Impact Toughness of Heat-Affected Zones of 11Cr Heat-Resistant Steels

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Abstract

Aiming at the requirements of structural steel in Gen-IV nuclear reactor, the high-chromium martensitic heat-resistant steels containing 10–12% chromium were developed. The toughness of heat-affected zones (HAZs) is one of the important factors for evaluating the weldability of steels. In this paper, the simulated HAZs were fabricated using tempered SIMP steels. The effects of microstructures on the impact toughness of materials were analyzed using Vickers hardness tester, optical microscope, transmission electron microscope. Experimental results demonstrated that the HAZs of weldment were poor in toughness, much lower than that of the base metal. However, after experiencing post-weld heat treatment, the toughness of the HAZs increased greatly. The toughness became better in terms of CG-HAZ, FG-HAZ and IC-HAZ for the two steels, regardless of as-welded or after PWHT. Compared with SIMP7 steel, chemical compositions, such as C, Si, Mn and Cr, were adjusted to a lower content; the toughness of base metal and simulated HAZs was better in the case of SIMP11. The conjunct roles of dislocation density and carbon contents retained in the martensite led to poor impact toughness of the as-welded HAZs, because dislocations and carbon atoms affected the inner stresses within lattices.

Keywords High-Cr F/M heat-resistant steel · Heat-affected zones · Impact toughness · Carbide precipitations

1 Introduction

The design of accelerator driving system (ADS) in association with the lead–bismuth (Pb–Bi) eutectic liquid cooled fast reactor requires the materials of high corrosion resistance as it is to be used under high-temperature liquid metal condition [1]. High-chromium F/M heat-resistant steel is much suitable to be used in Pb–Bi liquid cooled fast reactor, due to its good mechanical behaviors and corrosion/irradiation resistance in comparison with other candidates [2, 3].

In order to improve the corrosion/irradiation resistance, C and Si elements are added in high-chromium heat-resistant steels. However, high contents of alloying elements, such as Cr, C, Mn and Si, increase the hardening tendency of steel and eventually result in poor weldability, particularly the poor toughness of HAZs [4–8]. The heat-affected zone (HAZ) of high-chromium heat-resistant steel was usually believed to be the weakest region in a welded joint in respect of impact toughness, because of the quenched martensite and even δ -phase [9–12]. In-service experiments indicated that in most cases when the creep crack initiation and growth occur, defects predominate near the weldment [13, 14]. Moreover, welded joints of thick plates were fabricated for creep tests, and type IV cracking as the prominent damage form was found in the fine-grained HAZ [15]. The variations in microstructures in HAZs could lead to different mechanical properties, such as tensile strength and impact toughness. The HAZs always have higher tensile strength and lower impact toughness than those of base metals [16, 17], and the differences in mechanical properties between the HAZs and its neighbor base metal contributed to the multiaxial stress state in the weldment during high-temperature operation evenly leading to the type IV crack [18]. The impact

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toughness of HAZ not only affects the service behavior but also is an important factor for evaluating the weldability of materials [17]. Hence, the study of effects of impact toughness and related mechanism is very significant for the newly developed high-chromium heat-resistant steel. Microstructures containing ferrite phase generally show better toughness. Tempered martensitic phase contributed greatly to better toughness than quenched martensitic phase as weld for high-chrome F/M steel. Tempering heat treatment is a method to increase the toughness.

On the basis of the newly developed SIMP [19] steels for the fourth-generation nuclear power plant, this paper presents a basic study on the impact toughness of thermally simulated HAZs of SIMP7 and SIMP11 before and after post-weld heat treatment (PWHT). Using Vickers tester, optical microscope (OM) and transmission electron microscope (TEM), the impact toughness of the materials is analyzed. Related mechanism of the impact toughness of HAZs of high-chromium heat-resistant steel is investigated.

2 Experimental

Two newly developed high-chromium heat-resistant steels by the Institute of Metal Research of Chinese Academy of Sciences, named as SIMP steels, were employed in this work, and their primary chemical compositions are listed in Table 1. After casting, the ingot was forged at the temperature range of 1100–1200 °C and subsequently rolled at the temperature from 1100 to 900 °C. The temperatures of normalizing and annealing heat treatments were 1100 °C and 760 °C; thereafter, specimens were cooled in the air, respectively.

Quenching dilatometer (QD) was used for measuring the transition points (A_1 and A_3) at various heating rates. The specimen size is 3 mm in diameter and 10 mm in length. Combining finite element method (FEM), characteristic thermal cycle curves were obtained, plotted and used to simulate coarse-grained HAZ (CG-HAZ), fine-grained HAZ (FG-HAZ) and intercritical HAZ (IC-HAZ), and more details could be found in the reference [19]. The Charpy

impact toughness of base metal and simulated HAZs of two steels was tested at room temperature (about 25 °C), and the simulated HAZs (with 11 mm×11 mm×55 mm in sizes with thermal simulator) were fabricated with thermal simulator. Post-weld heat treatment was conducted at 760 °C and cooling in air. Microstructures and microhardness of the HAZs before and after PWHT were observed and measured, respectively.

3 Results and Discussion

3.1 Transition Temperatures of Martensite to Austenite During Heating

During heating, martensite transforms to austenite, beginning at A_1 point and ending at A_3 point. As shown in Fig. 1, the transition points were obtained at the heating rates ranging from 0.05 to 180 °C/s. The transformation region from austenite to martensite (temperature differences between A_1 and A_3) of SIMP11 is much narrow than that of SIMP7, when heating rates are larger than 5 °C/s, indicating that more transition time from martensite to austenite for SIMP7 is required than SIMP11 at the same heating rate. With the increase in heating rate, A_3 point increases fast within

Fig. 1 Phase transformation temperatures (A_1 and A_3) for SIMP7 and SIMP11 steels during heating

Table 1 Chemical compositions of the materials

Steels	Chemical compositions (wt%)							
SIMP7	C	Si	Mn	P	S	Cr	W	V
	0.29	1.77	0.7	0.007	0.001	11.24	1.38	0.18
	Ta	Fe						
SIMP11	0.14	Bal						
	C	Si	Mn	P	S	Cr	Ni	Ti
	0.22	1.22	0.52	0.004	0.0043	10.24	0.008	<0.01
	Al	Cu	W	V	Nb	Ta	Fe	
	<0.01	0.008	1.45	0.18	<0.01	0.11	Bal	

0.05–10 °C/s, but becomes slower when the heating rates are higher than 10 °C/s. A_1 point increases significantly from 0.05 to 10 °C/s for the two steels. After that, A_1 of SIMP7 increases slowly with heating rates, and the increasing rates of A_1 for SIMP11 become slower till 40 °C/s. From 0.05 to 10 °C/s, A_1 changes from 870 to 925 °C and from 884 to 928 °C for SIMP7 steel and SIMP11, respectively, with the heating rate. A_3 always increases from 990 to 1130 °C with heating rates ranging from 0.05 to 130 °C/s. For SIMP11 steel, experimental results indicated that A_1 and A_3 points

changed greatly with various heating rates. Because the heating rates of HAZs are higher during welding, the points of A_1 and A_3 within 100–150 °C/s are considered.

3.2 Characteristic Thermal Curves for the HAZs

According to the results in Sect. 3.1, 1330 °C, 1130 °C and 1030 °C were selected as peak temperatures for the characterization of CG-HAZ, FG-HAZ and IC-HAZ, respectively. In respect of FEM analysis, the characteristic temperatures were defined and are shown in Fig. 2.

Specimens were heated to the peak temperatures of CG-HAZ, FG-HAZ and IC-HAZ at the heating rate of 140 °C/s. The cooling time from 800 to 500 °C ($t_{8/5}$) is 27 s, 26 s and 26 s for CG-HAZ, FG-HAZ and IC-HAZ, respectively. Optical morphologies of the as-welded CG-HAZ, FG-HAZ and IC-HAZ and the base metal of SIMP11 are shown in Fig. 3a–d, respectively. CG-HAZ and IC-HAZ consist of martensite with prominent thick martensitic laths, while no prominent laths could be observed in FG-HAZ. Compared with the microstructure of base metal, martensitic laths of CG-HAZ and IC-HAZ are much coarser. In Fig. 3b, martensitic laths are small and grain boundaries are not very clear. δ -phase was not found in all of the as-welded HAZ specimens. As shown in Fig. 4, HAZs of SIMP11 steel after PWHT were observed by OM. Figure 5 shows the

Fig. 2 Characteristic thermal curves of CG-HAZ, FG-HAZ, IC-HAZ for SIMP11 steel

Fig. 3 Microstructures of **a** as-welded CG-HAZ, **b** as-welded FG-HAZ, **c** as-welded IC-HAZ, **d** base metal of SIMP11 steel by OM

Fig. 4 Microstructures of **a** CG-HAZ, **b** FG-HAZ, **c** IC-HAZ of SIMP11 steel after PWHT by OM

microstructures of HAZs of SIMP7 after PWHT observed by OM. Martensitic laths in SIMP7 were coarser than those in SIMP11.

3.3 Toughness of the HAZs Before and After PWHT

As shown in Figs. 6 and 7, the impact toughness of base metal and simulated HAZs of SIMP7 and SIMP11 was measured before and after PWHT, respectively. In Fig. 6, the impact toughness of base metal of SIMP11 (79 J) is much higher than that of SIMP7 (24 J). The chemical compositions of SIMP11 steel, such as C, Si, Mn and Cr etc., were adjusted on the basis of SIMP7. As-welded HAZs of the two steels are very low with no more than 10 J of impact energy, and HAZs of SIMP11 except CG-HAZ are higher than those of SIMP7. The impact toughness increases in the sequence of CG-HAZ, FG-HAZ and IC-HAZ for the two steels. With the modification of chemical composition, SIMP11 steel and its HAZs have much higher impact toughness after PWHT, while the modification has little effects on as-welded HAZs. The impact toughness of HAZs of SIMP7 steel increases after PWHT, and those of the CG-HAZ and FG-HAZ are lower than BM, while that of IC-HAZ is higher than BM. FG-HAZ and IC-HAZ have better toughness than the base metal of SIMP11. PWHT can significantly improve the toughness of HAZs of SIMP steels.

3.4 Microhardness of the HAZs of SIMP11

As shown in Fig. 8, the microhardness of HAZs of SIMP11 steel was measured before and after PWHT. Its value is very high for the as-welded HAZs and relatively higher in terms of CG-HAZ (about 603 HV), FG-HAZ (about 560 HV) and IC-HAZ (about 460 HV). The valid regions of specimens for CG-HAZ, FG-HAZ and IC-HAZ are not identical in width, increasing with the heat amount input. The valid regions indicate the characteristic microstructures of HAZs by thermal simulation. Under elevated temperatures, carbides decompose and carbon atoms dissolve in the austenite grains. Since austenite transforms completely into martensite after cooling, subsequently the HAZs show much higher hardness due to higher content of carbon in martensite at room temperature [20]. After PWHT, the microhardness of HAZs decreases significantly and gets closer to the base metal (about 250 HV). The hardness of CG-HAZ region is still the highest among all HAZ specimens.

3.5 Microstructures of the CG-HAZ of SIMP11 Before and After PWHT

Figure 9a and b shows the microstructures of CG-HAZ before and after PWHT by TEM, respectively. As shown in Fig. 9a, the boundaries of martensitic lath are very clear, and

Fig. 5 Microstructures of **a** CG-HAZ, **b** FG-HAZ, **c** IC-HAZ of SIMP7 steel after PWHT by OM

Fig. 6 Charpy impact energies of as-welded CG-HAZ, FG-HAZ, IC-HAZ and base metal of SIMP7 and SIMP11 steels

Fig. 7 Charpy impact energies of CG-HAZ, FG-HAZ, IC-HAZ and base metal of SIMP7 and SIMP11 steels after PWHT

a significant amount of dislocations is found within the laths and at its boundaries, while the carbides are rarely found in the specimen before PWHT. As shown in Fig. 9b, the boundaries of martensitic lath become unclear, and few dislocations could be found, and considerable amounts of carbides are observed at both of lath boundaries and its matrix. PWHT promotes the recovery of dislocations formed during weld. A huge amount of dislocations in the simulated CG-HAZs, as shown in Fig. 8a, is formed during fast heating

and cooling procedure due to severe plastic deformation [21]. Some researchers reported that the dislocation density could not drop apparently during creep in the long term, while it dropped apparently in the early stage of tempering [22]. Therefore, the hardness of HAZs decreases sharply after PWHT, while the value of CG-HAZ is still the highest due to the high density of dislocations generated. The strain hardening tendency of martensite increases due to lattice distortion [23]. A number of dislocations decrease during

Fig. 8 Microhardness of HAZs of SIMP11 before and after PWHT

PWHT. Strain hardening tendency of the HAZs decreases, and its impact toughness increases greatly after PWHT. For the martensitic steel, an increase in the density of dislocations enhances the strength while reducing its ductility and toughness [24, 25]. Therefore, the impact toughness of HAZs was better after PWHT. In combination with deformation, deformation twinning and glide of dislocations facilitate lattice invariant shear processes, which will help to accommodate high internal stresses [26, 27]. CG-HAZ has the severest deformation among all HAZs due to thermal procedure, and its toughness is the lowest.

Based on selected area electron diffraction (SAED) analysis, the diffraction patterns of carbide precipitation (Cr_xC_y) are in accordance with the direction of $[112]$ of face-centered cubic structure (FCC), and thus, the kind of precipitation could be confirmed as M_{23}C_6 , which was marked with white arrows in Fig. 9b. These precipitates should be formed during the carbon atom diffusion after

they escaped from the martensitic matrix when experiencing PWHT. Amounts of carbides (Cr_{23}C_6) dissolved into the martensitic matrix of HAZs during welding and the carbon content distributed in the matrix become higher. There is not enough time for the carbides to segregate from martensitic matrix again during the subsequent fast cooling procedure. Thus, plenty of carbon atoms are confined in the martensitic matrix, and supersaturated solid solution of martensitic phase is produced and kept at room temperature, so that more carbon content in martensitic matrix leads to much high level of inner stress and reduces toughness. Subsequently, carbon content in martensitic matrix reduces in HAZs after PWHT. The residual dislocations in CG-HAZ are still in high level compared to FG-HAZ and IC-HAZ after PWHT. Moreover, the grain sizes of original austenite are very higher and the microstructures are mostly coarse among all of the heat-affected zones. The coarse martensitic microstructures lead to poor toughness [28]. Therefore, the hardness of CG-HAZ is still higher than those of FG-HAZ and IC-HAZ after PWHT, and the toughness of CG-HAZ is lower.

4 Conclusions

To investigate the weldability of SIMP steels, this work was focused on the impact toughness of simulated HAZs fabricated by thermal simulator. Using the hardness tester, OM and TEM, the impact toughness of simulated HAZs was obtained. With the consideration of chemical compositions and tempering heat treatment, their effects and related mechanism of impact toughness were discussed. Relative conclusions are listed as follows:

Fig. 9 Microstructures of CG-HAZ of SIMP11 steel: **a** before, **b** after PWHT

1. The toughness of as-welded HAZs of SIMP7 and SIMP11 steels was poor, while those became better after PWHT. The toughness data were even higher than its base metal for SIMP11 steel except CG-HAZ after PWHT.
2. The toughness became better in terms of CG-HAZ, FG-HAZ and IC-HAZ for the two steels, regardless of as-welded or after PWHT.
3. Compared with SIMP7 steel, chemical compositions, such as C, Si, Mn and Cr, were adjusted to a lower content; the toughness of base metal and simulated HAZs was better in the case of SIMP11.
4. The conjunct roles of dislocation density and carbon contents retained in the martensite led to poor impact toughness of the as-welded HAZs, because dislocations and carbon atoms affected the inner stresses within lattices.

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