Materials Science and Engineering A 406 (2005) 254–260

MATERIALS SCIENCE & ENGINEERING A

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Mechanical and magnetic properties of a new austenitic structural steel

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Accepted 25 June 2005

Abstract

A new high carbon austenitic structural steel having low total alloy content has been developed. This steel, after melting, casting and hot-rolling has a fully austenitic microstructure. The mechanical, magnetic and thermodynamic properties of this new steel were studied extensively. Consistent with the fully austenitic structure, this steel is non ferromagnetic. Initial studies on this new alloy indicate that this steel has good strength and ductility and high fracture toughness. Two interesting phase transformations were observed in this steel, one around 550 °C and another close to the Curie temperature of ferrite phase. A major application of this steel is expected to be in power generation devices such as turbines, generators, etc. There will be very little power loss in power generation devices due to the low permeability and the non-magnetic nature of austenite. This steel also could be potentially used at elevated temperatures (remaining below 550 °C) because of its potentially high creep resistance in this temperature range.

Keywords: Austenite; Structural steel; Non-magnetic; Permeability; Toughness; Fracture toughness; Microstructure

1. Introduction

In this investigation, a new high carbon low alloy structural steel with fully austenitic crystal structure has been developed. Steels with austenitic or face centered cubic (γ) microstructures (such as austenitic stainless steels) typically have excellent mechanical properties [1–5], e.g., a combination of high strength and ductility, good formability and high work hardening rate. These properties of austenitic stainless steels make them highly desirable in many engineering applications, such as the petrochemical industry, food processing equipment and machinery parts requiring high corrosion resistance [6]. The diffusion of hydrogen in austenite is slower than in ferrite. Therefore, these steels also have higher stress corrosion cracking resistance. Moreover, because of the face centered cubic (FCC) structure, the creep resistance of these materials is very high [2], which make them suitable for applications at elevated temperatures as well. Additionally, the austenitic microstructure renders the steel non-ferromagnetic. These magnetic characteristics are advantageous for power generation devices such as components of turbine, generators, etc., because of reduced power loss, due to low magnetic permeability of the austenite.

The conventional austenitic stainless steels are very expensive, because they contain expensive alloying elements such as nickel and chromium in large percentages (typically 8% nickel and 18% chromium). In addition, the processing costs of these materials are very high since the carbon content of traditional austenitic stainless steels must be very low (less than 0.07%). Although some of the nickel in these alloys can be replaced by manganese [3,4] and the structure will still remain austenitic (e.g., AISI 201 grade), these materials remain comparatively expensive because of the expensive alloying elements, and costly processing required to produce them. If steels with austenitic microstructures can be produced without expensive alloying elements (or with lower alloy concentrations) but still retain the desirable mechanical properties and corrosion resistance, they could be used in a wide range of applications. The mechanical and the physical

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doi:10.1016/j.msea.2005.06.056

behavior of low carbon austenite has been extensively characterized. However, very little information is available in literature on the physical and mechanical properties of high carbon austenite.

In this investigation we have developed a high carbon steel having low allow concentrations. This steel after melting, casting and hot-rolling has a fully (100%) austenitic microstructure. This steel contains significantly less Cr (6% as compared to 18%) than conventional austenites and does not contain any nickel which dramatically reduces the processing cost of these materials. Additionally, the high carbon content allows inexpensive processing techniques to be used, further reducing the total cost of fabrication. We show in detail the mechanical and material characterization of this new austenitic steel, and discuss possible applications for this alloy.

2. Experimental procedure

2.1. Material

The chemical composition of the steel is reported in Table 1. It had about 1% carbon, 6% manganese and 6% chromium. Steel having the above composition was melted and cast and then hot-rolled into a 50.8 mm × 76.2 mm × 304.8 mm (2 in. × 3 in. × 12 in.) bars. After hot-rolling the steel bar was annealed at 800 °C for 1 h in an air furnace and air-cooled to remove the residual stress. The steel had a fully austenitic microstructure after hot-rolling and annealing, as determined by X-ray diffraction (XRD). The microstructure of the steel after hot-rolling and annealing is shown in Fig. 1. This steel was produced in a commercial foundry (Crucible Steel, PA) and thus it appears the industrial manufacturing of this steel should be feasible.

From annealed steel bars, compact tension samples for plane strain fracture toughness tests and cylindrical samples for tensile tests were prepared as per ASTM standards E-399 [7] and E-8, respectively [8]. Samples for Charpy impact tests were also prepared as per ASTM standard E-23 [9].

2.2. Mechanical testing

The tensile tests of the samples were carried out in a servo-hydraulic MTS (material test system) test machine at room temperature and ambient atmosphere. Three identical tensile specimens were tested and the average values from the three samples are reported in Table 2. The fracture toughness tests were carried out as described by ASTM standard E-399. These were also performed on a servo-hydraulic MTS machine. The specimens were initially pre-cracked in fatigue at a ΔK level of 10 MPa $\sqrt{\text{m}}$ to produce a 2 mm long sharp crack front. After fatigue pre-cracking, the specimens were loaded in tension and the load-displacement diagrams were obtained in a X–Y plot. From these load displacement diagrams, the P_Q values were determined using 5% secant deviation technique as detailed in ASTM standard E-399. From these P_Q values, the K_Q values were determined using the standard stress intensity factor calibration function. Since all the testing conditions of ASTM E-399 standard were satisfied, the K_Q values determined were all valid K_{IC} values. Six identical compact tension specimens were tested and the average values from six tests are reported in Table 3. V-notched Charpy impact tests were carried out as per ASTM standard E-23 [9]. Six samples were tested at room temperature. The average values from these tests are also reported in Table 3.

Table 1
Chemical composition of the material in wt.%

C	0.92
Mn	5.97
Cr	6.23
S	0.004
P	0.005
Nb	0.11
Al	0.01
Ni	0.01
N_2	0.004

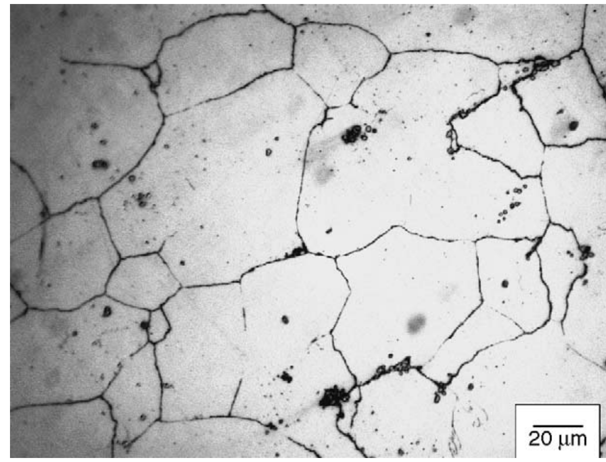

Fig. 1. Microstructure of the steel.

Table 2
Mechanical properties of the material

Yield strength, MPa (ksi)	472.8 (67.73)
Ultimate tensile strength, MPa (ksi)	743.11 (106.5)
Elongation (%)	12.22
Hardness, HRc	21
Strain hardening exponent (n)	0.15

2.3. X-ray diffraction

X-ray diffraction (XRD) analysis was performed to determine the volume fraction of austenite as well as to estimate

Table 3
Fracture toughness and impact strength of the material

Material condition	As-cast and hot-rolled
Fracture toughness, MPa $\sqrt{\text{m}}$	51.40
Impact strength, J	19.5