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Interpretation of cryogenic-temperature Charpy impact toughness by microstructural evolution of dynamically compressed specimens in austenitic 0.4C–(22–26)Mn steels

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Abstract—In this study, the Charpy impact toughness of three austenitic high-Mn steels was evaluated at room and cryogenic temperatures, and interpreted by deformation mechanisms in relation to the microstructural evolution of dynamically compressed specimens. Under dynamic compressive loading, nanocell structures composed of subgrains were formed by the reaction with twins and dislocations, and resulted in a high-strain-rate deformation mechanism that enhanced the strength, ductility and toughness within the stacking fault energy (SFE) range of the twinning-induced plasticity (TWIP) mechanism at room temperature. At cryogenic temperature, the formation of nanocell structures was activated with increasing Mn content, which showed the opposite trend to the room-temperature case. Since the cryogenic-temperature SFEs were lower by ~30% than the room-temperature SFEs, a considerable amount of ε-martensite was formed in the 0.4C–22Mn steel by the transformation-induced plasticity (TRIP) mechanism, while the TWIP mechanism was working, thereby leading to increased Charpy toughness compared to the 0.4C–24Mn and 0.4C–26Mn steels. The Charpy impact toughness results were discussed using a new schematic diagram of deformation mechanisms based on SFE, loading condition and test temperature.

Keywords: High-Mn steel; Charpy impact toughness; Cryogenic temperature; Dynamic compressive test; Twin

1. Introduction

Rapid developments in industry have created a demand for structural steels with enhanced strength, ductility and toughness. Recently, because of the global demand for liquefied natural gas, oxygen and hydrogen, high-Mn steels have been widely used for cryogenic-temperature transport applications such as vessels, containers and plumbing pipes [1–3]. Since structural steels used in these applications may cause serious human, environmental or economic damage should they fracture, high toughness properties are essential, together with strength and ductility [4,5]. In cryogenic-temperature applications, face-centered cubic (fcc) structure metals are widely utilized because of their sufficient toughness at cryogenic temperature, rather than body-centered cubic (bcc) metals, which undergo ductile–brittle transition [6,7]. Aluminum alloys have been conventionally used for cryogenic applications, but their applications are limited because of their relatively low toughness. In large-scale plants or vessels, Al alloys have been replaced by high-Ni-based invar alloys or austenitic stainless steels [8–11]. Ni, a typical austenite stabilizer, is very expensive (about ten times more expensive than any other alloying element of austenitic stainless steels) because the extraction of Ni from Ni ores containing Cu needs many complicated processing steps [12–14]. Recently, efforts have been made to replace expensive austenitic stainless steels with more reasonably priced high-Mn steels which are comparable to austenitic stainless steels in terms of strength, ductility and toughness. Given the economic cost of ecofriendliness, the area in which high-Mn steels find the greatest application is the mass production of high-quality steels requiring reasonable strength and toughness levels [8–10,15–17].

Conventional alloying methods usually pose the problem of deteriorating ductility or toughness as the strength is improved. However, efforts have been made to produce a useful combination of high strength and toughness in high-Mn steels composed of a single phase of austenite by utilizing deformation mechanisms that vary with the stacking fault energy (SFE). The SFE increases with increasing Mn content, and is calculated to be 35–43 $\mathrm{mJ\,m^{-2}}$ in 0.4C–(22–26)Mn steels at room temperature [18]. In this SFE range, the twinning-induced plasticity (TWIP) mechanism is well activated [19,20]. The mechanical twins that form during the deformation prevent the movement of dislocations as these twins result in grain boundary

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refinement, which is known as the dynamic Hall–Petch effect [21,22], and necking is suppressed during tensile deformation due to the high work-hardening rate [21–23]. Thus, high-Mn steels show high tensile strength and ductility simultaneously [24]. Since the SFE decreases by ~30% when the temperature drops from room temperature to the cryogenic temperature of −196 °C [25], the deformation mechanisms can be varied by decreasing the SFE. The transformation-induced plasticity (TRIP) mechanism can then operate, depending on Mn content and test temperature. This variation in deformation mechanism greatly affects the strength and toughness by forming complex microstructures that comprise a mixture of twins, nanocell structures and martensites [18,26,27]. Furthermore, under the dynamic loading condition of the Charpy impact test, such a microstructural evolution occurring near the notch-tip region and pendulum-impacted region, in which dynamic fracture initiation and propagation processes predominate, respectively, becomes more important than the quasi-static loading cases. Thus, studies on dynamic deformation mechanisms are essential for the evaluation of alloy design in relation to SFE, microstructural evolution and process control in order to improve the Charpy impact toughness as well as strength and ductility; however, only limited information is available.

On this basis, it should be possible to successfully fabricate high-Mn steels and to improve their strength and toughness simultaneously. In the present study, therefore, austenitic microstructures containing twins, nanocell structures and martensites were fabricated by varying the Mn content, and their tensile and Charpy impact properties were evaluated at room and cryogenic temperatures. Deformation mechanisms were investigated in relation to the dynamically deformed microstructures at room and cryogenic temperatures, and the correlation between microstructural evolution process and Charpy impact toughness was clarified.

2. Experimental procedure

The chemical compositions of the three high-Mn steels are 0.4C–22Mn, 0.4C–24Mn and 0.4C–26Mn, which are referred to hereinafter as "22Mn", "24Mn" and "26Mn", respectively, for convenience. According to the composition–temperature equations proposed by Curtze et al. [18], the SFE is calculated to be 35, 39 and 43 mJ m^{-2} for the 22Mn, 24Mn and 26Mn steels, respectively, i.e. the SFE increases with increasing Mn content. At the cryogenic temperature of −196 °C, the SFE is calculated to be 23, 28, and 33 mJ m^{-2} for the 22Mn, 24Mn and 26Mn steels, respectively. These steels were fabricated by a vacuum induction melting method. Plates 70 mm thick were homogenized at 1200 °C for 2 h, after which they were hot-rolled at 1100 °C to produce 12 mm thick plates. The final rolling temperature was 930 °C. The hot-rolled plates were then water-cooled to room temperature.

The steel plates were polished and electro-etched in an etchant of 5% perchloric acid + 95% acetic acid, and the microstructures of the longitudinal-transverse (L–T) plane were observed using an optical microscope. Electron backscatter diffraction (EBSD) analysis was conducted by field emission scanning electron microscopy (FE-SEM; S-4300SE, Hitachi, Japan). The data were interpreted by orientation imaging microscopy (OIM) analysis software provided by TexSEM Laboratories, Inc.

Tensile and Charpy impact specimens were obtained from the half-thickness location of the rolled plate. Plate-type tensile specimens (gauge length: 12.6 mm; gauge width: 5 mm; gauge thickness: 1 mm) were prepared in the longitudinal direction. They were tested at room temperature and cryogenic temperature (−196 °C) at a strain rate of 12.6×10^{-3} s^{-1} using a universal testing machine of 100 kN capacity (5582, Instron Corp., Canton, MA, USA). In the case of the cryogenic-temperature tensile test, a low-temperature chamber (20 cm × 15 cm × 15 cm) was attached to the universal testing machine. The 0.2% offset stress was determined to be the yield strength in the specimens showing continuous yielding behavior. Charpy impact tests were performed on standard Charpy V-notch specimens (size: 10 mm × 10 mm × 55 mm: orientation: transverse–longitudinal (T–L)) at room and cryogenic temperatures using a Tinius Olsen impact tester of 500 J capacity (FAHC-J-500-01, JT Toshi, Tokyo, Japan) according to the ASTM E23 standard [28]. Five standard specimens were used for each datum, and the results were averaged with standard deviations. All the specimens showed normal on-notch-tip fracture initiation–propagation behavior. After the Charpy impact test, fracture surfaces were observed by SEM.

A split Hopkinson's pressure bar was used for dynamic compressive tests [29,30]. Cylindrical specimens (5 mm diameter × 5 mm) were prepared vertical to the rolling direction so that their orientation could be matched to the pendulum-impact direction of the Charpy impact test. The specimen situated between incident and transmitter bars was compressed by a striker bar (19 mm diameter) projected at a high speed using an air pressure of 0.2 MPa (impact velocity: 26.7 m s^{-1}), and the strain rate could be controlled by varying the compressive pressure. During the dynamic compression, the incident wave, reflective wave and transmitted wave were detected by strain gages, and recorded using an oscilloscope. Among the recorded wave signals, the average compressive strain rate expressed as a function of time was measured from the reflected wave, while the compressive stress expressed as a function of time was measured from the transmitted wave. Dynamic compressive stress–strain curves were obtained from these two parameters by eliminating the time term. The compressive strain rate during the test was ~2500 s^{-1}. Detailed descriptions of the dynamic compressive test are provided in Refs. [29,30]. Transmission electron microscopy (TEM) specimens were prepared by focused ion beam (FIB; Quanta 3D FEG, FEI, USA) technique of the dynamically compressed specimen, and were observed by TEM (JEM-2100, JEOL, Japan) operating at an accelerating voltage of 200 kV.

3. Results

3.1. Microstructure

Optical micrographs of the three high-Mn steels are shown in Fig. 1a–c. All the steels are composed of austenite grains 5–30 μm in size, and these grains are homogeneously distributed throughout the steel plate. Fine submicron-sized particles are not found. These microstructural results