INTERNATIONAL JOURNAL OF PRECISION ENGINEERING AND MANUFACTURING Vol. 17, No. 9, pp. 1195-1200 SEPTEMBER 2016 / 1195
DOI: 10.1007/s12541-016-0143-4 ISSN 2234-7593 (Print) / ISSN 2005-4602 (Online)

Manufacturing and Mechanical Evaluation of Cooled Cooling Air (CCA) Heat Exchanger for Aero Engine

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KEYWORDS: Aero engine, Turbine blade cooling, Brazing, Fine tube, Heat exchanger

Recent studies on improving the efficiency of gas turbine engines have focused on increasing the inlet temperature of gas flowing into the turbine. For the high inlet temperature, it requires the development of a super-alloy based material that can withstand harsh operating conditions. However, it is essential to utilize alternative solutions such as turbine blade cooling technology. Unfortunately, lightweight, high performance, and high mechanical reliable heat exchangers for aircraft have not yet been examined because of the difficulties associated with design optimization and reliability verification under high temperatures and pressures. The purpose of this study is to develop a manufacturing process for a heat exchanger that can be used in aircraft gas turbine engines. The manufacturing process involved preparing fine tubes through multi-step drawing and annealing processes, and joining these to a tube sheet through brazing. In this work, we reported on the total fabrication processes and mechanical integrity tests of a cooled cooling air (CCA) heat exchanger for the aircraft turbine engine. Through the work, a prototype model of a heat exchanger based on a gas turbine assembly was then developed using each of the individual processes. An X-ray CT test and an endoscopy test were performed to inspect the heat exchanger. The results indicated good manufacturing integrity; thus, the developed heat exchanger can be used for cooling turbine blades.

Manuscript received: March 10, 2016 / Revised: May 19, 2016 / Accepted: May 20, 2016

1. Introduction

Gas turbine engine manufacturers are taking a part in several projects focusing on the development of eco-friendly gas turbines that emit less carbon dioxide to the atmosphere. Existing gas turbine engines for aircraft follow a simple cycle of high-pressure compression, combustion, low-pressure expansion, and exhaust. There are several ongoing studies focusing on improving the efficiency of an engine that follows such a simple cycle. Among the various methods considered, raising the temperature of gas flowing into a turbine is believed to be effective in increasing the efficiency.[1,2] However, developing novel materials that can withstand such high temperatures more than 1600°C is not easy.[3] For this reason, turbine-cooling technology should be examined instead of developing novel materials.[2,3]

A heat exchanger is one of core components of a gas turbine that can cool turbine blades. The development of heat exchangers for aero gas turbines is urgently required. Heat exchangers are not yet to be applied to aero gas turbine engines because it is difficult to select an appropriate material, design a lightweight structure that can withstand high temperatures and pressures, and evaluate its reliability.[4-7]

This paper shows the total fabrication process of a cooled cooling air (CCA) heat exchanger that was firstly developed in Korea for installation into a real civil aircraft engine (see Fig. 1). The heat exchanger can be operated under harsh conditions like temperature of 1000 K and pressure of 50 bar. It is set a target temperature drop of 300°C of the hot air through heat exchange with the cold air. It consists of a manifold that serves as a channel for heated gas, a brazed tube sheet that supports tubes, a case that guides cooled air, and baffles that prevent vibration. The brazing process is applied to join tubes and tube sheet.[8-11]

2. Manufacturing of Fine Tubes

2.1 Precise drawing process of fine tubes

In this study, Inconel 625 superalloy was used as the material for

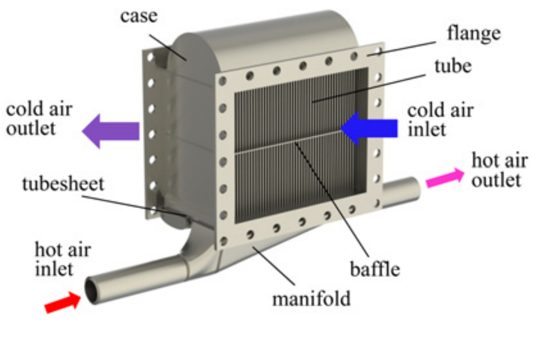


Fig. 1 Developed CCA heat exchanger

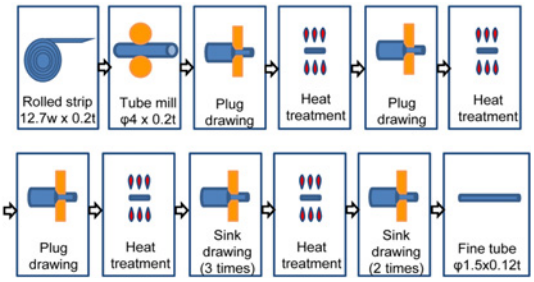


Fig. 2 Drawing process for manufacturing fine tubes

Table 1 Chemical composition of Inconel 625 (wt.%)

Ni	Cr	Mo	Fe	Nb	Co	Ti	Al	C	Mn	Si
Bal.	20-23	8-10	5	3.15-4.15	1	0.4	0.4	0.1	0.5	0.5

Table 2 Mechanical properties of Inconel 625

Melting temp. (°C)	Density (kg/m^3)	Tensile strength (MPa)	Yield strength (MPa)	Elongation (%)
1290-1350	8440	930	517	42.5

manufacturing the fine tubes. Inconel 625 has high strength and toughness and has the ability to withstand temperatures ranging from extremely low values to as high as 980°C. In addition, it has high oxidation resistance and fatigue strength. The chemical composition and mechanical properties of Inconel 625 are listed in Tables 1 and 2, respectively.[12]

As shown in Fig. 2, the manufacturing process of fine tubes involves forming tubes with Inconel 625 strip of 0.15 mm thickness by using TIG welding followed by a drawing process. An annealing process is performed at 1150°C after every two drawing steps. A total of five annealing processes are performed until the tubes attain an outer diameter of 1.5 mm and a thickness of 0.12 mm.

2.2 Brazing of tubes and tube sheet

Fig. 1 shows the developed heat exchanger that consists of 808 tubes designed with performance analysis. The applied material was Inconel 625 that could bear high temperature. The manifold has a thickness of 4.0 mm and the outer diameter of the inlet and outlet of the hot side is 19.0 mm.

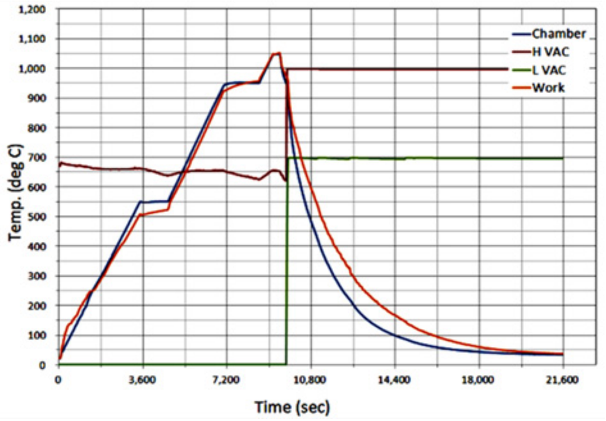


Fig. 3 Heating-cooling cycle for brazing

Table 3 Chemical composition of BNi-2 filler metal (wt.%)

Ni	Cr	Fe	B	Si	Melting range (°C)
Bal.	7.0	3.0	3.1	4.5	970-1000

A brazing process was used to connect a tube to the manifold. Ni-2 paste, which contained 7% Cr, was used for brazing. In addition, B and Si were added for reducing the melting temperature of Ni. Table 3 shows the chemical composition and melting temperature BNi-2.[13-15]

In order to develop a heat exchanger, several unit processes are adopted in order; fine tube manufacturing, material processing, washing, assembling, brazing, tube inspecting, primary welding, pneumatic leakage testing, secondary welding, and hydrostatic testing.

The tubes and tube sheet were brazed for 15 min at 1050 after heating under a pressure of 5×10^{-5} torr or less. Fig. 3 shows the heating-cooling cycle.

3. Mechanical Integrity Test of Tubes

3.1 Tensile at room temperature

A tube tensile test was performed to determine whether the manufactured fine tubes have the proper yield strength and tensile strength characteristics. The test results were compared with the properties of a non-brazed tube, a manifold, and a brazed tube to determine the effect of brazing.

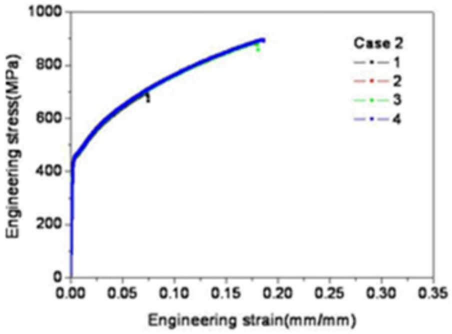
Fig. 4 illustrates the stress-strain curves of non-brazed tubes and brazed tubes that were exposed to at least one brazing cycle. The tensile test results for each specimen are listed in Table 4. The mean yield strength is 453 MPa and maximum tensile strength is 885 MPa for 300 K.

From the results, it can be seen that the tubes with and without brazing have similar yield strength and tensile strength.

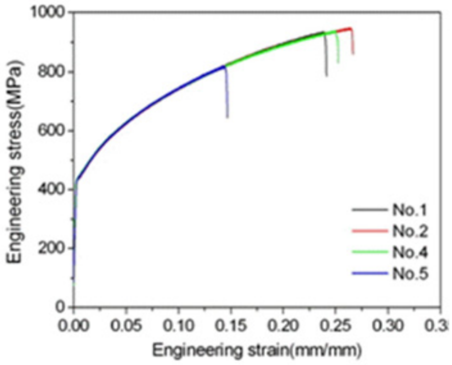
There was failure in the non-brazed zone of the tube for all tube specimens as shown in Fig. 5. This implies that the strength of the brazing zone was similar to or stronger than the tensile strength of the tube tensile.

3.2 Tensile test at high temperature

As a heat exchanger in an aero gas turbine is used under high



(a) Without brazing



(b) With brazing

Fig. 4 Comparison of stress-strain curve of tensile test

Table 4 Results of tensile test

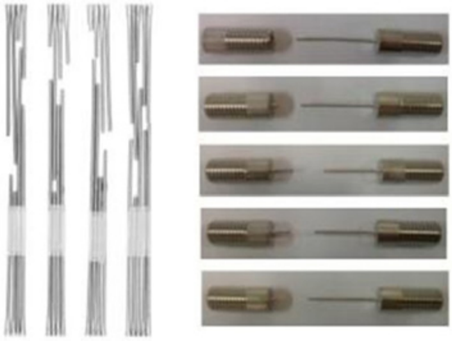
Property	Without brazing					With brazing				
	1	2	3	4	avg.	1	2	3	4	avg.
Yield strength (MPa)	452	454	453	456	454	449	448	450	449	449
Tensile strength (MPa)	694	883	884	895	839	887	842	859	859	862
Elongation (%)	7.5	17.9	18.1	18.6	15.6	18.4	15.7	16.6	16.3	16.8

pressure and temperature, it is important to test the applicability of the heat exchanger under such conditions and design it accordingly to ensure safety.

A tensile test was performed in a chamber at 1000 K that is similar to the operation temperature of an aero gas turbine.

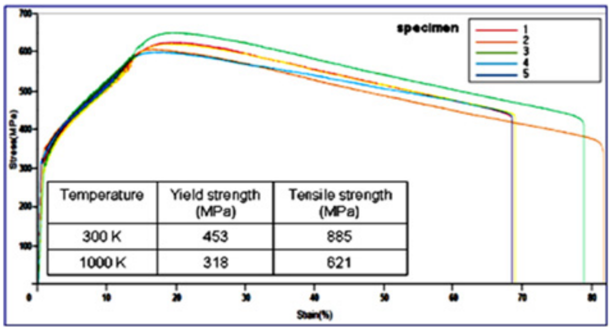
Fig. 6 shows the strain-stress curves for the high-temperature tensile test. A maximum yield strength of 351 MPa and a mean yield strength of 318 MPa were recorded. The mean tensile strength was determined to be 621 MPa. It was observed that the tensile strength at 1000 K was reduced by 30% compared to that at 300 K.

Fig. 7 shows images of failed Inconel fine tube specimens after a tensile test, showing the tube experienced failure during tensile test. Based on this, it can be said that the specimens had a good brazed joint, whose tensile strength was similar to or stronger than that of the base material.



(a) Without brazing (b) With brazing

Fig. 5 Specimens after testing



Temperature	Yield strength (MPa)	Tensile strength (MPa)
300 K	453	885
1000 K	318	621

Fig. 6 Strain-stress curve at 1000 K

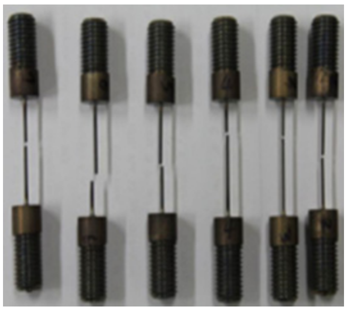


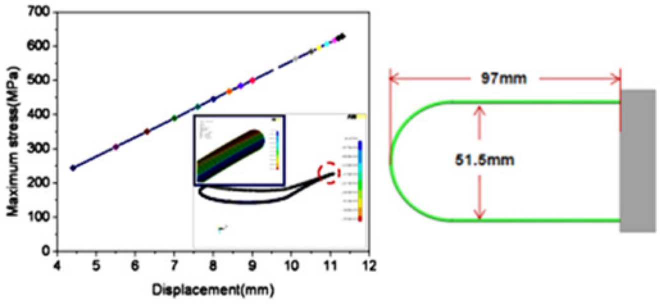
Fig. 7 Specimens after tensile test at 1000 K

3.3 Fatigue test under harmonic vibrations

In this study, a vibration test and a finite element analysis[16] with a stress prediction method were performed to determine the low cycle fatigue (LCF) stress of a single tube at room temperature with the LCF test.

Fig. 8(a) shows the relationship between the displacement and the maximum stress, and Fig. 8(b) shows the result of the harmonic vibration analysis based on the displacement. The size of each measured specimen and the maximum displacement generated from the excitation test were applied to develop a model for determining the trend of stress displacement. The result suggested the stress increased proportionately with the displacement, i.e., the higher the displacement, the higher the corresponding stress.

Based on the test and the result of the harmonic response analysis, a fatigue test was performed on a U-shaped single tube and the S-N curve was obtained by comparing the predicted stress and failure cycle.



(a) Displacement vs. maximum stress (b) Test specimen

Fig. 8 Specimens and result of harmonic vibration test

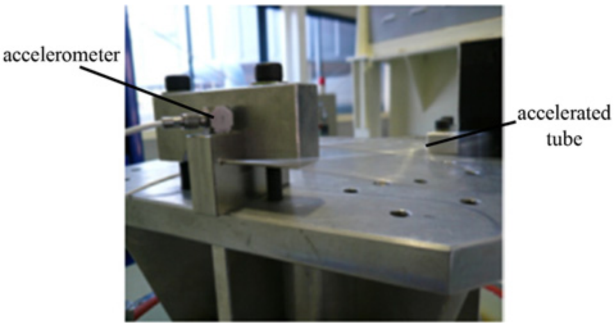


Fig. 9 Test set-up

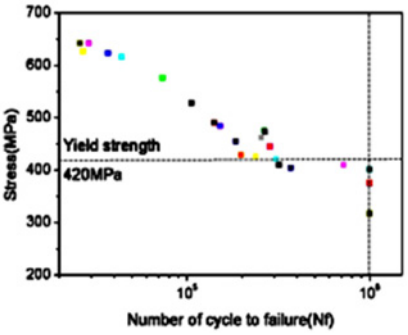


Fig. 10 Tested fatigue strength at 1000 K

The excitation force was adjusted as the acceleration was varied. The point where the vibration displacement drastically reduced was assumed as the point of failure. Fig. 9 shows the test set up and size measurement location for analysis. The each specimen was used for individual harmonic response analysis.[16]

Fig. 10 shows the relationship between the number of cycles to failure and stress, which can be simply calculated as the product of failure time and excitation frequency.

The result above indicated that fatigue failure started at a stress that was lower than the yield strength. In addition, increasing the stress rapidly reduced the number of cycles to failure.

Fig. 11 shows a failed specimen with a crack at the end of the brazed zone. The result of the harmonic response analysis indicated that this part generated the greatest stress and the location of the crack slightly changed depending on the surface condition of the specimen.

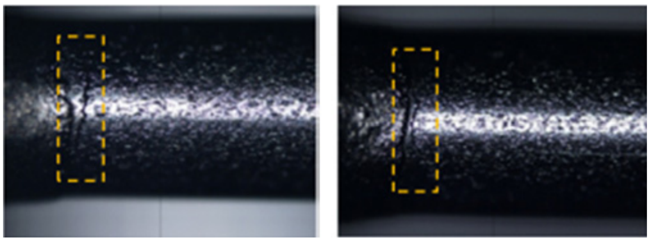


Fig. 11 Cracks on tubes during harmonic vibration

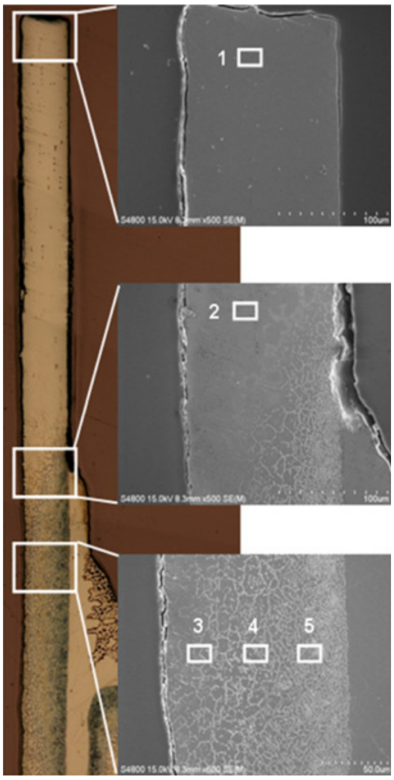


Fig. 12 Microstructure of brazed area and locations for EDS analysis. Five boxes indicate the location of EDS analysis points

Table 5 Chemical composition by EDS analysis (wt.%)

Elements	Locations in Fig. 12				
	1	2	3	4	5
Cr	22.05	20.31	21.05	22.43	22.41
Fe	4.05	4.13	4.57	3.54	3.55
Ni	61.02	59.76	60.06	57.08	56.20
Nb	7.46	9.03	8.16	9.33	7.97
Mo	5.42	6.77	6.16	7.62	9.87

3.4 Microstructure in brazed zone

Fig. 12 shows the microstructure of a specimen etched for EDS (Energy Dispersive Spectrometer) analysis. For quantitative analysis, etching was performed just enough to show the inserted metal and it

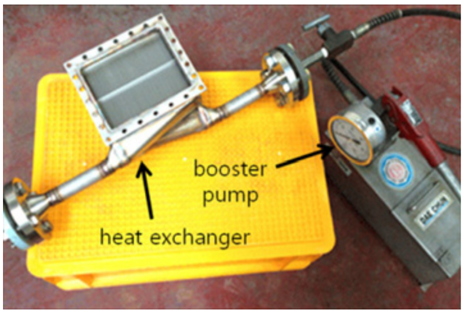


Fig. 13 Heat exchanger under proof hydrostatic test

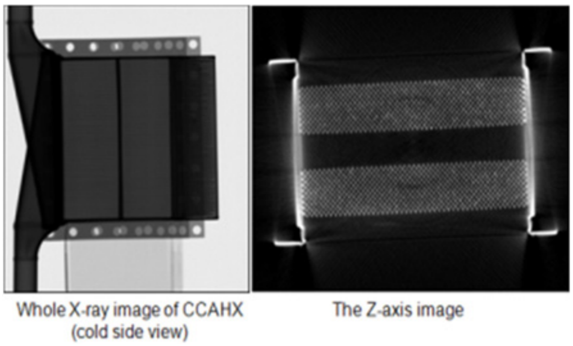


Fig. 14 X-ray CT inspection

was divided into three areas: area with no failure, area with frequent failure, and area near joint. The result indicated that elements like Mo and Nb spread from the inserted metal into the tube and tube sheet, resulting in an increase of weight percent by approximately 1-2% as shown in Table 5. It is shown that the effect of filler metal is negligible in the chemical composition near the brazed region.

4. Fabrication and Inspection of Full Heat Exchanger

Fig. 13 shows the manufactured heat exchanger with brazing process. It was observed from the pressure resistance test that no leakage occurred for 20 min under a pressure of 100 bar.

It was difficult to detect faults, such as tube blockage and buckling, inside the heat exchanger by using pressure resistance tests, leakage tests, and visual inspection. Therefore, an X-ray CT test was used to inspect the heat exchanger. As shown in Fig. 14, tube blockage or external blockage by an inserted material was not observed.

When the exchanger was manufactured, the inlet and outlet of the hot side was welded with the manifold after the tube and tube sheet were brazed.[6-14] At this point, there is a possibility that the tube may be damaged by the welding heat or the remelting of the inserted material; thus, the tube may be blocked because of the relative proximity between the welded part and tube. In this regard, the study an endoscopy test was performed to check for any blockage after the entire manufacturing process was completed. Fig. 15 shows the inspection result. It was determined from the test that the inlet and outlet of the hot side of the manufactured heat exchanger did not have any blockage.

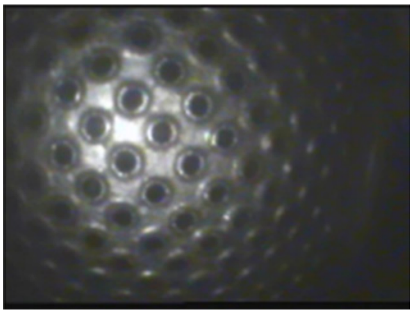


Fig. 15 Endoscopy inspection

5. Conclusions

This study developed a manufacturing process for a heat exchanger in order to decrease the temperature of pressurized air. A lower temperature of pressurized air cools down the aero turbine blade. The heat exchanger was designed to be used under high temperatures and pressures, and it exchanges air through fine tubes. The main findings can be summarized as follows.

(1) Fine tubes were developed from Inconel 625 through roll forming and drawing processes.

(2) The tensile strength, yield strength, and fatigue strength of the fine tubes were measured at 1000 K. Brazed tubes were not fractured at the brazed region.

(3) A process was developed to manufacture a fine tube heat exchanger by applying brazing and the manufacturing integrity was confirmed through various tests, such as tensile test of tubes, microstructure analysis, hydrostatic pressure test, X-ray CT and endoscopy inspection.

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