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Optimized Thermo-Mechanical Treatment Condition for Enhancing Fracture Toughness of 9Cr-Nanostructured Ferritic Alloy

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1. Introduction

The success in the development of future reactors is believed to largely depend on the capability of core materials. It is known that the existing materials have limitations such as when applied to harsh condition of extremely high dose and high temperature. The known limitations are the high swelling and low strength in austenitic stainless steels, radiation-induced embrittlement in refractory metals [1-3], and phase instability, swelling and radioactivity buildup in irradiation in nickel-based superalloy

Recently, the nanostructured ferritic alloys (NFAs), advanced oxide dispersion strengthened (ODS) alloys, with an enhanced high-temperature strength and a high swelling resistance were developed. However, the fracture behaviors describing the material resistance to crack initiation and growth in this temperature region have been rarely investigated, although the NFAs were designed to operate at high temperatures, typically above 550°C. A few recent researches have reported that the fracture toughness of high strength NFAs is very low at above 300°C [4, 5].

To overcome this drawback of NFAs, the optimized condition for thermo-mechanical treatments (TMTs) that can modify the microstructure of the 9Cr base NFA were developed.

2. Experimental

The toughness tests were conducted for NFAs up to 700°C using MTS 810 servo-hydraulic test machine in conjunction with high vacuum furnace. The pre-alloyed Fe-9Cr base metallic powder and 0.3 wt.% Y_2O_3 oxide particles were mixed and mechanically alloyed by ball milling. The mixed powder was sealed in 3 inch diameter mild steel cans, degassed, and extruded. The as-extruded coupons were isothermally annealed or controlled-rolled at 900-1000^{o}C for 20 or 50 % total thickness reduction. The schematic TMT schedules are presented in Fig. 1. The determination of TMT temperature range was guided by the results of CALPHAD calculation and crystallographic analyses.

The tensile and fracture were conducted at 700^{o}C for the samples those were hot rolled at 975^{o}C with 50% area reduction. The accelerated creep tests were conducted at 700^{o}C.

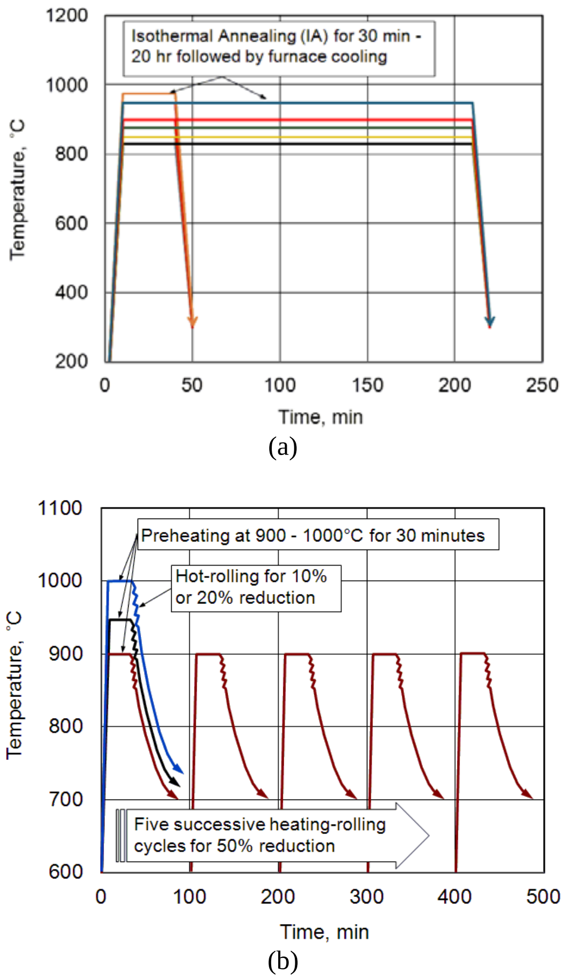

Fig. 1. Schematics of the TMT processes applied to 9Cr-NFAs: (a) Isothermal Annealing (IA) treatments and (b) Controlled Rolling (CR) treatments.

3. Results and Discussion

As shown in Fig. 2, all of the IA treatments increased fracture toughness of as-extruded 9Cr-NFA to at or above 150 MPa√m at RT. In the 500°C test dataset, although the two cases of anneals at 850°C and 950°C resulted in K_{JQ} values higher than 100 °C, fracture toughness appears to be much lower. A known, typical behavior for NFAs is that fracture toughness is relatively high at low temperatures and becomes significantly lower at elevated or high temperatures [6].

Such a typical behavior for NFAs, i.e., high-to-low toughness transition with temperature, was found for the 9Cr-NFA after various IA treatments.

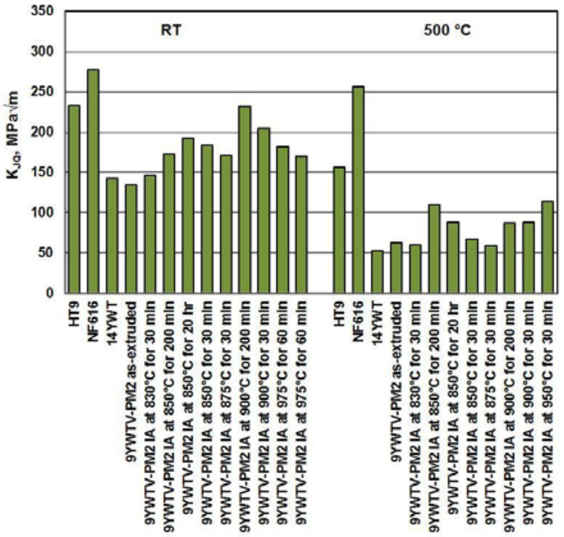

Fig. 2. Fracture toughness at room temperature and 500 °C before and after isothermal annealing treatments in the 9Cr-NFA.

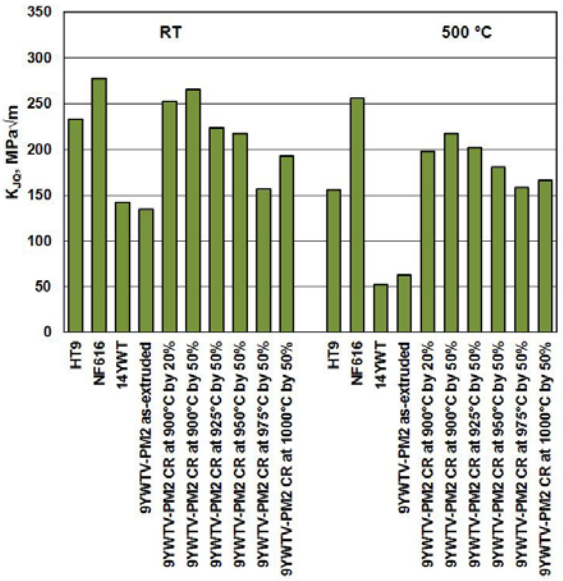

Fig. 3. Fracture toughness at room temperature and 500 °C before and after hot-rolling treatments in the 9Cr-NFA.

The improvement of fracture toughness by CR treatments is the 9Cr-NFA. All the CR cases compared in Fig. 3 display K_{JQ} values above 150 MPa√m at RT as well as at 500°C. A noticeable behavior is that the typical decrease of fracture toughness at high temperatures is not observed in the CR treated alloy. In particular, the highest fracture toughness values were measured with the 20% and 50% CR treatments at 900°C among all NFA cases. It is also observed in this comparison that the multi-step 50% CR treatment at 900°C yields slightly higher fracture toughness than that after 20% CR treatment. Therefore, we chose the multi-step 50% CR for the other CR treatment.

4. Summary

The enhancement of fracture toughness of 9Cr-NFA was significant after controlled rolling. It's fracture toughness was as high as those of non-ODS F/M steels. In particular, the 9Cr-NFA controlled-rolled at 900°C resulted in the best fracture toughness among NFAs (> 150 MPa√m at both representative temperatures: RT and 500°C. More detailed microstructural and mechanical characterizations for selected materials, i.e., the 9Cr-NFA after 50% CR at 900 °C are underway.

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