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Failure mechanisms and design of dissimilar welds of 9%Cr and CrMoV steels up to very high cycle fatigue regime

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ABSTRACT

Cross-weld and pure base metal specimens machined from dissimilar welded joints of 9%Cr and CrMoV steels were cyclically loaded up to very high cycle fatigue at 500 °C under load ratio of zero. Results showed fatigue strength of the welds was greatly weakened, lower than base metals. A transition of failure mechanisms from geometrical soft zone in heat-affected zone of CrMoV steel to micro-defects induced cracking at weld metal was responsible for decreasing fatigue strength reduction factor with the increasing of fatigue lifetime. A sound fatigue design requires careful selection of filler metal and consideration of soft zone and micro-defects.

1. Introduction

Dissimilar metal welding technology has been widely employed in manufacturing engineering structures and components in power plants, nuclear reactors, and petrochemical plants [1], due to lower cost and easiness to join pieces together to meet different property requirements [2,3]. Several studies have been reported since 1980s regarding to the failure of dissimilar joints that affects expected design life of components [4]. Fatigue is estimated to account for around 90% of failures in welded structures and components [5,6] with poor weld design and improper process parameters as the main cause. It is thus critical to investigate high cycle fatigue (HCF) and very high cycle fatigue (VHCF) behaviors of dissimilar welds upon which optimization of welding parameters should be based, and from which the approach to design against fatigue is expected.

The failure mechanisms and design of welded joint under cyclic loadings have been thoroughly explored during the past several decades [5–10]. Comparing with uniform materials and structures, welded joints consist of mismatched materials macroscopically, discontinuous microstructures microscopically, weld flaws, and residual stresses, which makes the prediction of fatigue failure a complicated issue [11]. It is known that fatigue strength of welded joint is not necessarily dependent on initial strength distribution and does not increase with enhancement of material strength [12], and metallurgical soft zones have been verified as weaker zone of welds as reported in [13,14]. Fatigue performance of welds is thus regarded as inferior to base metal (BM) due to geometrical factors [6], while little is documented quantitatively on the fatigue strength reduction relative to BM and the associated mechanisms, particularly for dissimilar welded joints. It is generally accepted that fatigue resistance is essentially related to microstructures at which damage is gradually developed until failure [15]; nevertheless, the roles of micro-defects, especially resulted from welding, and temperature cannot be neglected in the VHCF regime where failure is more dominant by micro-defect induced cracking [16–18]. This imposes revisiting rules of fatigue design of welded joint up to the VHCF regime [19] by balancing the significance of microstructures and micro-defects, an issue needs clarifying.

Therefore, in the present work, specimens machined from dissimilar welded joints of 9%Cr and CrMoV steels developed for power plant applications were cyclically loaded up to the VHCF regime at high temperature. Fatigue crack initiation behavior of welded joint and pure BMs was comparatively discussed to elucidate the underlying mechanisms of fatigue strength reduction, and the implication in fatigue design and safety of welds for long-term service requirement.

2. Materials and experiment

2.1. Materials and microstructures

The two base metals (BMs) to make dissimilar welded joint are 9%Cr and CrMoV steels whose chemical compositions are listed in Table 1. Using Cr2Mo1 steel as filler metal, the dissimilar structure was welded by submerged arc welding process, after which a post weld heat treatment was applied to relax residual stresses and stabilize microstructures along the dissimilar welds [20–22].

The whole welded joint was etched in different solutions for

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Table 1
Chemical compositions of the two BMs (in wt.%).

Materials	C	Si	Mn	Co	Cr	Ni	V	Mo	S	P	Fe
9%Cr	0.14	0.14	0.52	1.84	9.15	0.27	0.20	1.24	0.10	0.02	Balance
CrMoV	0.24	0.01	0.83	–	2.47	0.80	0.29	1.16	0.04	0.02	Balance

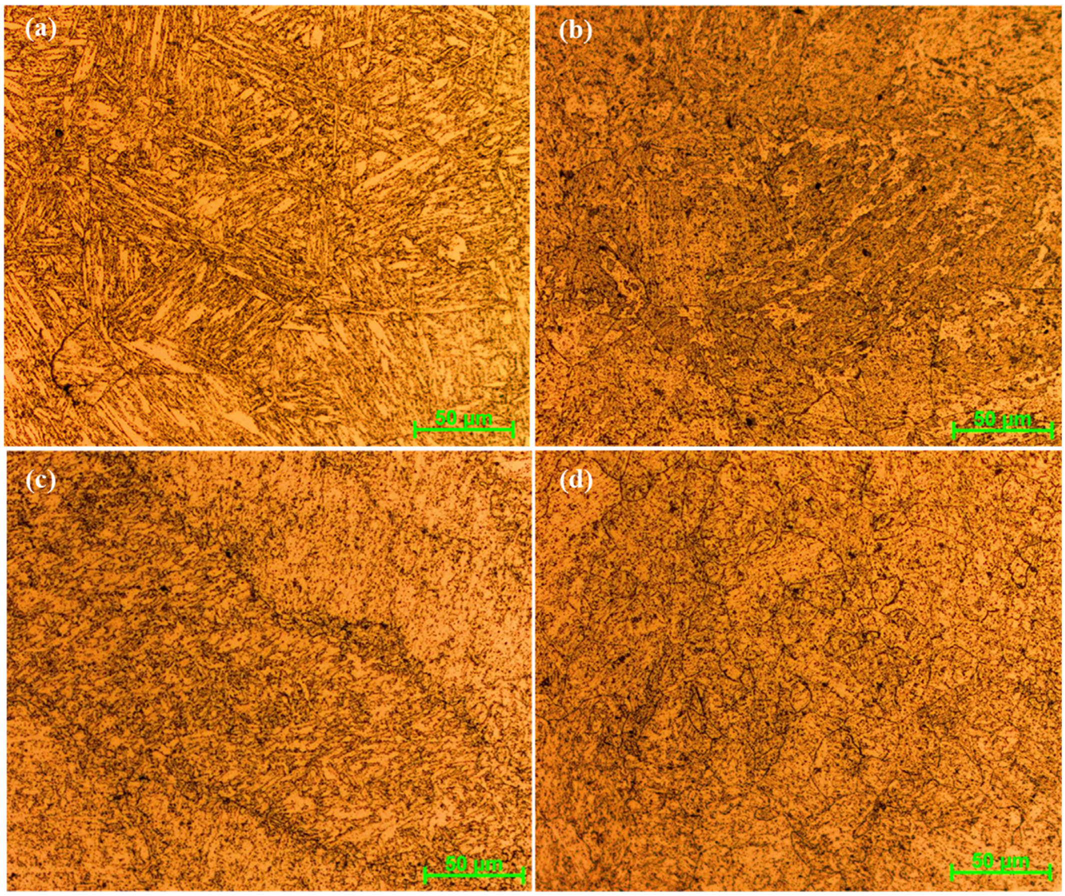

Fig. 1. OM observation of microstructures of the dissimilar welded joint: (a) BM of 9%Cr steel, (b) BM of CrMoV steel, (c) and (d) WM.

microstructure observation by optical microscopy (OM), i.e., CrMoV steel and weld metal (WM) were etched by a solution of 4% HNO3 + ethanol, while 9%Cr steel was etched by a mixed solution of HCl + HNO_3 + H_2O with a proportion of 3:5:5 because of its high corrosion resistance. Fig. 1 shows the microstructures of BMs and WM. It is observed that microstructures in 9%Cr steel mainly contain tempered martensites (Fig. 1a) while those in CrMoV steel include tempered bainities and tempered martensites (Fig. 1b). Interestingly, as indicated in Fig. 1c and d, the WM contains a periodic distribution of small equal-axial and large column-like grains in the form of tempered bainites and tempered martensites with the boundaries clearly observed, which is essentially related to multi-layer and multi-pass welding processes. Fig. 2 presents the microstructures within the two HAZs at corresponding BMs. A clear interface, i.e., the fusion zone, locates between WM and the HAZ at CrMoV steel (Fig. 2a) where contains a gradient distribution of coarse-grained to fine-grained microstructures. In addition, the amount of lathy martensites are greatly reduced which informs a direct influence on micro-hardness distribution. Fig. 2d shows typical microstructure morphology within the HAZ at 9%Cr steel side where tempered martensites are observed.

2.2. Tensile and micro-hardness tests

The tensile specimens were prepared by machining them as pure BMs and cross-weld. For cross-weld specimens, the parallel section part, with an equal diameter *d* of 10 mm, which actually covers the whole WM, HAZ and part of the BMs, has a total length of 55 mm, including 22 mm length of WM and 2 mm width of HAZ at both sides of the two BMs. Specimen for micro-hardness measurement was machined from the welded joint with a size of 50 mm × 10 mm × 5 mm, mechanically polished, and then chemically etched. Micro-Vickers hardness measurements were conducted along the specimen centerline on a hardness tester (HXD-1000TM) at room temperature by holding a test load of 4.9 N for 10 s. The measurement interval in WM and BMs was fixed at 0.5 mm, while the distance was 0.3 mm in HAZ.

2.3. High cycle fatigue test

Cross-weld specimens for fatigue testing, with surface roughness less than 0.2 μm, were prepared with a gauge length of 48 mm and a diameter of 6 mm, as illustrated in Fig. 3. Axially stress controlled fatigue tests with a stress ratio, *R*, of 0, were carried out at 500 °C to examine the fatigue performance at high temperature and related failure mechanisms. The testing temperature of 500 °C was chosen