Materials Science & Engineering A 718 (2018) 437–448

Contents lists available at ScienceDirect

Materials Science & Engineering A

journal homepage: www.elsevier.com/locate/msea

Phase evolution and mechanical properties of coarse-grained heat affected zone of a Cu-free high strength low alloy hull structure steel

Xuanwei Lei, Shi Dong, Jihua Huang*, Jiang Yang, Shuhai Chen, Xingke Zhao

School of Materials Science and Engineering, University of Science and Technology Beijing, Beijing 100083, China

ARTICLE INFO

Keywords:
High strength low alloy
Weldability
Strengthening
Continuous cooling transformation

ABSTRACT

Weldability of a Cu-free high strength low alloy (HSLA) hull structure steel is studied. Strengthening contributions of this steel are analyzed and phase continuous cooling transformation in simulated coarse-grained heat affected zone (CGHAZ) is investigated. Indeed, strengthening contributions of simulated CGHAZs under heat input 50 and 20 kJ/cm, respectively, are estimated. It shows this Cu-free HSLA hull structure steel is dominated at grain refinement strengthening and supplemented by precipitation strengthening and phase transformation strengthening, while the simulated CGHAZ under heat input 50 or 20 kJ/cm is dominated at phase transformation strengthening and supplemented by solid solution strengthening and grain refinement strengthening. The drawn simulated heat affected zone continuous cooling transformation (SH-CCT) diagram shows this Cu-free HSLA hull structure steel can obtain main lath-like microstructures in a wide cooling rate range with low phase start temperature. Mechanical property tests of simulated CGHAZ samples indicate high strengths and good low temperature impact toughness. All results exhibit this Cu-free HSLA hull structure steel has satisfactory weldability, which suggests its wide potential applications.

1. Introduction

The navy steels of HSLA series, such as HSLA80 and HSLA100, are known for high strength, enhanced low temperature toughness and improved weldability, which are widely used for shipbuilding, bridage, pressure vessels, offshore structures, heavy duty tracks and earth moving equipment [1–3]. These HSLA series steels are generally Cu-bearing and alloyed with high Ni content. Cu-bearing gives a large additional strengthening from fine Cu particles in the matrix and high Ni content induces good low temperature toughness. Cu is favourable in steels for it comes to render more resistant to corrosion and it also benefits for weldability for it increases less carbon equivalent while improves higher strength. But Cu is not considered as such as being a good alloying element since it has bad repercussions, such as harmful to the surface quality and less machinable for steels at high temperatures. Indeed, in a welding process, when the peak temperature is larger than about 1273 K (1000 °C), Cu particles would dissolve badly [4]. From finite number of literatures, the referential welding heat input for navy steels is about 20 kJ/cm [2]. The fast cooling rate in that welding process would generally make no Cu particles precipitate in the matrix. That's to say, the designed Cu content in basement usually has no additional precipitation strengthening contribution [2,5] but mainly causes a relatively smaller solid solution strengthening contribution in CGHAZ. Strength lost in HAZ is partly because of the dissolution of Cu particles. If the strength without Cu particles contribution of CGHAZ of a HSLA steel can be ensured with optimized composition design, the strength of this steel also can be ensured as HSLA80 or HSLA100. This tentative work has been done by Wang et al. and previous study has been carried out [6,7]. The designed HSLA hull structure steel shows high strength (yield strength 870 MPa) and excellent low temperature toughness (210 J at 223 K(− 50 °C)), and also exhibits high low temperature toughness (156, 173 and 181 J at 223 K(− 50 °C)) in CGHAZ under heat inputs of 15, 30 and 50 kJ/cm, respectively. [7] The HSLA hull structure steel gives similar chemical composition with navy HSLA series steel but with very low Cu content (0.2 wt%) and a little more Ni content. In their further work, the chemical composition of the HSLA hull structure steel has been improved and Cu content is reduced to make it Cu-free. This Cu-free HSLA hull structure steel is featured in high strength grade and with low yield ratio. Since welding is a very important working procedure in ship building, it's necessary to give an appropriate evaluation on weldability before its application.

CGHAZ which experiences peak temperature up to 1623 K(1350 °C) or higher has been found to be one typical weakest region in HAZ [8,9]. The mechanical properties of CGHAZ largely represents the performance of HAZ [10,11]. So study on mechanical properties and phase evaluation in CGHAZ could help greatly in evaluating the weldability.

* Corresponding author.
E-mail address: jhhuang62@sina.com (J. Huang).

https://doi.org/10.1016/j.msea.2018.02.008
Received 14 January 2018; Received in revised form 1 February 2018; Accepted 2 February 2018
Available online 03 February 2018
0921-5093/

Table 1
Chemical composition of the Cu-free HSLA hull structure steel.

C	Si	Mn	Ni	Cr	Mo	V	Nb	Ti	Al	N	O
0.045	0.10	1.00	4.08	0.42	0.42	0.040	0.041	0.019	0.022	0.0044	0.0034

In practical welded joint, CGHAZ is very narrow in width make it difficult to extract for investigation. When strength and toughness are measured using true weldment [2], the results are usual on behalf of several fine regions of HAZ. But since welding thermal simulation can generate with Gleeble, the study on phase evaluation and toughness in CGHAZ become easy. A disadvantage for weld thermal simulation is the thermal pinning effect is not considered in austenite grain growth, that the simulated region may not fully reflect the true region in HAZ. But even a slight larger austenite grain size would be caused in CGHAZ by thermal simulation than that by practical welding, thermal simulation can still be an effective technique to study the characterization of CGHAZ [11].

In our previous investigation on practical weld joint of the Cu-free HSLA hull structure steel, the weakest region is found near the fusion line, which suggests CGHAZ is the weakest zone in HAZ. In the present work, phase continuous cooling transformation in simulated CGHAZ of this steel is studied. Together with mechanical properties testing in CGHAZ, the weldability of the Cu-free HSLA hull structure steel is thus discussed.

2. Experimental procedure

The Cu-free HSLA hull structure steel was provided by Lab. of Metal Micro/nano Structure Materials and Lab. of Material Forming Process Simulation and Control in University of Science and Technology Beijing. Specimens of this steel were picked up from a 25 mm thickness plate which was produced by a 500 kg vacuum induction melting furnace and under thermo mechanical control process. Specimens were followed by heat treatment including two times quenching and one time tempering. The average yield strength of the HSLA hull structure steel were tested 820 MPa with standard columnar samples from the 1/4 thickness of plate. The average charp impact value at 223 K (− 50 °C) is 229 J.

The chemical composition of this steel is updated as shown in Table 1. The carbon equivalent is about 0.66 wt%. Specimens from the 1/4 thickness of plate were polished, etched with 4 vol% nital solution and observed by optical microscopy (OM) and scanning electron microscopy (SEM). Specimens were polished again and electrochemically polished using a solution of 5 vol% $HClO_4$ ethanol electrolyte at room temperature for an electron backscattering diffraction (EBSD) experiment by SEM. Microstructures of the steel were further investigated by transmission electron microscopy (TEM). The TEM foils was cut and prepared to wafers by mechanically thinning to about 50 μm in thickness. Three millimeter discs were punched from the wafers and electrochemically-polished using a solution of 5 vol% $HClO_4$ methanol electrolyte. An in-depth study of TEM carbon extraction replicas analysis was focused on types and sizes of precipitates in this steel. TEM carbon extraction replicas were prepared according to conventional procedure [12].

Specimens were picked up again from the 1/4 thickness of plate along the rolling direction and machined into cylinders, 6 mm in diameter and 76 mm in length (Ø6 × 76 mm), then simulated using a Gleeble ®1500 thermo-mechanical simulator. First, to measure A_{C1} and A_{C3} temperature, specimen was heated to 1273 K (1000 °C) with heating rate of 0.056 K/s. Second, specimens were hated at a rate of 280 K/s to peak temperature 1623 K (1350 °C), held for 0.5 s and cooled with different processes. In the first stage of temperature range 1623–1173 K (1350–900 °C) in the cooling process, Rykalin-3D mode for thick plate [13] was used. In the second stage of temperature range 1173–473 K (900–200 °C), linear cooling with each cooling rate of about 0.25, 0.5, 1, 2, 4, 7, 10, 14, 20, 25, 35 and 70 K/s, respectively, was conducted. The linear cooling time from 1073 to 573 K

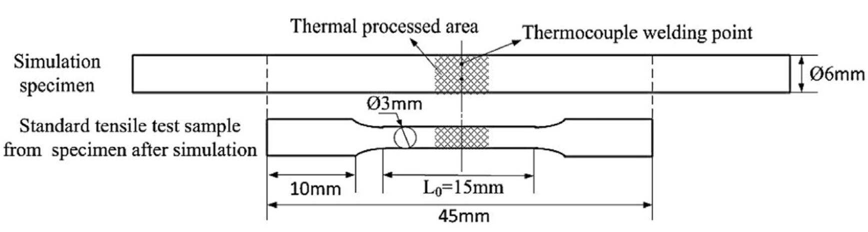

Fig. 1. The standard tensile test sample sizes and location at the simulation specimen.

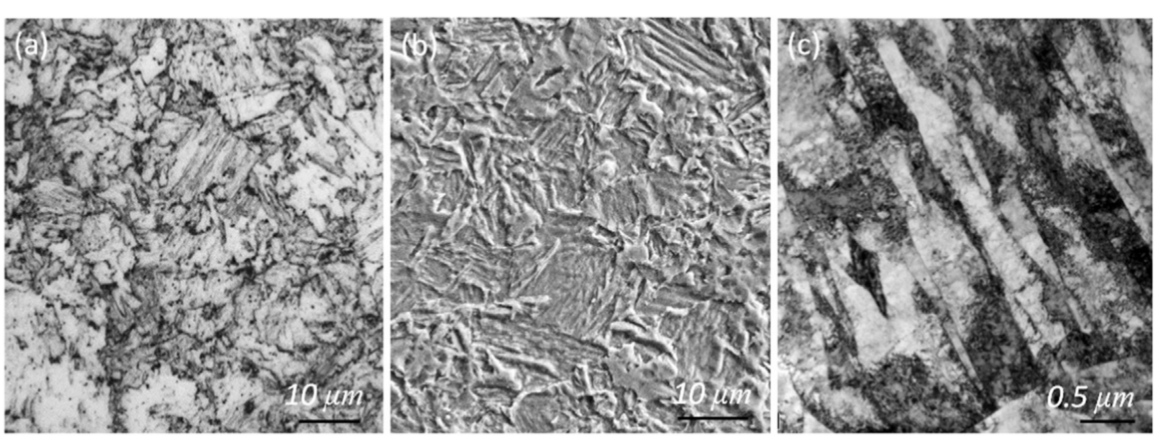

Fig. 2. Microstructure of the Cu-free HSLA hull structure steel by (a) OM, (b) SEM, (c) TEM.