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Metallurgical Design of Steel Plates with Advanced Cryogenic Properties for Fabrication of Pressurized-LNG Containers

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This paper discusses the plate development technology for manufacture of the containment system for a new concept of transporting gas by Pressurized LNG. The plates to produce the cylindrical containment system were required to exhibit a combination of strength and toughness at cryogenic temperatures down to −101°C (172 K). The plate toughness was achieved over a range of nickel contents from 2% to 5%, by chemistry control, thermo-mechanical processing and controlled cooling to achieve a combination of martensite, fine granular bainite (FGB) and retained austenite. It was observed that the formation of FGB was required to achieve the toughness.

INTRODUCTION

Critical to the development of the Pressurized LNG (PLNG) technology described in this conference (Bowen et al., 2005; Fairchild et al., 2005; US Patents 2000, 2001) were the development of plates and weldments that exhibit high strength and toughness at a service temperature of 172 K to manufacture the containers for transport. Specifically, the steel plates, weld metal and HAZ have to meet the fracture-toughness target of 0.08 MPa-$\sqrt{m}$ at 172 K and the tensile strength target of 1000 MPa. In order to maintain the economic advantage of the PLNG technology, it was also required that the cost of the plates, the major volume component of the containers, be kept low. Because steel plates based on very high nickel contents (>9%) were considered uneconomical, a maximum level of 5% Ni was identified to preserve the economic incentives. Hence a cost-effective approach was required to impart toughness to steels containing relatively low levels of nickel (i.e. ≤5%). This paper describes a novel approach, consisting of a combination of steel cleanliness and thermo-mechanical processing coupled with phase transformation to achieve the required low-temperature toughness in low nickel steels. Fig. shows a schematic representation of a systematic approach to decrease the Ductile to Brittle Transition Temperature (DBTT) through a series of steps from a value of 240 K for current carbon steels to a value of 172 K required for this technology. Step 1 consists of making a clean steel with low levels of impurity elements, e.g. oxygen, sulfur, phosphorus. The second step consists of minimizing the inclusion content through reducing the oxygen level in the melt. The third step consists of thermo-mechanical deformation to decrease the grain size through controlled recrystallization. The final step is to achieve a final domain size of less that 0.5 micron through phase transformation. Of these, Steps 1 and 2 relate to melting and casting, and because methods to achieve them were developed by the steel companies, the details of these steps will not be detailed here. This paper will concentrate on the grain size refinement through recrystallization and phase transformation, which provided the ultrafine domain size critical to the attainment of the target strength and toughness. Refinement of grain size was identified as the only means of achieving both high strength and toughness in low nickel steels. The science and technology developments to achieve properties in welds and HAZ were also successfully developed for the PLNG technology and will be discussed in a future forum.

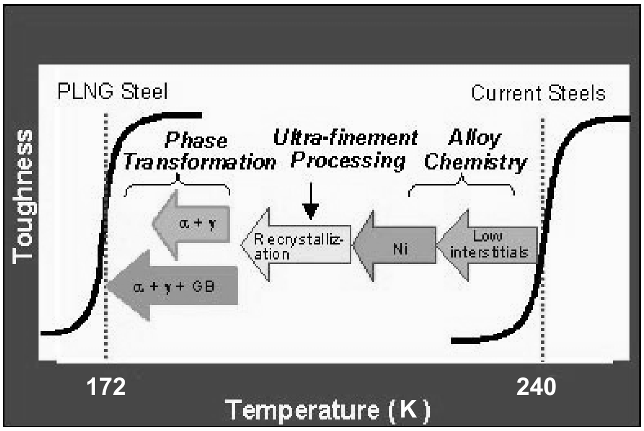

Fig. 1 Schematic representation of approach to achieve enhanced strength and cryogenic toughness in low nickel steels

The dimensions of the plates to be produced were determined based on the dimensions of the container. As the containers were designed to have 5-m diam and 50-m height (see Fig. 2), the plates were required to be 16-m long and 3.3-m wide. This width was essentially determined by the width of the rolls in the hot mill. The thickness of the plates was set at 25 mm, based on the stress calculations from the pressure of the containment and the strength of the steel plates.

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KEY WORDS: High strength, cryogenic toughness, microstructure, Martensite, granular bainite.