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Processing effects in aluminum micro-channel tube for brazed R744 heat exchangers

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Abstract

The effects of processing on the mechanical behavior of aluminum alloy micro-channel tubing used in brazed automotive heat exchangers are evaluated in light of the stringent requirements of CO_2 (R744 refrigerant) based systems. An apparatus was developed to simulate system operating conditions of pressure and elevated temperature in tube samples. Commercially extruded and processed AA3102 micro-channel tube samples were given a simulated brazing thermal cycle and a series of static and cyclic pressure tests were performed at various temperatures. Failure stress in the tube walls was estimated and compared to tensile test data. At room temperature, the strength of the post-braze micro-channel decreased by about 17%, and about 22% at 180 °C (compared to tube that was not given a simulated brazing thermal cycle). This decrease in strength is attributed to large grains that form during the brazing thermal cycle.

Keywords: Micro-channel tube; Pressure testing; Stress analysis; Burst pressure

1. Introduction

Development of R744 (CO_2) based climate control systems is due to several issues, including the desire to develop an environmentally friendly alternative to current R134a (CF_3CH_2F) based systems. Components in the "high-pressure side" of R744 based systems however must operate at 16 MPa and 180 °C (compared to 3 MPa and 125 °C for R134a systems) [1]. One such component is the gas cooler, which is a brazed heat exchanger assembled from an array of aluminum alloy micro-channel tube such as that seen in Fig. 1a. Condensers (for R134a systems) and gas coolers essentially serve similar purposes.

Processing of aluminum micro-channel tube involves hot extrusion and subsequent straightening and roll-sizing to achieve precise external tube dimensions (Fig. 1a) required for assembly of parallel-flow heat exchangers. After assembly, these heat-exchangers are furnace-brazed at approximately 600 °C in an inert atmosphere. It is during the brazing process that the micro-channel tube experiences recyrstallization and grain growth, driven by the small amount of plastic strain during the roll-sizing operation. Fig. 1b shows this grain growth in the internal walls, and the unrecrystallized regions in the outer walls. The large grains lead to a significant decrease in mechanical properties and it was the objective of this work to assess these properties in light of the process effects and the system requirements. A computer controlled test apparatus able to apply static and cyclic internal pressures to tube samples at temperatures to 180 °C was developed for this effort. Test samples were alloy AA3102, a common alloy for this application.

2. Experimental apparatus

The basic premise of the test apparatus that was developed for this work is to apply a force to the piston of a water-filled cylinder, and this develops hydrostatic pressure in a tube sample to which the outlet is connected. A schematic of the apparatus is shown in Fig. 2.

A single acting high pressure cylinder is fixed between the cross-head and ram of a computer-controlled servo-hydraulic MTS machine. When the MTS machine exerts force on the cylinder, the treated water inside the cylinder is pressurized. This pressure is transferred to the tube sample inserted into a pair of quick disconnect fixtures. An air actuated charge tank, a three way valve and a pair of ball (bleeder) valves are used to force the water into the cylinder and tube sample, and to evacuate entrapped air. A pressure transducer is attached to the system to measure the internal pressure applied to the tube sample. A forced air convection heater (seen in the inset of Fig. 2) is used to test samples at elevated temperatures.

3. Stress analysis

Initial tube failure occurs at one or more internal tube walls, and testing has confirmed this (see inset of Fig. 4). Hence only

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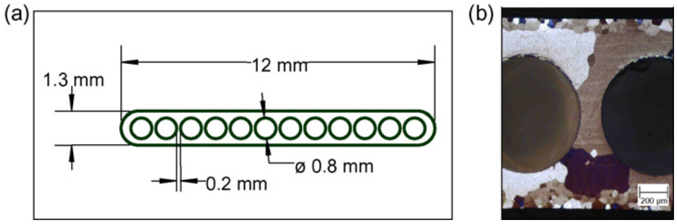

Fig. 1. (a) Sketch of micro-channel tube used in this work. (b) Typical large-grain microstructure of tube sample as a result of roll-sizing and the subsequent brazing thermal-cycle simulation. This tube sample was pressure tested, resulting in the thinner internal wall shown.

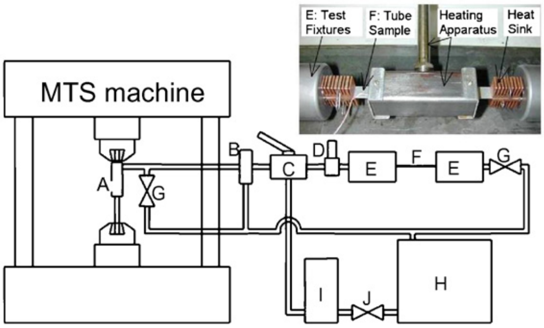

Fig. 2. Schematic of the test apparatus with MTS machine [2,3]. Inset is a photograph of the test region (A) Single acting high-pressure cylinder. (B) High pressure relieve valve. (C) Three-way control valve. (D) Pressure transducer. (E) Quick-disconnect test fixtures. (F) Micro-channel tube sample. (G) Bleeder valves. (H) Fluid reservoir. (I) Air-operated fluid charge tank. (J) Solenoid valve.

the relationship between the internal pressure and the effective stress in the internal wall between two adjacent channels was considered, as depicted in Fig. 3.

The tangential stress at a distance r from the center of an internally pressurized cylinder (with no external pressure) is given by Eq. (1) [4].

$$\sigma_t = \frac{a^2 p_i}{b^2 - a^2}\left(1 + \frac{b^2}{r^2}\right) \tag{1}$$

The micro-channel tube with circular channels can be considered as a series of parallel circular tubes as shown Fig. 3b. This approach was first proposed by Künesch [5]. Using Eq. (1) for the tangential stress at a point distance (r) from the center of the cylinder, the resulting tangential stress at that point due to superposition of stress from two adjacent pressurized channels is expressed as:

$$\sigma_t = \frac{a^2 p_i}{b^2 - a^2}\left(2 + \frac{b^2}{r^2} + \frac{b^2}{(a + b - r)^2}\right) \tag{2}$$

where $a = D/2$ and $b = (D + 2t)/2$. The mean tangential stress ($\bar{\sigma}_t$) across the internal wall is determined by integrating the tangential stress and dividing it by the corresponding area as follows:

$$\bar{\sigma}_t = \frac{2}{b - a}\int_a^b \sigma_t \, dr \tag{3}$$

Eq. (3) simplifies to Eq. (4), which is taken as the σ_1 principal stress.

$$\bar{\sigma}_t = \frac{2aP_i}{b - a} = \frac{DP_i}{t} = \sigma_1 \tag{4}$$

Assuming no variation of stress in the radial direction, then $\sigma_3 = -P_i$. From the principal stresses, σ_1 and σ_3, and the assumption that plane strain conditions prevail, the von Mises stress is given in Eq. (5) as a function of wall thickness, channel diameter and internal pressure.

$$\bar{\sigma} = \frac{\sqrt{3}}{2} P_i \left(\frac{D}{t} + 1\right) \tag{5}$$

where $\bar{\sigma}$ is the von Mises stress, P_i the internal pressure, D the diameter of the channel and t is the thickness of the internal wall at its vertical center (where it is minimum).

4. Results

4.1. Static pressure test results

A typical test pressure curve is shown in Fig. 4a. The non-linearity to about 32 mm ram (piston) displacement is due to the compliance of the system as pressure increases. A ram displacement of 1 mm corresponds to a volume displaced of 0.5 ml. A linear portion to the point of maximum pressure ensues. Failure is very abrupt with no discernable non-linear region or yield point. Hence, an equivalent failure stress was calculated by substituting the maximum pressure into Eq. (5).

The variation of failure (burst) pressure with test temperature is plotted in Fig. 4b. The reductions in burst pressure and static equivalent failure stress from an increase in test temperature, and

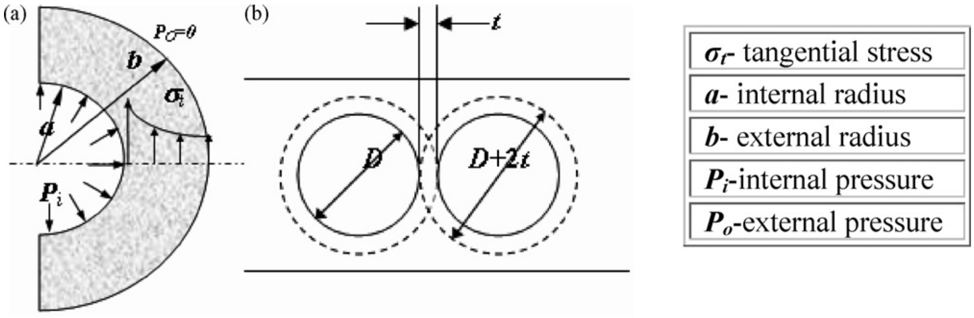

Fig. 3. (a) Schematic showing tangential stress in single tube wall. (b) Schematic depicting superposition of tangential stress on the common wall of two adjacent tubes.