.088	0.23	0.03	0.068	0.028	54/46

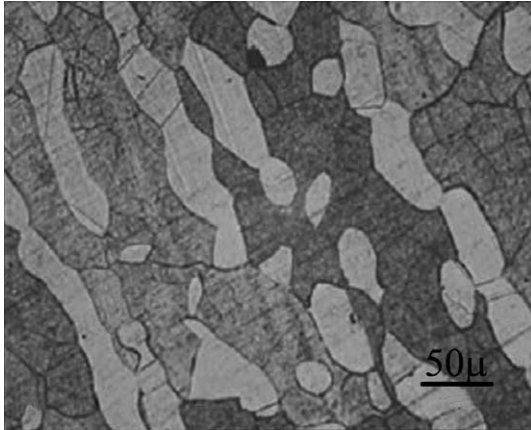


Fig. 1. Microstructure of the as-received 2205 DSS after annealing treatment across the transversal section. The light phase is austenite and the dark one is δ -ferrite.

The aim of this work is to study the high-temperature behavior of a DSS under hot compression tests, using the analysis of flow curves as well as hot-working response of each constituent phase.

2. Experimental procedures

Chemical composition of the DSS 2205 used in the present study is shown in Table 1. The material had been manufactured by AB Sandvik Steel (Sweden) and supplied as round bars of 30 mm in diameter. The as-received bars were hot rolled in the range of 950–1100 °C and annealed at 1050 °C followed by quenching in water to obtain homogeneous and equiaxed distribution of δ -ferrite and austenite, Fig. 1.

Cylindrical compression samples of 15 mm height and 10 mm diameter were prepared with the axis along the rolling direction. Concentric grooves of 0.5 mm depth were made on the top and bottom surfaces to keep lubricant material and reduce friction. A 1 mm 45° chamfer was machined on the specimens edges to avoid fold-over of the material during the early stages of deformation. A small hole of 0.8 mm diameter and 5 mm depth was drilled at mid height of the specimens for embedding a thermocouple. It was used to measure real temperature of the specimens. Boron nitride was sprayed on both surfaces of specimens to reduce the friction coefficient. The temperature of the specimens was monitored using a chromel–alumel thermocouple and isothermal condition was maintained within ± 2 °C. An INSTRON 8503 testing machine equipped with a fully digital control furnace was employed to perform hot compression tests under constant strain rates, ranging from 10^{-3} s^{-1} to 1 s^{-1} at an interval of an order of magnitude

and at 800, 900, 1000, and 1100 °C temperatures. After hot deformation, the specimens were quenched within two seconds to retain the hot worked structure at room temperature. Deformed specimens were sectioned parallel to the deformation axis and surfaces were prepared using standard techniques for optical microscopy observations. Afterwards, the prepared specimens were etched in a solution of HCl, HNO₃ and H₂O with equal volumes. The volume percent of the constituents in the starting and hot deformed specimens were determined using a computerized image analyzer.

In order to model the hot deformation behavior of the duplex steel used in the present work, composition of each phase was analyzed by an Electron Probe Microanalyzer. To obtain accurate results diverge beam was employed to avoid any interaction effect from atomic elements in the surrounding matrix. Based on the obtained results for the composition of each constituent, two grades of ferritic and austenitic steels were produced using a vacuum induction furnace. The composition of the produced steels was controlled by a precise steel making procedure.

The chemical compositions of δ -ferrite and austenite phases in the studied DSS together with those of the produced single phase ferritic and austenitic steels are shown in Table 2. The ingots were hot rolled at temperatures of 950 °C and 1050 °C for ferritic steel and austenitic steel, respectively. The hot rolled of 30 mm thick specimens were then annealed at 1050 °C followed by quenching in water. Similar to the studied DSS, the produced ferritic and austenitic steels were tested under the same condition.

3. Results and discussion

3.1. Flow stress analysis

True stress–strain curves at different temperatures and strain rates are shown in Fig. 2. It is well established and also clearly seen here that flow stress level actually increases with strain rate and decreases with deformation temperature.

It has well understood that the characteristic points of flow curve and their relationship with processing variables are of great importance in studying hot deformation behavior of alloys. In this respect, the peak point of flow curve and the point corresponding to the onset of steady state flow should be noticed. The strain rate, $\dot{\epsilon}$ (s^{-1}), and deformation temperature, T (K), are often incorporated into a single parameter which is very well-known as Zener–Hollomon parameter, Z , given by [26]:

$$Z = \dot{\epsilon} \exp(Q/RT) \quad (1)$$

where Q (J/mol) and R donate apparent activation energy and gas constant ($=8.314 \text{ J/mol K}$), respectively. In order to determine the relationship between peak strain, ϵ_p or peak stress, σ_p and Z the first step is to determine the strain rate sensitivity m and apparent acti-

Table 2
Chemical composition (wt%) of the δ -ferrite and austenite phases in the dual phase structure together with those produced single phases ferritic and austenitic steels.

Material	Cr	Ni	Mo	C	Mn	P	S	Si	Cu
δ -Ferrite in DSS	25.9	3.3	2.77	0.02	0.4	0.02	0.001	0.38	0.29
Austenite in DSS	20	8.8	2.3	0.03	2.8	0.031	0.001	0.24	0.15
Single phase ferritic steel	25.8	3.31	2.68	0.02	0.4	0.018	0.001	0.35	0.3
Single phase austenitic steel	20.09	8.78	2.33	0.03	2.8	0.033	0.001	0.26	0.16

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