Assessment of Fracture Mechanical Characteristics Including Welding Residual Stress at the Weld of Ni-base Super Alloy 617

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Abstract. So far, it has become known that the most effective methodology for green power plant systems is to increase the generative efficiency of steam power plants. The core technology for increasing the generative efficiency is to improve the performance of steam turbines. In order to improve the performance of steam turbines, since the temperature of operating steam should be elevated greatly, it is very important to develop a high temperature material that is able to enable both durability and reliability under extreme environments above 700oC. Among the materials developed so far, it is known that the most practical and applicable materials are Ni-based alloys. However, in order to apply these Ni base alloys to the rotor of a steam turbine, it is necessary to first guarantee mechanical reliability of the weld.

In this study, firstly, after numerically analyzing the welding residual stress at the weld of Ni base super alloy 617. And then the fracture mechanical characteristics at the weld including welding residual stress were assessed. From the results, the fatigue crack growth rate of the weld those were post weld heat treated does not show large difference compare to not heat-treated ones. These results mean that the weld of Ni base super Alloy617 is not influenced remarkably by post weld heat treatment in the metallurgical and mechanical changes. However, the da/dN- ΔK curves taking account welding residual stress into at the HAZ of a welded joint increased by 19.8% compared with the results that were not taken account welding residual stress into. Therefore, when Alloy 617 is used as a material of the green power plant systems, it is necessary to consider seriously the welding residual stresses at weld in the process of the safe design and management.

Introduction

Some of the topical issues in the world today are to address environmental pollution and develop green energy. One of the pollutants of utmost concern is exhaust gases, specif., CO_2 gas, from thermal power plants that use fossil fuels. Therefore, it is important to reduce exhaust gases for mitigating environmental pollution. So far, ever since it has become known that the most effective methodology for green power plant systems is to increase the generative efficiency of thermal power plants, many researchers have tried to develop related technologies. The core technology for increasing the generative efficiency is to improve the performance of steam turbines [1]. In order to improve the performance of steam turbines, since the temperature of operating steam should be elevated greatly, it is very important to develop a high temperature material that is able to enable both durability and reliability under extreme environments. Among the materials developed so far, it is known that the most practical and applicable materials above 700^{o}C are Ni-based alloys. However, in order to apply these Ni alloys to the rotor of a steam turbine, it is necessary to first develop the following: welding technologies to weld similar and dissimilar materials; welding stress analysis; post-weld heat treatment technology; and mechanical property testing procedures under high temperatures above 700^{o}C. In this study, Alloy 617, which is a Ni- based super alloy, was investigated to secure its reliability for welding technology and technical information. In this study, firstly, after numerically analyzing the welding residual stress at the weld of Ni base super alloy 617 and assessed fatigue strength of the welded joints those were post weld heat treated and not. And next the fatigue crack growth behaviors at the weld were assessed under the lower fatigue limit. Then finally the fracture mechanical characteristics at the weld including welding residual stress were assessed.

Welding Residual Stress Analysis at the Weld of Alloy 617

Modeling for Finite Element Analysis A seven-pass welded Alloy617 plate model was considered in this study. The chemical composition and mechanical properties at room temperature are presented in Tables 1 and 2, respectively. This material is using in thermal power plant. The groove for welding was machined in a narrow gap U-type [2, 3]. The welding heat input and condition for each pass are given in Table 3. The thickness of the model was 12.7 mm. Axisymmetric three-dimensional finite element analysis (FEA) model was used for analyzing the welding residual-stress. The cross-section and the multi-pass welded plate for the finite element model are shown in Fig. 1. The area represents the layers of the weld bead that are determined by the actual weld coupon. Finer meshes that used eight-node elements were generated in the weld metal regions to handle the greater non-linearity and to obtain accurate results. Hyper-mesh®, which are commercial pre- and post-processors, respectively, were used for mesh generation. ABAQUS was employed for the transient-temperature analysis and the subsequent residual-stress analyses. The total number of elements was 368,550 and the total number of nodes was 385,112.

Table 1. Chemical composition of Alloy 617

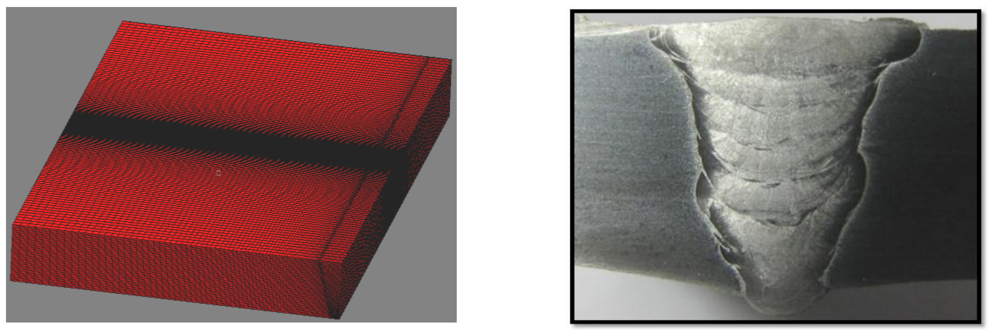
Material	Ni	Cr	Co	Mo	Al	C	Fee	Mg	Si	S	Ti	Co	B
Alloy617	44.5	20.0~ 24.0	10.0~ 15.0	8.0~ 10.0	0.8~ 1.5	0.05~ 0.15	3.0	1.0	1.0	0.015	0.6	0.5	0.006

Table 2. Mechanical properties of Alloy 617

Density [g/cc]	Specific heat capacity at 28℃[J/Kg℃]	Melting Point [℃]	Thermal conductivity at 500℃[W/m℃]	UTS [MPa]
8.36	419	1332~1380	20.9	755

Table 3 Welding condition and heat input

Pass	1	2	3	4	5	6	7
Current [A]	120	150	180	180	180	180	180
Voltage[V]	10	13	16	16	16	16	16
Travel speed[mm/min]	90						
Heat input[J/mm]	800	1600	1920	1920	1920	1920	1920



(a) 3-dimensional FEA model (b) Cross-section of the weld

Fig. 1 3-dimensional FEA model for the weld of Alloy617 plate

Assumption and Simulation Procedures The uncoupled thermal-mechanical analysis was conducted, which means that the temperature fields and histories were calculated from the thermal analysis and then used as an input data for the subsequent stress analysis. Identical time steps were used for both thermal and mechanical analyses. The heat-source model for welding simulation used the lamp function heat input model shown in Fig. 2 [4]. In Fig. 2, the actual welding time for the arc to travel across a unit thickness of the model is t_1+t_2.The numerical procedures for the uncoupled thermal-mechanical analysis are shown in Fig.3. In performing the temperature analysis, it was assumed that the initial temperatures of base and weld metals were assumed at a constant room temperature (21 °C). The material properties (Fig. 4) used in the analysis were temperature-dependent. However, the conductivity and specific heat in the molten pool were assumed to be constant. The effect of the latent heat of fusion, which is the change in the internal energy during melting or solidification, was also considered in the thermal analysis. The heat loss coefficient that was applied to all exposed surfaces was 0.0817 W/m²·°C (0.0001 Btu/in²·°F).

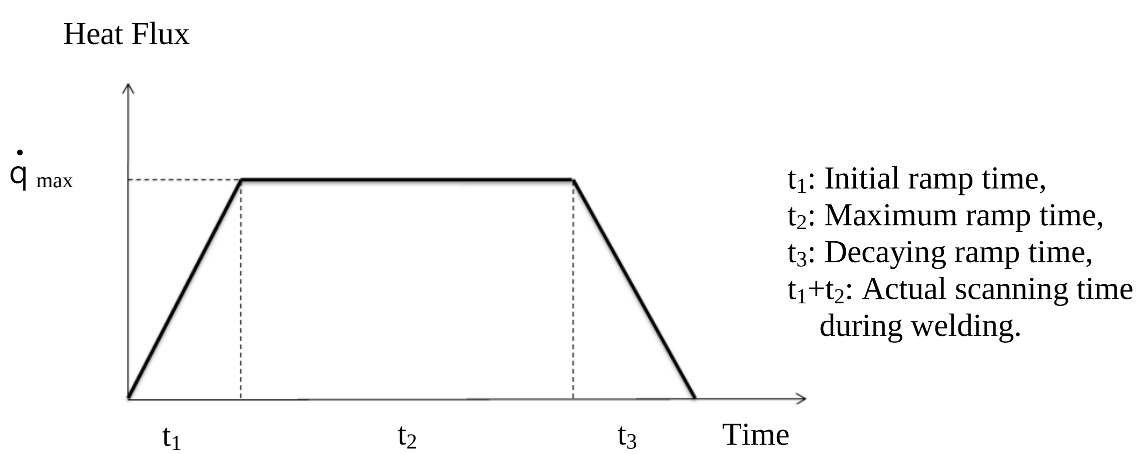


Fig. 2. Shape of the ramp function heat input model [4].

Other thermal boundary conditions, such as radiation and convective influences on the microstructures and cooling rates in the weld metal, as well as heat losses or gains from phase transformation, were neglected. In the stress analysis, the mechanical and physical properties, viz., the yield stress, elastic and plastic modules, and thermal expansion coefficient, were considered to be temperature dependent. The element-rebirth technique [5] was employed to include the multi-pass weld metal deposition effects. With this technique, the elements that simulated each weld pass were grouped at the model-generation stage. During analysis, these element groups, which represented weld passes, were first removed and then reactivated at a specified moment to simulate a given depositional sequence of weld passes. When a group of weld elements was activated, specific initial temperatures were imposed at all nodes that were associated with the weld elements.

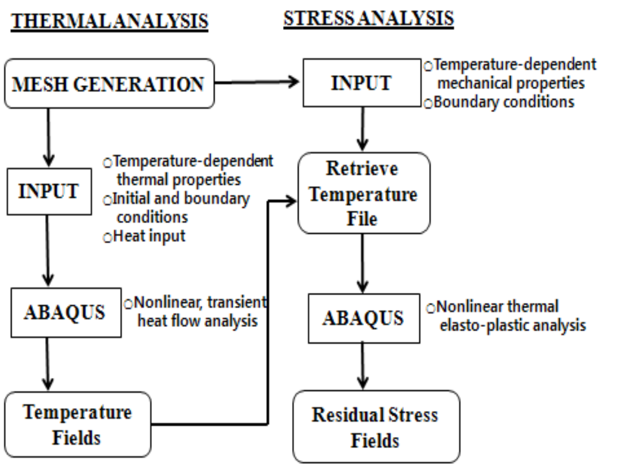


Fig. 3 The numerical procedures for the uncoupled thermal-mechanical analysis

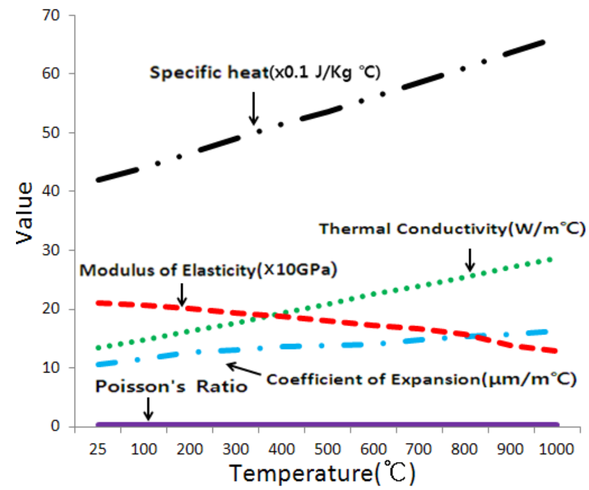


Fig. 4. The temperature dependent material properties of Alloy 617

Results and Discussion The numerically predicted longitudinal and transverse welding residual-stress distributions on the top surface are presented in Figs. 4 and 5. The peak stress value on the longitudinal direction was predicted around 560 MPa, and the peak stress value on the transverse direction was predicted around 100 MPa. In multi-pass welding, the residual stresses that are generated from the earlier passes dominate the residual stresses of the later passes (and the final pass). In this manner, since welding residual-stress distributions in multi-pass welds are very complex and large, it is necessary to consider the welding residual-stress for the strength assessment of multi-pass welded Alloy617 in the weld design and damage analysis.

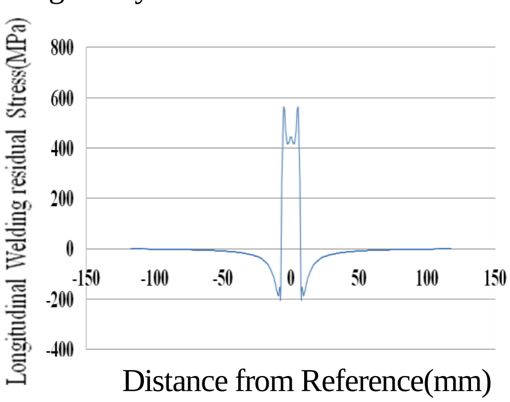


Fig. 4 Longitudinal welding residual stress distribution on the top surface of a seven pass welded Alloy 617 plate

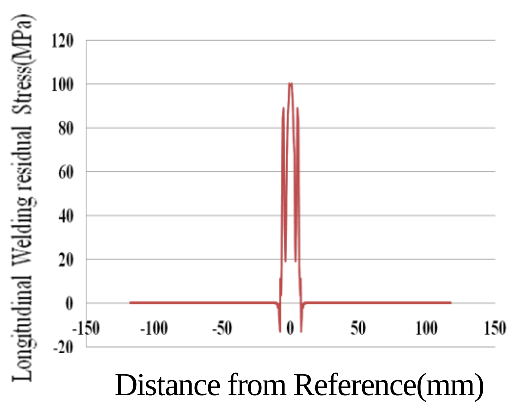
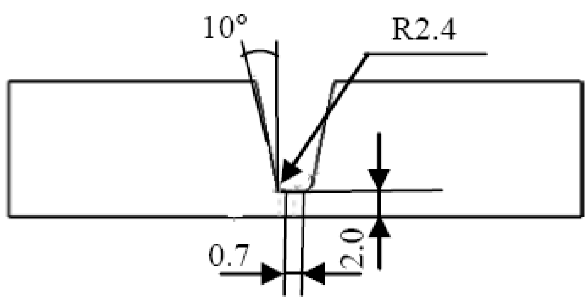


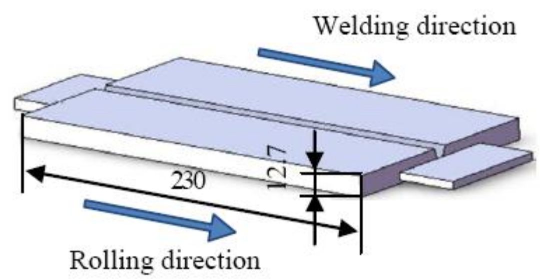
Fig. 5 Transverse welding residual stress distribution on the top surface of a seven pass welded Alloy 617 plate

Assessment of Fracture Mechanical Characteristics including the welding residual stress in an Alloy 617 weld

Specimen and Test Procedure DCEN TIG welding technology was used for welding of Alloy 617 plate. The welding processes including the electrode shape, arc length, welding wave mode (CW or pulse), welding heat input, the Ar-2.5% H_2 shield gas, etc., were controlled through welding monitoring system. The welding direction was made parallel to the rolling direction of the base metal, as shown in Fig. 6. The groove shape was machined in a U-groove for narrow gap welding. When welding was completed for each pass, the surface conditions of the weld bead were carefully observed, and the welding condition was confirmed. The filler metal used was Tissen 617. Configuration of the test specimen to assess fatigue crack growth behavior of a multi pass welded Alloy617 is as shown in Fig. 7. The CT (compact tension) specimen in Fig. 7 includes the weld metal, HAZ (heat affected zone), and the base metal. As shown in Fig.7, all specimens were prepared in an orthogonal direction to the weld line. An artificial notch was machined in the area of HAZ, and then pre-cracked in 3mm for the fatigue test in air. The fatigue tester was used a material testing system(MTS810, capacity:100kN), and fatigue test was conducted under the condition illustrated in Table 4. Electric potential variation during fatigue test was measured by using the DCPD method illustrated in Fig. 8 [6, 7]. The fatigue crack growth was calculated by a calibration curve of Fig. 9, which is a relationship between the voltage (V) and fatigue crack length (a) that was obtained through the fatigue test in air.



(a) U-groove with a narrow gap.



(b) Welding direction

Fig. 6 U-groove with a narrow gap and the welding direction for Alloy 617 plate

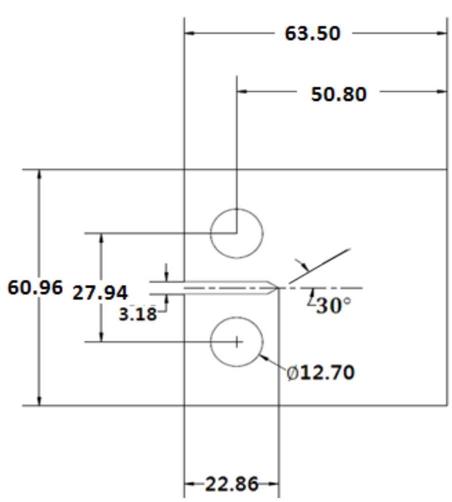


Fig 7. Configuration of CT specimen

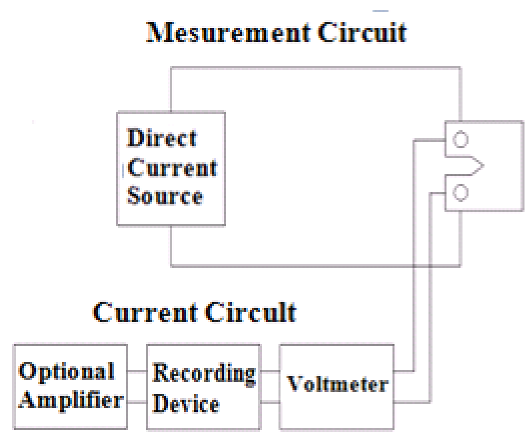


Fig. 8 Schematic diagram of a DC potential system

Table 4 Fracture mechanical fatigue test condition for a multi-pass welded Alloy 617 plate

Conditions	Contents	
Loading condition	Load ratio ($R = P_{min}/P_{max}$)	0.1
	Load range(ΔP)	Constant
	Maximum load (P_{max})	12060N
	Load frequency(f)	20Hz (sine wave)
Environmental condition	Temperature	R.T
	in air	

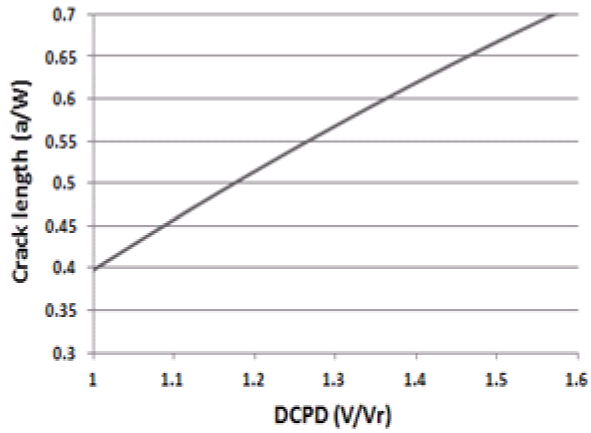


Fig. 9 Relationship between a/W and V/Vr

Result and Discussion Welding processes are vital in the production and maintenance of pipelines and power plants in the area of heavy construction. However, welding processes produce residual stresses such as those in Figs. 4 and 5 owing to the large nonlinear thermal loading created by a moving heat source. Since this formidable residual stress generation by a fusion welding process increases the cracking driving force and reduces the resistance to brittle fracture as well as environmental fracture, it is necessary to evaluate the fracture characteristics regarding welds of the material for reasonable safety and integrity diagnoses of facilities, reliable life prediction of degraded materials, and the establishment of an economical term of inspection. Thus, the crack growth rate in the Alloy 617 weld was fracture-mechanically assessed after taking into account the welding residual stress. In this study, an effective stress intensity factor taking into account the welding residual stress was applied in Forman's equation. The modified Forman equation [8] is defined as follows.

$$\frac{da}{dN} = \frac{C(\Delta K_{eff})^m}{(1-R_{eff})} \quad \text{for } R>0 \qquad \text{------(1)}$$

In Eq. (1), C, m: material constant, R: stress ratio, da/dN: crack growth rate (m/cycle),

ΔK: stress intensity factor range (MPa m $^{3/2}$).

$$\Delta K_{eff} = (K_{\max} + K_{residual}) - (K_{\min} + K_{residual}) = K_{\max} - K_{\min} = \Delta K \qquad \text{------(2)}$$

$$R = \frac{\sigma_{mim}}{\sigma_{\max}}, \quad R_{eff} = \frac{\sigma_{\min} + \sigma_{res}}{\sigma_{\max} + \sigma_{res}} \qquad \text{------(3)}$$

Substituting (2) and (3) into (1), we get: $$\frac{da}{dN} = \frac{C(\Delta K)^m}{(1-R_{eff})} \qquad \text{------(4)}$$

In Eq. (3), the magnitude of the welding residual stress (σ_{res}) is derived from the numerical result at the HAZ of the welded pipe from Fig. 4. Fig. 10 shows the comparison of the da/dN-ΔK curves rearranged using Eq. 4. The da/dN-ΔK values, after taking account into the welding residual stress at the HAZ of the welded plate, increased by 19.7% than that of not included one. From the results, when Alloy 617 is used as a material in thermal power plant, it is necessary to carefully consider welding residual stresses at the weld in the process of safe design and management. Thus, it is expected that the results such as the nominal stress range (Δσ) and the stress range taking account into the welding residual stress(σ_{res}), and fracture mechanical da/dN-ΔK curves revealed in this paper could provide fundamental data and information for such purposes. Table 5 illustrates the C and m values in Paris' law.

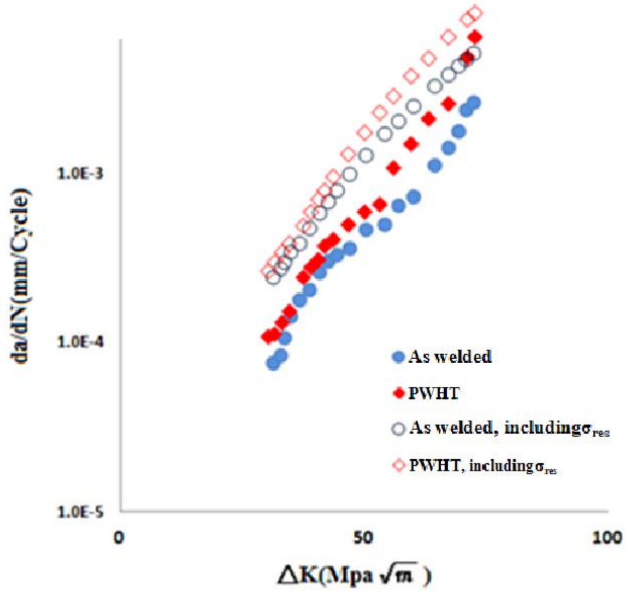


Fig.10. Comparison of the da/dN-ΔK curves between taking account into the welding residual stress(σ_{res})and not

Table 5. C and m of Paris's law

Condition	C		m	
		Included σ_{res}		Included σ_{res}
As welded	2.0E-10	9.0E-10	3.76	3.57
PWHT	3.0E-11	2.0E-10	4.33	4.05

Summary

Alloy 617, which is a Ni- based super alloy, was investigated to secure its reliability for welding technology andmechanical properties. In this study, firstly, after numerically analyzing the welding residual stress at the weld of Ni base super Alloy 617 And then the fracture mechanical characteristics at the weld taking account welding residual stress into were assessed.

Summarized conclusions are as follows;

1) The peak stress value on the longitudinal direction was predicted around 560 MPa, and the peak stress value on the transverse direction was predicted around 100 MPa. In multi-pass welding, the residual stresses that are generated from the earlier passes dominate the residual stresses of the later passes (and the final pass). In this manner, since welding residual-stress distributions in multi-pass welds are very complex

and large, it is necessary to consider the welding residual-stress for the strength assessment of multi-pass welded Alloy617 in the weld design and damage analysis.

2) The fatigue crack growth rate of the weld those were post weld heat treated does not show large difference compare to not heat-treated ones. These results mean that the weld of Ni base super Alloy617 is not influenced remarkably by post weld heat treatment in the metallurgical and mechanical changes.

3) The da/dN-ΔK values, after taking account into the welding residual stress at the HAZ of the welded plate, increased by 19.7% than that of not included one. Therefore, when Alloy 617 is used as a material in thermal power plant, it is necessary to carefully consider welding residual stresses at the weld in the process of safe design and management.

Acknowledgements

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