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# Effect of rare earth cerium on brittleness of simulated welding heat-affected zones in a reactor pressure vessel steel

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**Abstract:** The welding coarse-grained heat-affected zones (CGHAZs) in the undoped and Ce-doped samples of SA508CL-3 reactor pressure vessel steel were simulated using a Gleeble 1500D thermomechanical simulator with a peak temperature of 1320 ºC at the heat inputs of 30, 50 and 100 kJ/cm, respectively. The ductile-to-brittle transition temperature (DBTT) of the simulated CGHAZs was evaluated along with microstructural and microchemical characterizations. The results indicated that Ce could substantially lower the DBTT of the CGHAZs by its microstructural and microchemical effects. After the thermal cycling of welding, the microstructure in the Ce-doped samples was apparently finer than that in the undoped samples, regardless of the lath bainite obtained at the heat inputs of 30 and 50 kJ/cm or the granular bainite acquired at the heat input of 100 kJ/cm, leading to lower DBTTs for the Ce-doped samples. Moreover, grain boundary segregation of Ce occurred apparently in the Ce-doped samples and exhibited a non-equilibrium characteristic. The segregation of Ce could play an important role in lowering the DBTT of CGHAZs or toughening the CGHAZs.

**Keywords:** grain boundaries; non-equilibrium segregation; rare earths; embrittlement; pressure vessel steel

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A pressure vessel is one of the most important parts in a thermal or nuclear power plant, whose size determines the capacity of the power plant. The higher the capacity, the larger the pressure vessel, and the thicker the vessel wall. To improve the efficiency, the welding methods of high heat input are usually used, such as electroslag welding and submerged arc welding. Nevertheless, these welding methods would decrease the cooling rate of heat-affected zones (HAZs) and thus allow the growth of austenite grains, thereby worsening the properties of HAZs, especially the toughness. Coarse microstructure is one of the main factors worsening the toughness of HAZs. Normally, the coarser the microstructure, the lower the toughness of HAZs. The constituents of the microstructure also play an important role in the toughening or embrittling of HAZs. Generally, the acicular ferrite is good for the toughness of HAZs. It can cut the austenite into several pieces prior to bainite transformation. After that, the occurrence of bainite transformation can create fine microstructures[1,2]. For the bainitic steel, typically, the microstructure is composed of granular bainite and lath bainite. Apparently, the M/A (martenite/austenite) constituents or carbide particles and lath ferrite have a considerable influence on the properties of HAZs. In studies by Lan[3,4] and Andia[5], the appearance of M/A constituents deteriorates the toughness of HAZs at the condition of high heat input, and the common mechanism for this is that the boundaries between M/A constituents and matrix are easy to produce microcracks. However, a study by Duan et al.[6] indicates that a mixture of granular bainite, lath bainite and M/A constituents exhibits the best toughness when the M/A constituents are very small and uniformly dispersed in the matrix. Besides the microstructural effect, the segregation of impurity atoms (P or Sb) at austenite grain boundaries produced during welding can reduce the grain boundary cohesion, thereby worsening the toughness of HAZs[7,8].

As is well known, rare earths (REs) such as Ce and La are beneficial to the mechanical properties of steels, especially to the toughness. The REs may improve the temper embrittlement of low-alloy steels by grain refinement and suppression of grain boundary embrittlement[9]. Yu et al.[10] and Yuan et al.[11] found that the REs could segregate to grain boundaries and restrain the segregation of impurities P, Sn and Sb in Fe-based alloys, thereby reducing the grain boundary brittleness. Also, the grain boundary segregation of REs could reduce the grain boundary energy, thereby reducing the driving force of grain growth and suppressing the growth of austenite grains[12–14]. Recently, Jiang and Song[15] demonstrated that the rare earth cerium could enhance the hot ductility of Cr-Mo low alloy steels by its grain boundary segregation. Theoretical predictions[16,17] also indicated that grain boundary segregation of REs could increase the grain boundary cohesion in Fe, leading to toughening of Fe-based materials. In addition, a detailed study by Li

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and Liu[18] showed that the rare earth cerium could shift the critical temperatures $A_{c1}$, $A_{r1}$, $A_{c3}$ and $A_{r3}$ to lower temperatures and meanwhile the continuous cooling transformation (CCT) diagram to both lower temperatures and longer time for many Mn low-alloy steels, thereby affecting their microstructural features.

Based on the above information, it is envisaged that the REs may reduce the brittleness of coarse-grained heat-affected zones (CGHAZs) in steel weldments through their boundary segregation and microstructural influence. To clarify this, in the present work, we examined the effect of rare earth cerium on the brittleness of CGHAZs simulated with different heat inputs by a Gleeble thermomechanical simulator in SA508CL-3 reactor pressure vessel steel. SA508CL-3 steel is a low-C Mn steel alloyed with some amount of Ni and Mo, which is widely used for pressure vessels in the present nuclear power plants[19–21].

## 1 Experimental

Two heats of SA508CL-3 steel, undoped and doped with rare earth Ce, were melted by a vacuum induction melting furnace. The raw materials for the steel melting included pure iron, graphite, ferro-silicon, ferro-manganese and ferro-molybdenum along with nickel and cerium. In the melting, a proper piece of cerium was placed on the bottom of the melting furnace in order to ensure the cerium to be added into the steel. The chemical composition of the steel is listed in Table 1. Obviously, the steel is a C-Mn steel alloyed with a small amount of Ni and Mo. The ingot of each heat of steel (50 kg) was hot rolled into a plate with 16 mm in thickness from which the Gleeble specimens were machined with a size of 11 mm×11 mm×90 mm for subsequent thermal-cycling simulation. A Gleeble-1500D thermomechanical simulator was used to simulate welding thermal cycles of CGHAZs with a peak temperature of 1320 ºC at different heat inputs (30, 50 and 100 kJ/cm). The Rykalin-2D model[22] was employed to simulate these thermal cycles. In the simulation, the thickness of steel plate was chosen as 25 mm. The measured thermal cycles were well consistent with the simulated ones, which are shown in Fig. 1. The cooling periods from 1320 to 500 ºC of the thermal cycles were 29, 107 and 420 s, respectively, for the heat inputs of 36, 60 and 100 kJ/cm, demonstrating that the cooling rate from the peak temperature decreases considerably with increasing heat input. The heat input of 30 kJ/cm could correspond to the submerged arc welding, and the heat inputs of 50 and 100 kJ/cm to the electrogas welding[23–25].

**Table 1 Chemical composition of experimental SA508CL-3 steel (wt.%)**

| | C | Si | Mn | Ni | Mo | P | S | Ce | Fe |
|---|---|---|---|---|---|---|---|---|---|
| Undoped | 0.18 | 0.21 | 1.45 | 0.776 | 0.495 | 0.008 | 0.004 | – | Bal. |
| Ce-doped | 0.18 | 0.23 | 1.41 | 0.770 | 0.500 | 0.008 | 0.004 | 0.068 | Bal. |

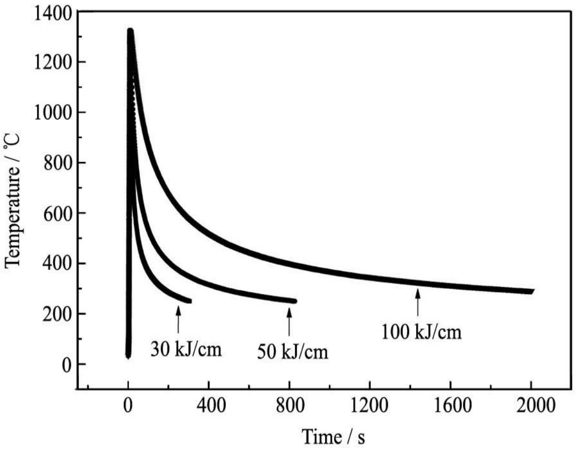

Fig. 1 Thermal cycles in CGHAZs with a peak temperature of 1320 ºC at different welding heat inputs, simulated by a Gleeble 1500D thermomechanical simulator

The ductile-to-brittle transition temperature (DBTT) was used to characterize the brittleness of the simulated CGHAZs. Normally, the higher the DBTT, the larger the brittleness. The DBTT was evaluated by means of impact tests at different temperatures. Non-standard miniaturized rectangular impact specimens with a V-notch were employed with a size of 2.5 mm×2.5 mm×50 mm. The utilization of the miniaturized specimens should be acceptable for a self-contained comparative study. In addition, it is worth mentioning that since the nuclear materials are radioactive after irradiation it is usual to use miniaturized specimens to evaluate their mechanical properties[26,27]. The specimens were soaked in ethanol, which was cooled to different test temperatures by adding liquid nitrogen, followed by impact. In the impact test, each specimen was soaked for at least 10 min at each test temperature and then fractured by impact. An S-4700 scanning electron microscope (SEM) along with image analysis was used to analyze fracture surfaces, and the DBTT was represented by the fracture appearance transition temperature, i.e., the temperature corresponding to 50% brittle fracture and 50% ductile fracture. Microstructural observations were carried out using both optical microscopy (OM) and transmission electron microscopy (TEM). Electron backscatter diffraction (EBSD) equipped on the scanning electron microscope was also employed to demonstrate microstructural features.

A JEM-2100F field emission gun scanning transmission electron microscope equipped with an Oxford INCA energy dispersive X-ray spectrometer (FEGSTEM-EDS) was used to observe high-magnification microstructures and to evaluate grain boundary concentrations of Ce. Field emission of electrons from a very fine tip results in a very high value of brightness. Consequently, an FEG is an ideal electron source for microanalysis. For the JEM-2100F machine, the nominal probe size for microanalysis is 0.5 nm. Three-millimeter diameter disc