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Accelerated Fatigue Testing of Aluminum Refrigeration Press Fittings for HVAC & R Applications

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ABSTRACT

Components of HVAC and refrigeration systems are subjected to various parameters and conditions that affect their operating life. Rapid changes in pressure and temperature along with mechanical vibrations caused by rotating equipment such as compressors and fans induce fatigue in the components. Additionally, freezing and thawing of ice between the joints of fittings can also be a factor leading to failure of couplings and joints. Aluminum is being more widely used in the refrigeration industry as a replacement for copper due to economics of lower cost and easy manufacturing. A series of tests were conducted to simulate conditions experienced by fittings in a real life refrigeration system at an accelerated rate. The aluminum fittings of this study are subjected to same accelerated fatigue test conditions which the copper fittings were earlier subjected to. The test methodology is identical to the one developed and performed on copper fittings in an earlier study by Wilson and Bowers (2014). Because the fitting manufacturer and the test lab are the same, it is possible to fairly compare the results between the two studies. The first test is a rapid pressure-temperature cycling test where the fittings are subjected to rapid changes in pressure and temperature which occur due start/stop cycles and during frost/defrost modes of a residential R410A heat pump system. The second test is a vibration test which subjects the fittings to vibration loads experienced due to rotating components in the system. The third test is a freeze/thaw test which simulates ice buildup and melting at the joints during frost/defrost cycles. The test were conducted on flame free aluminum press fittings which are designed to be used with R410A. Aluminum press fittings of six different sizes (9.5 mm to 28.3 mm) were exposed and investigated according to the accelerated tests described above. Pressure, temperature, strains and acceleration were measured and analyzed and compared to the earlier copper fitting results obtained by Wilson and Bowers (2014) where possible. At the end of each test the exposed specimen were carefully investigated for possible damage and leak tightness was confirmed. The main contribution of the work is to extend the previously established test method to evaluate a family of new aluminum press fittings at identical conditions as the earlier study that used copper fittings. It was found that both fitting materials, when exposed to identical accelerated test conditions, were able to withstand all tests without showing any signs of premature failure. It was concluded that the aluminum version of the fittings is a suitable alternative to the earlier copper connectors, giving manufacturing a reliable, yet low-cost alternative.

1. INTRODUCTION

As summarized by Wilson and Bowers (2014), brazing is one of the most commonly used methods to join refrigerant lines and its components. Brazing has a few drawbacks which include the safety risks of using an open flame, formation of oxides inside the lines due to high temperature, the risk of burning up compressor lubricant in the system, the risk to damage sensitive components (valve seats, solenoids) and the difficulty to join dissimilar metals, especially copper to aluminum. Furthermore, a great deal depends upon the skill of the operator and also there is the cost involved with the brazing material which is usually an alloy of silver. Many of the common alternatives to brazing are generally expensive. The press-connect fittings (CDA, 2010) are finding wider use in the refrigeration industry. These crimp fittings use a polymer O-ring to establish a leak free connection, thereby eliminating the use of a high temperature flame and the drawbacks associated with brazing.

Aluminum is finding wide spread use in refrigeration components, e.g. for heat exchangers and piping. Also, the relative low cost and ease of machining of aluminum are the major factors for its widespread acceptability. The earlier study carried out by Wilson and Bowers (2014) proved the ability of copper fittings to withstand a series of accelerated fatigue tests which were developed during that study. This study focuses on subjecting aluminum fittings to the same accelerated fatigue test conditions using the same fitting manufacturer and the same test lab and equipment to allow a direct comparison of the test results. Aluminum fittings of six different sizes were exposed to realistic operating conditions. The test specimen underwent pressure/temperature cycling, freeze/thaw cycling, and vibration testing.

2. FLAME FREE REFRIGERANT TUBE FITTINGS

This continuation of the earlier copper fitting study (Wilson and Bowers, 2014) focuses on an aluminum flame-free fitting designed for use in HVAC and refrigeration systems. The construction of the aluminum fittings is identical to the construction of the copper fittings described by the original study. The fittings are made of an aluminum tube slightly larger than the outer tube diameter it is intended for, with two bulges at the ends for the O-ring placement. The O-ring material is compatible with most widely used refrigerants and lubricants. A special tool is required to deform the fitting and create a leak tight seal around the tubes. It only takes several seconds to complete a fitting connection. An example of such an aluminum press fit connection is shown in Figure 1.

Figure 1: Aluminum flame-free fitting installed on a 15.9 mm tube

3. PRESSURE-TEMPERATURE CYCLE TEST

Rapid changes in pressure and temperature are experienced by the components of an air conditioning or refrigeration system during start up and shut down. Systems utilizing R410A typically experience changes in pressures from 1100kPa to 3000kPa during start up and a temperature range of 20°C to 70°C. An experiment was carried out to subject the aluminum fittings to rapid changes in pressure and temperature for around 80,000 cycles, which is typically representative of the number of frost/defrost cycles in a heat pump system. Similar experimentation was earlier conducted on copper flame free fittings by Wilson and Bowers, 2014. The test facility used earlier for testing the copper fittings was slightly modified for the purpose of testing the aluminum fittings. The modification involved using fewer solenoid valves.

An experiment was set up to test the ability of the fittings to withstand thermal and pressure fatigue. Twelve fittings of diameters 28.5 mm, 22.2 mm, 19.1 mm, 16.1 mm, 12.7 mm, and 9.5 mm were evaluated simultaneously. The test facility involves a R410A vapor compression system with two solenoid valves which are used to divert a part of the refrigerant flow from the low side and the high side of the system into the test section. The test involves two separate modes of operation: firstly, the heating mode where the fittings are subjected to high pressure, high temperature refrigerant diverted from the compressor discharge by opening the relevant solenoids. The system operates in heating mode until a temperature of 71°C is reached at the outlet of the test section. The refrigerant pressure rises to approximately 3000 kPa during the heating mode. Figure 2 shows the facility schematic for heating and cooling mode.

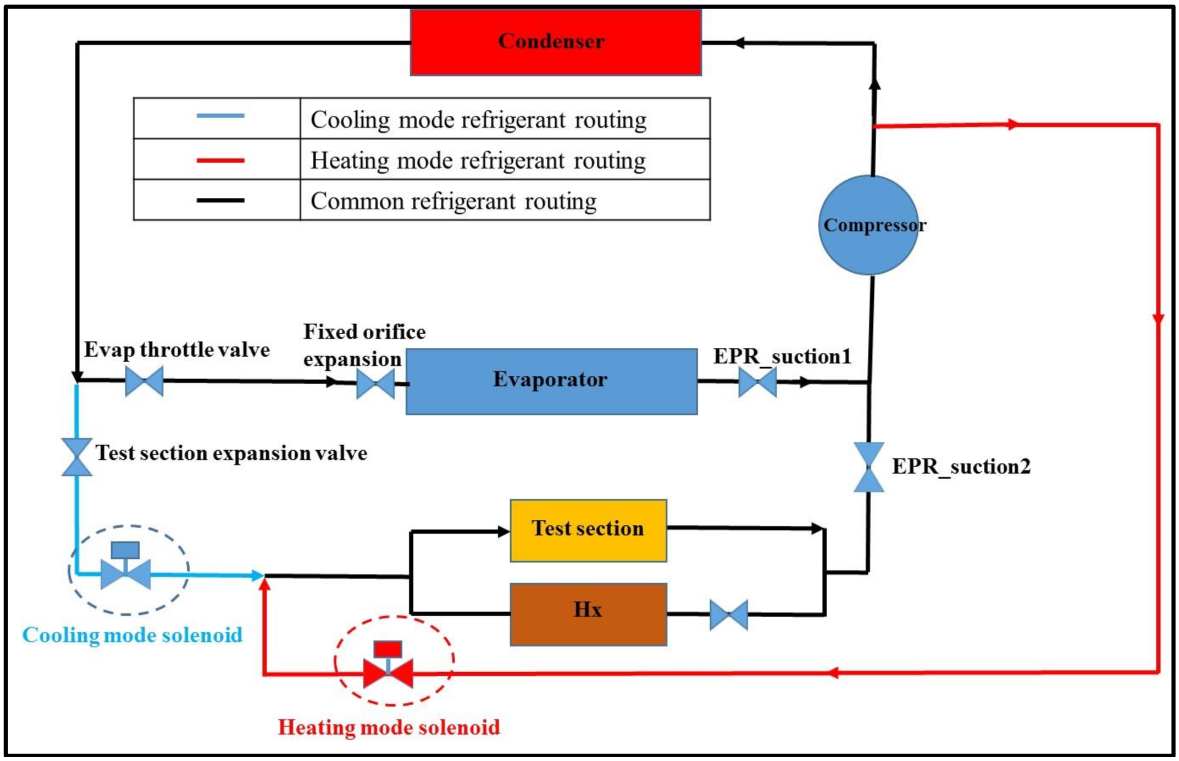

Figure 2: Facility schematic for heating and cooling mode

The heating mode is followed by the cooling mode where the low pressure, low temperature refrigerant is diverted from downstream of the expansion valve by opening the relevant solenoids. The system operates in cooling mode until a temperature of 20°C is measured at the outlet of the test section. The refrigerant pressure drops to around 1200 kPa during the cooling mode. The refrigerant exiting through the test section passes through a pressure reduction valve before combining with the main flow of the refrigerant at the evaporator outlet.

By varying the temperature set point, the fittings can be subjected to different levels of thermal fatigue. The high side and low side pressures are controlled by modifying the operating conditions of the vapor compression system. The fittings can be subjected to different stress levels by controlling the operating pressures and temperatures of the vapor compression system. The test rig generally accomplishes 1200 cycles per day with cycle times between 40-60 seconds.

Figure 3 shows examples of representative temperature and pressure profiles of the test fitting. Comparable pressure and temperature profiles were obtained during earlier tests with copper fittings (Wilson and Bowers, 2014). It should be noted that the plotted temperatures were determined with surface-mount Type-T thermocouple probes at the exit of the test section. There is a rapid rise in pressure during the start of the heating mode accompanied by rise in temperature. The pressure and temperature continue to rise until the predetermined set point is reached at which point the system switches to cooling mode. During the cooling mode there is a rapid drop in pressure and temperature in the test section; this drop in pressure and temperature continues until the predetermined set point is reached. A new cycle starts after the system reverts back to heating mode.

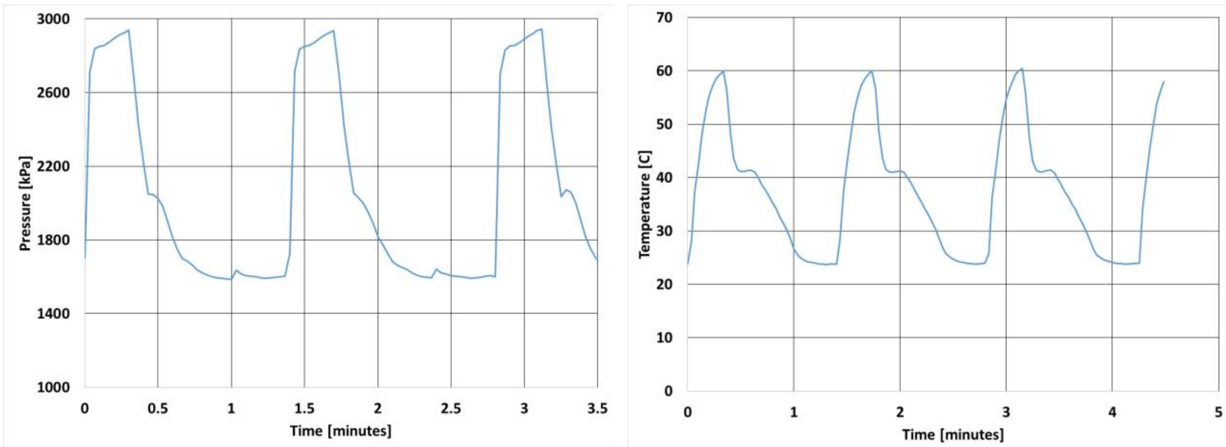

Figure 3: Example of pressure and temperature profile of the test fitting

Single-axis strain gauges were attached to the surface of each of the test fittings. Measurements were taken using a quarter bridge strain gauge card connected to the data acquisition system. Figure 4 shows a sample strain profile of the 28.5 mm fitting.

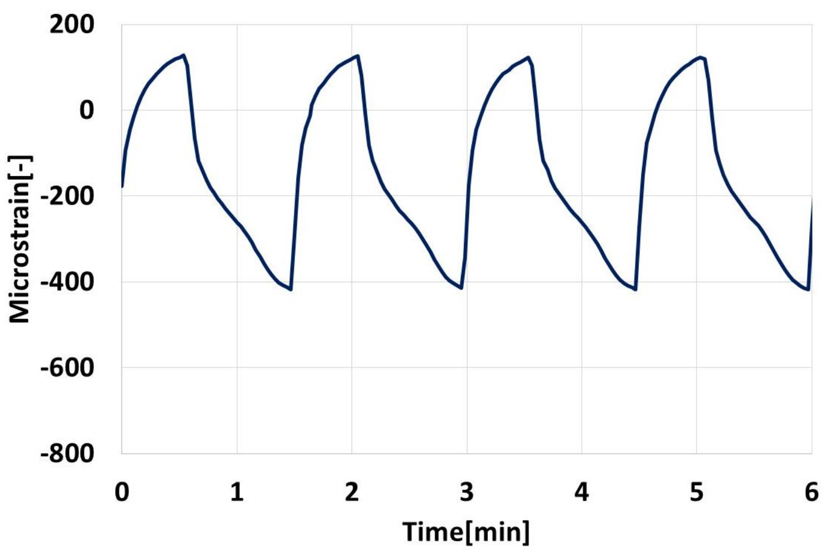

Figure 4: Sample strain profile of a 28.5 mm fitting

Over the course of approximately sixty days the fittings are subjected to 80,000 pressure/temperature cycles. Periodic leak tests are conducted every week to determine if the sealing capability of the fittings have been compromised by fatigue. The test cycles conducted did not result in any fitting failures. As the previously investigated copper fittings, the aluminum fittings were able to maintain their sealing capability.

4. VIBRATION TESTING

Vibration induced fatigue is one of the significant factors involved in failure of brazed joints and fittings. Mechanical vibrations of an HVAC system induced by components using electric motors are one of the major causes of concern. A fatigue test is designed to realistically simulate field vibrations in refrigerant carrying tubes. The same facility was used earlier for copper fitting evaluation (Wilson and Bowers, 2014). The setup shown in Figure 5 consists of a test stand with two clamps to support the test tubes. One clamp is rigidly attached to the test stand, while the other oscillates with an amplitude of ± 3 mm. The oscillation is achieved by means of an electric motor with an eccentric shaft coupled to a four-bar oscillating mechanism. The motor is operated at 1000 rpm during the tests providing an oscillating motion of 16.6 Hz. All fatigue tests were carried out at 16.6 Hz for 1.8 million cycles.

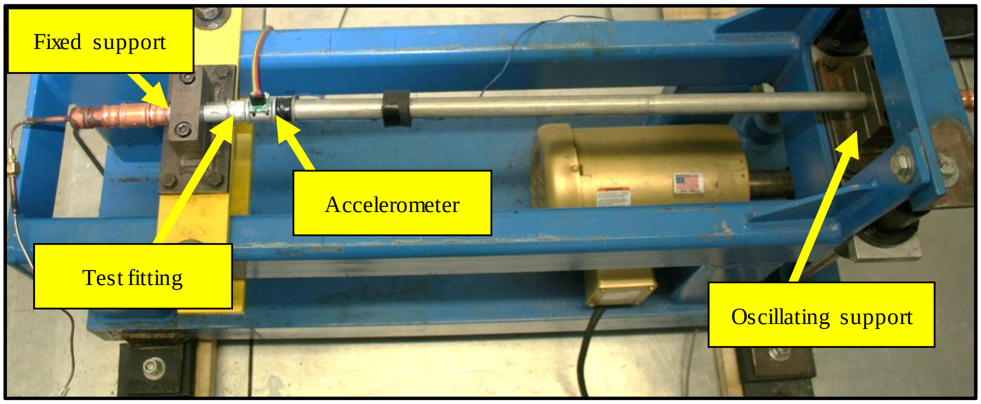

Figure 5: Vibrational fatigue test rig with 19.1 mm test sample installed for testing

Table 1 shows for each nominal fitting diameter the tube length required for the test. For each fitting size the tube length is measured between the closest edge of the fitting and the oscillating clamp. This relation between tube diameter and length is based on UL109 Standard (1997) which was developed for evaluating durability of tube fittings.

Table 1: Nominal fitting sizes and corresponding test tube lengths

Tube outer diameter [mm]	Tube length [mm]
9.5	305
12.7	458
15.9	458
19.1	458
22.2	610
28.5	610

The test involves rigidly clamping the tubes at both ends. A distance of 12.7 mm is maintained between the fitting and the stationary clamp to avoid leakage due to local deformation near the tube-fitting joint. The other end of the fitting is rigidly fixed to the oscillating clamp. The test assembly is pressurized with nitrogen at 3000 kPa. The pressure is monitored during the duration of the test to indicate whether the fitting maintained its sealing capability. To measure the intensity of the vibrational load a three-axis accelerometer is attached to the fitting. Acceleration is recorded using a data logger sampling at 500 Hz. During the tests consistent accelerations between ± 1g were recorded, with slight variations between the different nominal fitting diameters. Using Fast Fourier Transform analysis on the acceleration data, it was determined that the primary frequency occurred at 16.6 Hz which corresponds to the excitation frequency of the motor. Figure 6 shows an example of acceleration data in time and frequency domains for the 19.1 mm fitting. As in the case of the copper fittings, no failure of the aluminum fittings were observed, as evidenced by a thorough leak check at the end of testing. It should be noted that the earlier copper fitting study by Wilson and Bowers (2014) used a rotational excitation of 28.5 Hz, resulting in slightly higher accelerations measured at the fitting surface. It was decided to use 16.6 Hz for the new tests to more closely follow UL109 Standard (1997).

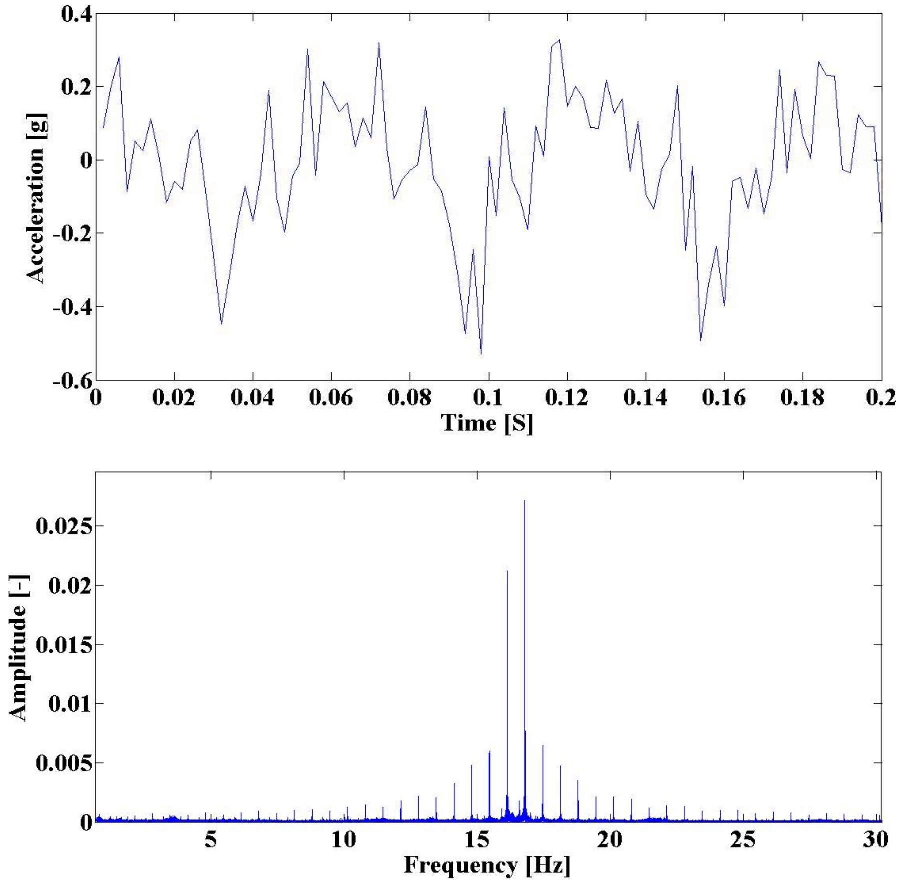

Figure 6: Example of acceleration data in time and frequency domains for a 19.1 mm fitting

5. FREEZE/THAW TESTING

The freeze/thaw test intends to simulate freezing and thawing of ice build-up of components during the defrost cycle. Water finding its way into small gaps of the joint connection could freeze and expand during consecutive freeze/thaw cycles and potentially result in premature failure of the fitting. To accelerate the results in the lab an experimental setup was assembled to rapidly freeze and thaw the fittings which are placed in a high humidity environment. A series of 5000 freeze/thaw cycles were performed on each test fitting to represent frosting/defrosting over a ten year period in a typical heat pump system.

Figure 7 shows the experimental schematic for the freeze/thaw facility identical to the facility on which the earlier copper fittings were tested (Wilson and Bowers, 2014). The working fluid used for heating and cooling is a 50% (by volume) ethylene glycol/water solution. The cold bath and the hot bath are maintained at -35°C and 20°C, respectively. A fitting tree was designed and fabricated which consisted of twelve fittings of nominal sizes 28.5 mm, 22.2 mm, 19.1 mm, 16.1 mm, 12.7 mm, and 9.5 mm.

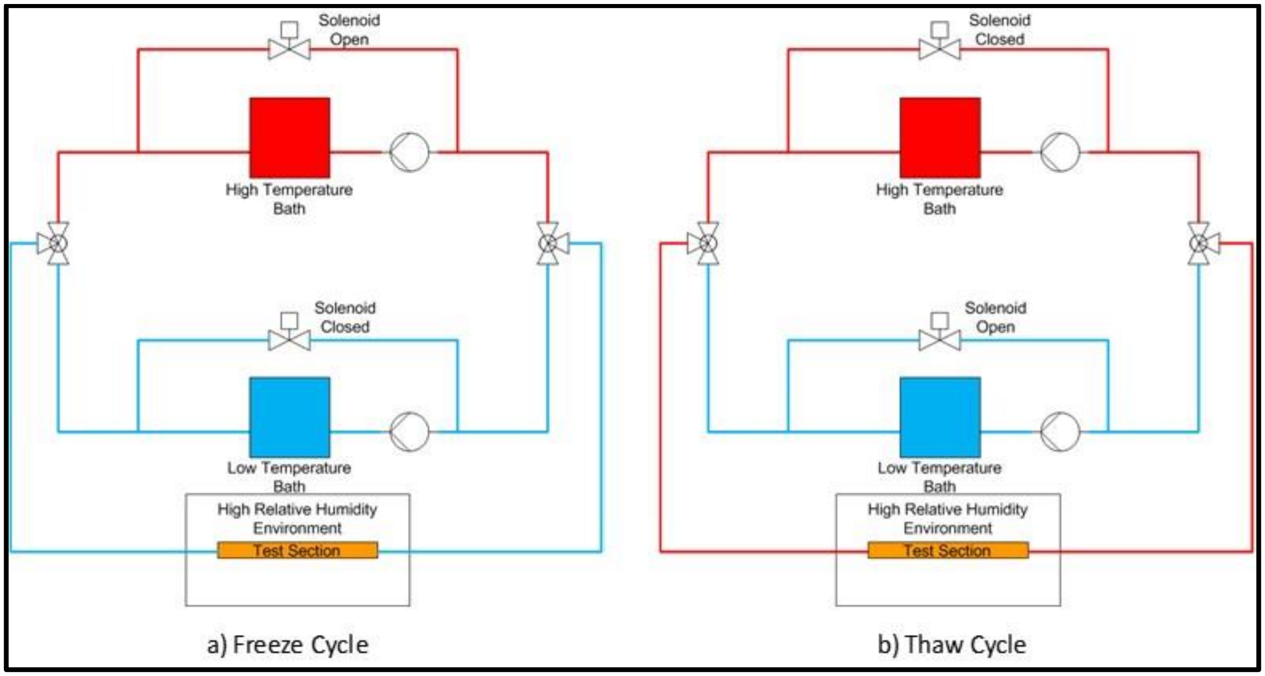

Figure 7: Experimental schematic for the freeze/thaw facility in cooling (a) and heating (b) modes (Wilson and Bowers, 2014)

First the cold fluid at -35°C is pumped through the test fitting tree, which lowers the surface temperature of the fittings to -21°C. This results in condensation, followed by ice formation on the surface and the joints of the fitting. This freezing cycle is then followed by the thawing cycle which involves pumping the hot fluid at 20°C into the fitting tree. The warm fluid causes the ice formed on the fittings to melt completely. Figure 8 shows the temperature profile during the freeze/thaw cycle of the 28.5 mm fitting. The temperature reaches a minimum of -21°C during the freezing cycle after approximately 240 s. At this point the solenoid valves are switched resulting in hot fluid flow through the fitting. The wall temperatures reach a peak temperature of 6°C during the thaw cycle. Complete freezing and thawing of the ice is confirmed by temperature measurement and visual observation. The temperature of the fittings are measured using T-type thermocouples located after each fitting, and with the help of an infrared camera as shown in Figure 9.

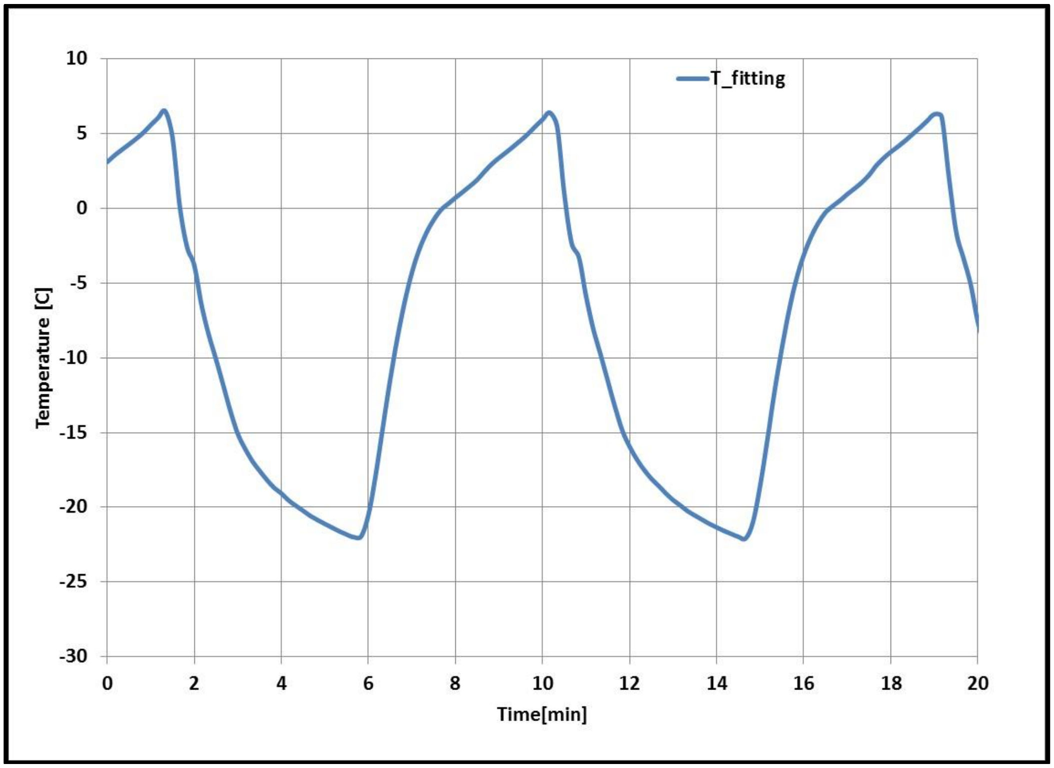

Figure 8: Temperature profile of the 28.5 mm fitting during freeze/thaw testing

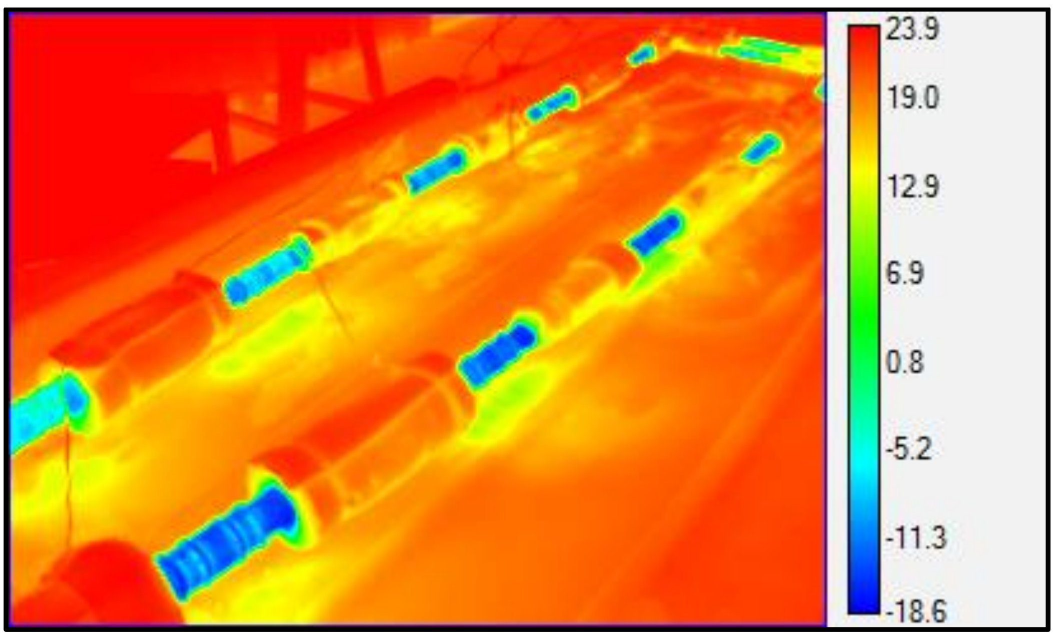

Figure 9: Infrared image of the test fittings during freezing mode (temperature scale in ºC)

Freezing around the joints of the fittings was accomplished by continuous freezing/thawing of the fittings. Figure 10 shows the ice formation at the joint of the fittings. The switching time between the heating and cooling mode was accomplished using a timer. A cycle time of 9 minutes was found to be sufficient for complete freezing and thawing of the fittings.

Figure 10: Ice formation at the joints of the fittings

Figure 11 shows the different stages of thawing on the fittings. Over the course of 30 days, 5000 freeze/thaw cycles were carried out to simulate 10 years of heat pump frosting defrosting operations. The fittings were leak tested every 1250 cycles to determine if there were any failures. The leak test was performed by pressurizing the fittings with nitrogen at 2750 kPa. No fitting failures were observed, showing that the aluminum fittings can withstand the same test conditions that were applied to the copper fittings.

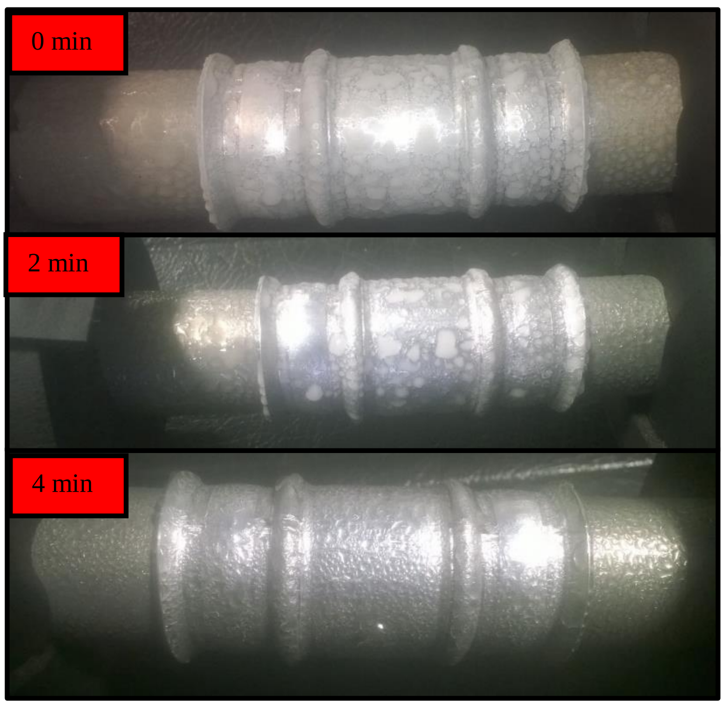

Figure 11: Ice melting process during the thawing cycle of the 28.5 mm fitting

4. CONCLUSIONS

Advances in press fitting technology notably by using aluminum has led to the development of flame-free aluminum fittings. Six aluminum press fitting sizes ranging from 9.5 mm to 28.5 mm in nominal diameter were subjected to accelerated fatigue testing developed in an earlier study. The first test involved subjecting the fittings to rapid pressure/temperature cycles where the pressures were varied from 3000 kPa to 1200 kPa and temperatures from 71°C to 20°C during the heating and cooling cycles, respectively. Approximately 80,000 pressure/temperature cycles were conducted. The second test involved subjecting the fittings to mechanical vibrations at 16.6 Hz for a total of 1.8 million cycles per fitting. The test sections were pressurized and pressure was monitored to observe any leakage or failure of the fitting. The third test involved simulating freezing and thawing of ice on the fittings as seen during frost/defrost operations. A series of 5000 freeze/thaw cycles were conducted. Leak tests were conducted periodically to ensure the sealing capability of the fittings were not compromised. None of these fatigue tests performed resulted in any fitting failures. The aluminum fittings were subjected to the same fatigue test approach as the copper fittings investigated in the earlier study by Wilson and Bowers (2014). Both the aluminum and copper fittings withstood the fatigue tests outlined above. It is concluded that the aluminum fittings are equally well suited to withstand the same accelerated life cycle testing as copper fittings when subjected to the same conditions, giving manufacturers a cost effective alternative.

NOMENCLATURE

Symbols and Abbreviations

EPR	evaporation pressure regulator
HVAC	heating, ventilation and air-conditioning
Hx	heat exchanger

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