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Study on fatigue property and microstructure characteristics of welded nuclear power rotor with heavy section

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ABSTRACT

The fatigue property and microstructure characteristics of the welded joint for nuclear power rotor with heavy section, were systematically reported in this paper. The welded joint microstructure is inhomogeneous for NiCrMoV rotor made by narrow gap submerged arc welding (NG-SAW), which could affect the properties in different zones of welded joint. As one of the important indicator to evaluate the running performance of welded rotor, the fatigue crack propagation behavior of the base metal (BM), weld metal (WM) and heat affected zone (HAZ) was comparatively studied. It was found that the fatigue crack propagation threshold (ΔK_{th}) of BM was higher than that of WM and HAZ as stress ratio (R) was 0.1, but ΔK_{th} was very close to each other as R increased. The microstructure, revealed by an optimized corrosive process, was granular bainite in WM and tempered martensite in HAZ, leading to their approximately equivalent resistance of fatigue crack propagation with BM. The experimental results showed that fatigue properties of welded joint for NiCrMoV rotor with heavy section could meet the design requirement, and also push NG-SAW into manufacturing large size rotor.

1. Introduction

With the development of economy, demand for energy increased greatly around the globe. It was reported that the thermal power industry contributed more than 80% of electricity and environmental costs in China [1]. Nuclear power, as a kind of green energy, attracts much more attentions attributing to its efficiency, reliability and economic feasibility, and also it could meet over 20% of the power requirement for electricity in the world at present [2,3].

Turbine rotor plays an important role in the whole power plant, it is necessary to improve rotor's performance through various methods. NiCrMoV steels, as a commonly materials used to manufacture low pressure (LP) rotors in steam turbine [4], which are hot forged to manufacture high quality dense rotors. However, hot forging requires an expensive heating furnace and a large-sized press, and subsequent machining [5]. Especially for large scale rotor forge, it is difficult to manufacture large size heavy section rotor with high and uniform quality. In this case, welding method becomes an appropriate alternative to fabricate large size rotor.

With increasing capacity combined the requirement to reduce the delivery time and obtain various properties in the integrated structure, welding has been gradually used in power industry to manufacture large components such as welded turbine rotors [6]. In particular, multi-layer or multi-pass techniques are often utilized in the welding of thick plates [7,8] attributing to their advantages to normalize the pre-layer and/or pre-pass microstructure and therefore increase the ductility and improve the final quality [9,10]. The common weld techniques include oxyacetylene welding (OAW), gas tungsten arc welding (GTAW) or tungsten inert gas welding (TIG), submerged arc welding (SAW), plasma transferred arc welding (PTA), etc. [11]. Among which narrow gap SAW (NG-SAW) process is a high quality welding process with a very high deposition rate and commonly used to join thick sections in the flat position. Also, it was deemed that SAW could increase the productivity and decrease the product cost [12,13]. With the application of NG-SAW in the manufacture of the steam turbine rotor, the cost of rotor production was anticipated to be significantly reduced and meanwhile the efficiency could be obviously improved.

Besides, fatigue is, for many critical components, the primary failure mode [14]. Fatigue resistance, especially the performance of fatigue crack propagation, is an important issue in material development and life design of the components used in power plants [15]. In general, fatigue crack propagation of the relatively long crack is divided into three regimes: the near-threshold regime, the Paris regime and the unstable regime. In the Paris regime, the fatigue crack growth rate da/dN is linearly related to the stress

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intensity factor range ($\Delta K = K_{max} - K_{min}$) in a double logarithmic plot. The introduction of the stress intensity factor range ΔK and fatigue crack propagation rate per stress cycle da/dN, introduced by Paris et al. [16], has made it possible to predict the fatigue crack propagation behavior. In the threshold regime, the value of threshold stress intensity factor range (ΔK_{th}), which is a critical parameter in the fatigue design of structural parts and components, is influenced by the load ratio, environment, microstructure and mechanical properties of materials.

Until now, many studies have been conducted on the fatigue crack propagation behavior of aluminum alloys [17–19], magnesium alloys [20–22], titanium alloys [23,24] and Cr–Mo steels [25], etc. However, there is still an ongoing discussion on relevant mechanisms which can explain fatigue crack growth behavior in some multi-phase materials. Previous studies on welded joints indicated that the microstructure have some effects on da/dN and ΔK_{th} decreased with increasing the stress ratio [15,26]. However, few investigations involving the fatigue crack propagation for huge section rotor and corresponding structure details are available.

For nuclear power rotor with heavy section, it is hard to achieve an integral forging rotor with uniform and high quality. Attribute to its small weld deformation and less filler wire consumption, narrow gap welding method provides an effective method to make a large scale rotor by welding separate forging parts. Narrow gap submerged arc welding (NG-SAW) was employed in this test for its higher efficiency compared with narrow gap tungsten inert gas welding (NG-TIG), even though the weld quality of NG-TIG was better than that of NG-SAW. But for CrNiMoV steel rings with 200 mm super thickness and 2000 mm diameter, it took around 250 h non-stop to finish five weld seams for one rotor using NG-SAW. In contrast, at least 1500 h non-stop was required for NG-TIG. In order to investigate the properties of weld joint made by NG-SAW whether meet the design requirement and also provide test data for design reference, the fatigue cracking propagation and threshold were investigated in this paper. And also the correlation between property and microstructure was studied to help further understand the effect of weld joint on the rotor performance.

As for the welded nuclear power rotor, the application of welded joint could bring some influence on the properties of the whole rotor. And it is significant to compare the fatigue crack propagation rate and fatigue threshold of base metal (BM), weld metal (WM) and heat affected zone (HAZ) and therefore probe the feasibility and reliability to manufacture heavy section rotors by welding method. In this paper, the ΔK_{th} under different stress ratio R of the NiCrMoV rotor with 2 m in diameter, was systematically investigated. In particular, the macrostructure details of the BM, WM and HAZ of the welded joint were clearly revealed by the optimized corrosive agent.

2. Experimental procedure

The material used in this investigation was 25Cr2Ni2MoV (wt.%) welded rotor steel manufactured by multilayer submerged arc welding with narrow gap. The filler wire is the low alloy steel with about 1.5–2.2 wt.% Ni. The chemical composition of the base metal and filler metal was listed in Table 1. Standard specimens adopted in the fatigue crack propagation experiments were measured at the Zwick HPF100 high fatigue testing machine by the constant stress ratio amplitude experiment. The specimens in the fatigue testing were the standard compact tensile (CT) specimen prepared according to ASTM standard E647. Before the fatigue test, the pre-crack was made via cyclic loading. The length of the crack was measured on both sides of the CT specimens with optical microscope with accuracy of 0.01 mm. And the average length of the both sides was determined as the crack length.

After the fatigue test, all specimens were cut longitudinally. One part was used to analyze the fatigue crack propagation path and the other part was broken open to observe the fracture morphology. Micro-hardness measurements were conducted along the specimen center line on a hardness tester at room temperature by holding a test load of 500 N for 5 s. The samples were polished and etched with 4% Nital and Picric acid solution. Then the macrostructure, microstructure and chemical microanalysis of different zones in various weld joints were observed and analyzed by optical microscope (OM, Zeiss Image A2 m), X-ray diffraction (XRD, 3 kW D/MAX-2200) with Cu Kα radiation (λ = 0.154056 nm), scanning electron microscope (SEM, JSM-6700F by Hitachi High-Technologies Corp.), and energy diffraction spectrum (EDS: INCA by Oxford). Moreover, transmission electron microscope (TEM, JEM-2010F), including bright-field and selected area electron diffraction (SAED) modes, were used to reveal the microstructure details of the joint.

3. Results and discussion

3.1. Fatigue crack propagation behavior and the effect of stress ratio (R) on ΔK_{th}

The stress ratios ($R = K_{min}/K_{max}$) [27] with value of 0.1, 0.5, 0.7 and 0.9 were selected to study their effects on fatigue crack propagation at room temperature. The relationship between the fatigue crack propagation rate (da/dN) and the stress intensity factor amplitude (ΔK) was plotted in a double logarithmic plot and shown in Fig. 1(a)–(c), and all of which were integrated in Fig. 1(d) so as to more clearly highlight the difference of da/dN among BM, WM and HAZ specimens.

The stress intensity factor amplitude ΔK for CT specimens could be calculated according to Eq. (1) [25]:

$$\Delta K = \frac{\Delta P}{B\sqrt{W}} \frac{(2+\alpha)}{(1-\alpha)^{3/2}} (0.886 + 4.64\alpha - 13.32\alpha^2 + 14.72\alpha^3 - 5.64\alpha^4) \quad (1)$$

where W is the specimen width, a is the crack length, $\alpha = a/W$, ΔP is the applied loading amplitude, and B is the specimen thickness.

In Fig. 1(a)–(c), it was found that da/dN decreased gradually with decrease of ΔK for BM and WM. As for HAZ, the change of da/dN with ΔK was similar to that of BM and WM, yet no obvious decrease was detected at small stress ratio 0.1 and 0.5. And this phenomenon could be attributed to the non-uniform microstructure in HAZ. In order to shed much light on the relationship of da/dN and ΔK, the curves in Fig. 1(a)–(c) were integrated in Fig. 1(d) to clearly exhibit their differences. Take the specimen of $R = 0.1$ for example, it was clearly observed that the $(da/dN)_{BM} < (da/dN)_{WM} < (da/dN)_{HAZ}$ at same ΔK, reflecting that the fatigue resistance of BM was super than others. But the small difference implied approximately equivalent fatigue resistances obtained in these three zones as far as its practical application was concerned.

When the crack growth rate da/dN < 1×10^5 mm/cycle, the fatigue crack propagated in the near-threshold regime and it propagated to the Paris regime while the crack growth rate 1×10^5 mm/cycle < da/dN < 1×10^3 mm/cycle. The difference of da/dN for different R in near-threshold regime was much larger than that in Paris regime, indicating that the influence of R on da/dN was dominated in the near-threshold regime.

Table 1
Chemical composition of rotor steel (BM) and filler metal (FM) (wt.%).

Elements	C	Si	Mn	P	S	Cr	Mo	V	Ni	Cu
BM	⩽0.30	⩽0.12	0.10–0.30	⩽0.15	⩽0.15	2.15–2.45	0.60–0.68	⩽0.20	2.00–2.50	⩽0.17
FM	<0.12	<0.15	<1.50	<0.01	<0.01	0.40–0.60	0.30–0.50	<0.01	1.50–2.20	<0.10