DEVELOPMENT AND EVALUATION OF
BRAZED JOINTS FOR A PLATE
MICROCHANNEL HEAT EXCHANGER

by

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Development and Evaluation of Brazed Joints for a Plate Microchannel Heat Exchanger

Abstract

by

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A brazing method is developed for high efficiency microchannel heat plate heat exchangers for waste heat recovery. Prototype elements for these heat exchangers are fabricated by laser machining 316 stainless steel, and bonding with AMS 4777 brazing alloy. Specifications require that the heat exchangers withstand in excess of 5000psi of fluid pressure, tested with a high pressure water system that was developed for this project. Due to the costly nature of the pressure test, a model is developed to correlate braze performance in the heat exchanger with data from inexpensive mechanical tensile and peel tests. The model predicts that the maximum peel load per specimen width will be 342lbs/in and a maximum pressure of 7200psi in the heat exchanger. The highest value from the experiments is 330lbs/in for peel load and 6467psi in the pressure test, 97% and 90% of their respective theoretical values.
Chapter 1

Introduction

1.1 Heat Exchangers

Heat exchangers are critical elements of equipment and industrial processes worldwide. They can be used to heat or cool equipment, and to perform processes or chemical reactions at a set temperature. The variety of heat exchangers available is enormous, and each has applications where it excels. Heat exchanger types can be grouped into several categories.

The most basic type of heat exchanger is a mixed flow heat exchanger, where two or more fluids are mixed in a single vessel to provide the correct temperature for the system. [1] This rudimentary design is uncommon in industrial applications, but is often used in cooling boat engines where there is a large supply of water that is too cold to be used directly. It is also used to provide tap water at the correct temperature in homes and buildings.

Parallel flow heat exchangers are more common in industry and are typically designed with a series of tubes inside another, large tubular vessel. The tubes contain one fluid and the vessel contains another, allowing the fluids to exchange heat without mixing. These designs work well for high volume applications, where size is not critical, but maintaining high flow rates is. Flow of the fluids can either be in the same direction (coflow) or opposing directions (counterflow). In a coflow design, the
best heat transfer that can occur results in both fluids having the same temperature. Counterflow designs are more efficient, with the high temperature fluid able to reach the low temperature of the other fluid at the output. [1] Both designs are used in industry.

Figure 1.1: A parallel flow heat exchanger used for experimental chemical synthesis in the chemical engineering department of Case Western Reserve University. The area wrapped in foil is the heat exchanger. One fluid enters and exits through the fittings on the top and bottom of the unit, and the other fluid uses the fittings on the right side.

Cross flow heat exchangers are a more compact design, favored when transferring heat between a fluid and a gas. As gas convection is a slow process, relying on the movement of molecules to transfer heat, these designs tend to have a very high surface area on the gas side compared to the liquid side. One of the most common examples of a cross flow design is a car radiator. Most liquid/gas cross flow designs incorporate a tube and fin style of heat exchanger element. A tube carries liquid through a series of thin fins, allowing the heat from the fluid to conduct along the fins increasing
effective surface area. [1] Some cross flow heat exchangers are gas/gas types, such as those used to cool gas in a turbocharged automobile. These designs are commonly designated bar and plate style, which have approximately equal surface area for both gases. [2] The working fluid is contained in a series of square tubes with internal fins, which are joined together with external fins as seen in figure 1.2

Figure 1.2: A cross flow gas/gas heat exchanger. This bar and plate design is an intercooler from an automotive turbocharged application.

1.2 Waste Heat Recovery

Historically, standard practice in industry has involved exhausting waste heat directly to the atmosphere, or to a body of water such as a lake or river. Today, however, concerns are growing about energy consumption and efficiency, environmental effects, and operational costs. Because many industrial processes produce a great quantity of
unused energy in the form of heat, it makes sense to attempt to harvest that energy and use it for productive work.

A number of green technologies have been developed recently to generate electricity from alternative sources to fossil fuels. The key to waste heat recovery is that it doesn’t generate any more energy than has already been made, but rather uses energy more efficiently for multiple purposes. Modern technology allows for the design of efficient systems that can recycle heat energy in a number of ways. The three most common uses for recycled energy are heating, electricity, and cooling. [3]

The most basic way to use heat energy is to heat something, either a building or an industrial process depending on the situation. If a certain process requires a high temperature, rerouting otherwise wasted heat to provide a preheat to the process is a simple and valuable way to save energy and reduce costs. Additionally, in cooler
weather, industrial waste heat could easily be used to produce steam heat for a nearby building or for the factory itself. [3]

The next reasonable use for waste heat is to turn it into electrical energy. Modern infrastructure relies heavily on electricity to provide power for just about everything. The simplest way to create electricity from waste heat is to incorporate it into a steam generator. The heat will vaporize water which creates high pressure steam which can be routed through a turbine to transfer heat energy to mechanical energy. If the turbine is connected to a generator, that mechanical energy is efficiently turned into electricity, and can be used or routed back to the grid depending on the needs of the area. This works well only with higher temperature working fluid. For low quality heat energy, it is possible to expand the working fluid itself through a turbine to generate electricity, though this requires special consideration when choosing a
working fluid as a gas is needed. [3, 4]

The final and most complex way to reuse heat energy is to provide cooling. This counterintuitive process utilizes an evaporative ammonia cooler, and instead of providing mechanical energy in the form of a compressor, evaporation comes from heating ammonia dissolved in water and mixing with hydrogen gas. Ammonia is dissolved in water and heated, to boil the ammonia. The hot water and ammonia are separated, and the ammonia is cooled to condense it to a liquid. It enters a chamber with hydrogen, where the low vapor pressure causes it to boil and consume heat, providing the cooling. The ammonia is then redisolved in water to separate it from the hydrogen, and the cycle starts again. [5]

Often, these steps are combined in a heat recycling unit to provide cogeneration (typically heat and electricity) or to provide trigeneration (heating, electricity, and cooling). With the possibility for converting waste heat energy into other necessary energy resources, industrial efficiencies will improve substantially for the foreseeable future. [6, 7, 8]
Chapter 2

Background

2.1 Plate Heat Exchangers

Plate heat exchangers are used in a wide variety of industries because of their efficient design and compact size. Unlike traditional designs, the fluid flows in wide passageways between two plates rather than round tubes. The small separation between the plates allows for maximized surface area contact with the working fluid, often aided by geometric features on the plates that enhance flow and heat transfer characteristics. [2]

Many plate heat exchanger systems are modular, allowing the user to add more elements simply by bolting them in place. Many designs use gaskets between the plates, so it is simply a matter of putting additional stacks of plates and gaskets in place. Designs that operate under higher stress are often brazed or welded together, and the system can be modified by adding a block of plates, typically attached through the use of fluid fittings. [2]

The majority of plate heat exchangers are liquid/liquid designs. Because the liquids used tend to have similar thermal properties, heat exchanger plates can be symmetrical, reducing manufacturing costs. Plate heat exchangers are typically stamped metal
sheet, formed into a set of channels in a deformation process. These plates are then stacked to form the unit, and fastened either by bolting with a gasket between the plates, or by welding or brazing for a permanent bond. When possible, bolted gasket designs are favorable because they are very easy to disassemble for cleaning. Cleaning of permanently bonded heat exchangers is much more difficult, typically requiring a chemical cleaning to break up and dissolve fouling deposits. \cite{2}

Because of their accessibility and ease of maintenance, gasketed plate heat exchangers are favored in food and drug processing. Manufacture and production of food and drugs often requires controlled heating processes, and facilities must be very clean to ensure the product does not become contaminated. One of the most common places to find plate heat exchangers is in milk processing plants, where they are used in the pasteurization process. Because the process requires that the milk be heated and then cooled, it makes sense to use a counter flow design and transfer heat from the hot milk to the cold milk. Some of these systems are so efficient that more than 98% of the heat can be transferred, so additional heat input is minimized, maintaining low operating costs. \cite{2}

Because plate heat exchangers are typically made out of sheet metal stampings without substantial machining processes, they can be made from almost any ductile metal. Copper and aluminum are very common because of their good thermal conductivity characteristics. Stainless steel is the material of choice in the food and drug processing industry, where high standards of cleanliness must be maintained. Stainless steel is also used in chemical and petroleum processing, as well as nickel based super alloys. Some initial work is being done with titanium alloys too, beneficial because of its high strength and light weight.

The design of the surface geometry in plate heat exchangers is critical. The goal is to maximize wetted surface area between the plates in the desired flow regime, laminar or turbulent. It is also important to build a unit that has enough length
of the heat transfer area so many designs incorporate geometries that force the fluid to follow a curved path to increase the linear distance it must travel. Plate heat exchangers can be designed to operate in generally laminar or generally turbulent flow regimes. Traditionally, heat exchangers are designed to operate in the turbulent regime to maximize fluid mixing and heat transfer. This also increases drag and pressure drop, requiring a more powerful pump and generally a reduced flow rate. Plate heat exchangers can be built with very narrow spacing between the plates, allowing for efficient operation in the laminar regime. Without a big cross section of fluid, only a small temperature gradient exists, so mixing isn’t as critical. [9, 10, 11] Plate heat exchangers are typically made from stamped sheet, though they can also be made by conventional machining operations, and electro-discharge machining (EDM) operations for special applications. Stamping sheet metal is generally the lowest cost
manufacturing process available. [2] Metal is cut to shape, either in a large shear punch, laser or water-jet cutting, or some other process. After the required geometry is made, the sheet enters a press, where rams compress the sheet into a closed die, forcing the metal to plastically deform and take the shape of the die. Once the shape of the plate is made, any final preparation of the part is done, such as drilling mounting holes, cleaning and polishing, chemical baths, or electroplating. The finished plate is then ready to be built into a heat exchanger. The simplest way to build a unit is to use a rubber or liquid gasket between the plates and bolt them together. This also offers the benefit of easy access for modification or cleaning, as previously mentioned. Certain applications, most notably in the petroleum processing industry, require more robust units, so the edges are brazed or welded together instead of using gaskets. Brazing or welding might be necessary if the unit is to withstand higher operating pressures and temperatures. So long as both fluids operate at the same pressure, the plates will not deform during use as there is an equal reaction to the forces induced by the fluid pressure on one side. The weak point of the system is the edges, where the pressure can cause gaskets to blow out or the welded or brazed section to split and rupture. If one fluid experiences a sudden loss in pressure, the new pressure differential will cause the plates to balloon and deform, eventually leading to failure by cracking or by separation at the edge, so it is important that the system be monitored during operation to avoid the destruction of a heat exchanger unit. [2]

While plate heat exchangers excel in transferring heat between two liquid mediums, it becomes distinctly more challenging when air or some other gas is being used. Typically, heat exchangers that use air have space between fins or plates to allow an air stream to pass. In the case of plate heat exchangers, having an air stream becomes difficult because the pressure of the internal fluid must be close to atmospheric to prevent ballooning and rupturing, and because air is not a good heat conductor, external surface area needs to be maximized. In traditional heat exchangers, this is
done with a series of fins through which the fluid tubes pass. The unique geometry of plate heat exchangers makes this solution unfeasible.

Current research is being pursued to develop plate geometries that will allow for efficient transfer of heat between gaseous and liquid mediums. [12] There are many different approaches including development of fins such as those used on standard heat exchangers, changing the surface finish to increase surface area, ducting to increase forced convection, and combination units which allow transfer at high temperature differentials to occur in plate heat exchangers and revert to standard heat exchangers to remove the residual, lower quality heat. [13] Another important field of research for developing plate heat exchangers involves micro channel heat exchangers in plate geometry. [14]

![Figure 2.2: A plate heat exchanger with attached pressure gauge.](image)
2.2 Micro Channel Heat Exchangers

Micro channel heat exchangers (MCHX) are a relatively new field with the promise of high efficiency and compact size. Theoretically, MCHX designs can be around 95% effective thermodynamically. [15] In comparison, current industrial heat exchangers are limited to around 70% for the most efficient designs, and most are around 60% effective. The reason MCHX are so much more efficient is that they allow much more heat to transfer from or to the working fluid by maximizing the surface area with which the volume of fluid is in contact. [16]

As the name indicates, MCHX have channel dimensions on the order of 10’s to 100’s of micrometers. [15] This is in contrast with conventional heat exchangers, which have passageways measured in millimeters for high efficiency designs and often moving into the range of several centimeters for large industrial heat exchangers. With such large passageways, there is a low amount of surface area contact for the amount of fluid volume being transferred. As such, these designs are inherently inefficient. To combat these inefficiencies, typical heat exchangers are designed such that the fluid flows in a turbulent manner, to maximize mixing and heat transfer at the walls. Turbulent flows have higher friction and therefore require more pumping energy. Good MCHX can be designed to operate in a more efficient, laminar flow regime. [17]

One simple measure of a heat exchanger’s effectiveness is the surface area to volume ratio. This number gives a quantitative estimate of the ability for the heat exchanger to efficiently transfer heat. Standard industrial tube and shell heat exchangers have a low A/V, generally on the order of 50-100 $m^{-1}$. A well designed compact heat exchanger can move up towards 1000 $m^{-1}$ or more, and MCHX have been produced with an A/V well in excess of 1500 $m^{-1}$. [18, 19]

Despite being very effective, MCHX are currently unable to flow the high volumes of fluid that large heat exchangers deal with. [20] This is due to increased fluid friction (which is partially mitigated by the laminar flow characteristics) and also due to the
small size of units which are currently feasible for manufacturing. This shortcoming can be fixed by using a system that diverts partial flow through the heat exchanger and then mixes with the main flow. Since the heat exchanger is more effective, it can cool down a smaller portion of fluid to a larger extent, resulting in the same or better net transfer of heat, despite not acting on the whole body of fluid.

Microchannel heat exchangers are typically designed to be cross flow heat exchangers, or have unique designs for specialty applications. For example, cooling of critical electronic components can be achieved by building a MCHX which is a three dimensional mesh block of a conductive metal. Fluid can be pumped through the block and the high surface area and conductivity can pull out a great deal of heat, especially when compared to a standard convective heat sink. There are also some designs of MCHX that operate in essentially a parallel flow pattern, but unlike a tube and shell, all the fluid is contained in alternating channels. While these can be exceptionally efficient, plumbing presents a problem, especially on larger units.

Current MCHX designs tend to be small due to feasibility difficulties of producing large units. Therefore, they are frequently used to cool critical electronic components, rather than operate in more traditional industrial settings. Small heat exchangers are also very desirable for use in MEMS devices, and are starting to be used in aerospace and chemical processing applications. Because the technology is so new, there is not yet an industry standard for fabrication techniques or materials. Ashman and Kandlikar have overviewed standard industry practices for fabricating MCHX devices. Because of their use in electronic components and MEMS devices, much of the early development of MCHX units has been with etched silicon or silicate glass, just like computer chips. Silicon is a good material for these applications as it can be fabricated with close tolerances and very deep channels, and it maintains good thermal conductivity of \(149 \ W m^{-1} K^{-1}\). [14]

Silicon and its glasses have many drawbacks for industrial applications, however.
The etching process is a delicate operation, and large scale production is not feasible. Furthermore, silicon does not have ideal mechanical properties for a heat exchanger being used in a dynamic industrial process. Development of metal heat exchangers is being done to remedy these shortcomings, but metals cannot currently be easily etched like silicon. Because of the microprocessor and computer chip industry, etching silicon is a well known and mature practice, but processing metals in this manner has lagged behind. As such, experimentation is being done with a number of different processes to fabricate microchannel heat exchangers out of metal. [14]

Machining and micromachining are techniques where material is mechanically, and in the case of electrical discharge machining (EDM), electromechanically removed. Conventional machining techniques are able to break into the micro-dimensional realm, but just barely. EDM can be used to cut material to smaller dimensions with good accuracy, but requires special equipment and tends to be costly to operate. Laser machining also falls into this category, with powerful lasers used to melt and ablate material in a computer controlled pattern. Lasers can be used to cut a wide array of materials, generally not limited to softer materials as some other forms of machining are. [14]

Another method for construction of MCHX is LIGA (German acronym for 'lithography, molding, and electroplating'). This process utilizes an X-ray to form an image on a photo resist material mounted to a substrate. After the image is burned, the photo resist material is electroplated with nickel to build a structure that matches the pattern drawn by the X-ray. After the structure is built in nickel, it can be used by itself, or can be used as a mold. Typically with MCHX, the nickel structure is used directly in the heat exchanger. [14]

While current manufacturing techniques for MCHX are limited in what they can do, the possible applications for such high efficiency heat exchangers will push development of new methods for low cost production on a larger scale.
2.3 Brazing

2.3.1 Brazing Overview

Brazing is an industrial process used to join multiple metal components into a rigid assembly. The brazing process is very similar to soldering except that it uses higher temperature filler alloys. In these processes, a secondary alloy is melted between the mating surfaces of the parts to be joined, without melting the base metal, as is done in welding processes. The difference between soldering and brazing is typically defined by the process temperature, with soldering occurring below 450°F and brazing occurring above that temperature. This temperature distinction is made due to the fact that, while brazing does not melt the base metal, there is diffusion of the filler into the base structure, creating a stronger bond. Soldering processes typically do not involve this diffusion mechanism. The amount of diffusion is based on the brazing time and temperature. Soldering and brazing processes are used to make components from multiple parts that need to maintain tight geometric tolerances in the final product. Brazing is often a better choice than welding because a joint can be made with larger joined surface area, and the microstructure of the base metal is not altered nearly as much as it is with welding. Also, deformation due to thermal gradients and cooling in the parts is much less severe, so warping can be reduced in the finished component. Brazing can also be more easily automated than welding, and can be done in steps such that fitting and application of filler can be done when the piece is cold, making the process easier and safer for the workers. [21]

A robust braze joint is typically characterized by the filler metal wicking between the surfaces via capillary action. Because the filler metal is selected to produce good wetting characteristics, it tends to run and fill thin gaps between the parts to be brazed. To maintain good surface tension of the braze and wetting characteristics so the braze wicks into the joint, the gap to be brazed is critical. A smaller gap will
always produce a better braze joint as long as the braze has enough room to flow
into it. Smaller gaps will also make a stronger joint, due to the triaxiality of stresses
induced on the joint from the much stronger base metal. The constraint provided by
the substrate induces triaxial tension in the braze joint, increasing its yield strength.
Careful selection of the filler metal is important in developing a strong joint. The
filler metal must have similar thermal expansion characteristics to the base metal,
and produce a braze joint of sufficient strength such that the failure of the completed
part will occur at some other location than the joint. [22]

2.3.2 Brazing Techniques

Generally, the braze joint must be protected from oxidation during the brazing process
due to the high temperatures that promote oxide growth. As the filler metal will not
wet and bond to an oxide surface, a number of techniques are used to keep clean metal
exposed for brazing. The simplest method, commonly associated with torch brazing,
is to apply flux to the joint. Fluxes are typically an acidic paste solution containing
salts that etch the surface and prevent formation of oxides. At high temperatures,
they melt and form a glassy coating that protects the joint from the atmosphere. The
braze can be applied through the flux as it flows easily under the protective layer,
displacing the flux from the gap to be brazed. After cooling, the brittle flux layer can
be cleaned off either chemically or mechanically, depending on the application.
Inert atmospheres, such as argon, are also used to braze, typically in a furnace brazing
process. Clean metal is placed in the furnace with braze material in place at the
joint, either in foil, wire, powder, or paste form. The component is then heated in
an inert atmosphere so the clean metal surface does not degrade with the increased
temperature. This process can be taken even further by using hydrogen, which instead
of being inert is quite reactive. Hydrogen reacts with surface oxides, forming H₂O,
and cleaning the surface in the process. This means hydrogen furnaces can be used
to clean any leftover contaminants from the braze surface, producing a stronger braze than might be possible in an argon atmosphere. Hydrogen furnaces can also be used to simply clean metal, in a process called a bright anneal. This process might be used prior to brazing if the components are not in a satisfactorily clean condition.

For critical components, brazing is typically done in a vacuum, so there is no possibility of contamination. In fact, some of these furnaces are flushed with argon multiple times, to ensure that any remaining gas in the chamber is inert when the vacuum is applied. Vacuum brazing is a batch process that requires substantial investment in equipment and is therefore used almost exclusively for high quality, critical components, especially in the aerospace and medical industries.

Braze alloy selection is important for brazed components. Consideration needs to be given for thermal expansion characteristics, strength, high temperature performance, environmental corrosion, and chemical interaction. The alloy choice has to be carefully tailored to the specific application, to ensure the best performance characteristics at a reasonable cost.

Braze alloys are formulated with multiple elements, for a number of reasons. The alloys can be designed to provide the mechanical and chemical properties necessary, as well as have near-eutectic behavior so that they solidify quickly after melting with a uniform microstructure. [23] In addition to alloy choices, braze is available in a number of different forms. Wire is one of the most common, and can be used for torch brazing with flux as well as various furnace processes. Powders and pastes can also be used for furnace brazing, and can be applied during fitment, prior to the components entering the furnace. Paste braze can be made with flux or with volatile binders, depending on the application requirements. Thin foils are also available, often as a strong amorphous material that allows large flat surfaces to be brazed together. The amorphous nature of the thin films is beneficial because they are very resilient during handling and fitment, and because they are homogeneous in composition.
Chapter 3

Experimental Procedure

3.1 Introduction

The goal of developing high performance heat exchangers requires that the manufacturing methods used be robust, mechanically sound, and highly repeatable. Development of these methods requires a series of tests to provide quantitative data on the quality of each process step. The data from these tests can then be incorporated into a model derived from adhesive behavior and basic mechanics, to accurately describe the expected mechanical performance of the brazed heat exchanger components.

3.2 Environmental Testing

The combined effects of high temperature and possibly corrosive exhaust gas composition requires a careful materials selection process to ensure consistent performance over the lifespan of the heat exchanger unit. Environmental testing of the heat exchangers was carried out in a long term natural gas powered exposure system. The system, as shown in figure 3.1 is enclosed in steel ductwork and powered by a natural gas burner with safety shutoffs to prevent gas leaks.

The initial metal alloys tested for the heat exchangers were 6061 aluminum, 1018 mild
steel, 110 copper, and 316 stainless. These alloys were subject to constant heating in a nominally clean exhaust atmosphere at a temperature of 1100°F. Corrosion measurements were taken using the mass change as oxide layers built up on the sample surface.

A second test was developed using the same testing apparatus to test more exotic alloys. Using 316 stainless steel as a baseline from the previous tests, nickel superalloys were tested over a longer term test. The alloys tested in comparison with the 316SS were Incoloy 800H and Inconel 617. These alloys are used in demanding environments where high temperatures and corrosive species are present and high mechanical properties are required, as the nickel superalloys maintain high strength levels to near their melting point, unlike traditional materials.
3.3 Heat Exchanger Plate Manufacturing

The micro channel heat exchangers are fabricated from two metal plates with machined features. The front plate is cut from 16 gauge (.0625in thick) sheet metal and has the micro channels and manifolds machined into the surface. The back plate is cut from .020in thick sheet, but has no features machined in it. Both plates are 5in X 1.5in dimensionally.

The channels are machined using a 100W Neodymium-doped Yttrium Aluminum Garnet (Nd-YAG) laser, as seen in figure 3.2. The channels have a nominally square cross section, with a width and depth of 500microns (.020in). The initial design of the heat exchanger calls for a series of channels equally spaced along the length of the plate. The manifolds are the same depth as the channels and are 3/16in wide, machined with a conventional endmill. Ports of 3/16in diameter are drilled in both plates to allow the working fluid to enter and leave the plate element. The heat exchanger element prior to brazing can be seen in figure 3.3.

Following the machining operations, the plates must be prepared for brazing. All sharp edges are broken and deburred, and machining marks are removed from the surfaces to be brazed. The plates are flattened to within .005in total indicated runout.

Table 3.1: List of alloy compositions

<table>
<thead>
<tr>
<th>Alloy</th>
<th>316 SS</th>
<th>1018 Steel</th>
<th>6061 Al</th>
<th>110 Cu</th>
<th>Inconel 800H</th>
<th>Inconel 617</th>
<th>AMS 4777</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>–</td>
<td>–</td>
<td>Bal</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
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<tr>
<td>Cr</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>19-23</td>
<td>20-24</td>
<td>14</td>
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<tr>
<td>Ni</td>
<td>10-14</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>Bal</td>
<td>Bal</td>
<td>–</td>
</tr>
<tr>
<td>P</td>
<td>&lt;.045</td>
<td>&lt;.04</td>
<td>–</td>
<td>–</td>
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<td>–</td>
</tr>
<tr>
<td>Si</td>
<td>&lt;.1</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>&lt;1.0</td>
<td>5.6</td>
<td>5.5</td>
</tr>
<tr>
<td>Ti</td>
<td>–</td>
<td>–</td>
<td>&lt;.15</td>
<td>–</td>
<td>&lt;.6</td>
<td>&lt;3.0</td>
<td>–</td>
</tr>
<tr>
<td>Zn</td>
<td>–</td>
<td>–</td>
<td>&lt;.25</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Other</td>
<td>–</td>
<td>–</td>
<td>&lt;.05</td>
<td>&lt;.1</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Standard (ASTM)</td>
<td>A240</td>
<td>A36</td>
<td>B221</td>
<td>B187</td>
<td>B409</td>
<td>B168-08</td>
<td>AMS 4777</td>
</tr>
</tbody>
</table>
Figure 3.2: The 100W Nd-YAG laser system used to machine the microchannel heat exchangers.

to provide a good brazing surface. The faces are then sanded to remove all oxide and leave a rougher surface for good braze adhesion. Finally, the surfaces are cleaned with acetone to remove any residues and packed in a clean plastic bag for storage until they can be brazed. Brazing occurs within a few days of final cleaning to limit environmental exposure of the newly cleaned surfaces.

3.4 Brazing Processes

Several different methods have been used to braze components throughout this project. Using various methods provides insight into manufacturing feasibility for commercial heat exchanger unit. Brazing has been carried out in a vacuum, hydrogen atmosphere, and an atmosphere of 95% argon 5% hydrogen. Using a controlled atmosphere eliminates the need for fluxes in the brazing process, increasing quality and removing
possible sources of problems in the final product.

Vacuum brazing is a batch process, considered the industry standard for producing the highest quality components. It requires charging of a vacuum furnace and then pulling a vacuum, often several times with intermediate argon purges for the most stringent parts. Despite the high quality associated with vacuum furnaces, high operating costs limit the practical application of these units. [24]

Hydrogen furnaces operate with a reducing hydrogen atmosphere. While hydrogen is not inert, its reaction with surface contamination is beneficial in that it typically leaves the part cleaner than it started. During the brazing process at 1975°F hydrogen reacts with oxygen and other contaminants in the surface oxide layer of a metal specimen and leaves bare metal exposed. The hydrogen furnace used in production of the heat exchanger elements and test samples is a conveyor furnace, allowing for continuous...
Figure 3.4: A heat exchanger plate fixtured in the laser machine. Note the compressed air cooling nozzles used to reduce warping.

Figure 3.5: A set of heat exchanger plates after laser machining. These are ready to have manifolds and ports machined using conventional milling techniques.
production on the belted system. This is the most economical way to process brazed components, as it is a continuous operation that can be fully automated. Also, surface preparation of the material is not as critical as with other methods, as the hydrogen atmosphere does have cleaning properties. [25]

A special graphite fixture (see figure 3.6) was developed and built to operate in the hydrogen conveyor furnace. The fixture was designed to allow several plates to be located and brazed simultaneously. Spot brazing was also utilized to provide initial location of the plates. This process uses a spot welder to braze a very localized portion of the plates so they are geometrically fixed in relative position. [25]

Figure 3.6: The graphite fixture developed for use in the hydrogen furnace. A machined plate is shown in the fixture with spare fixturing pegs.

The argon and hydrogen atmosphere was utilized in a resistively heated tube furnace in the laboratory, as shown in figure 3.7. This furnace, while not suitable for production scale volumes, allows quick access to brazed parts. Typically, this unit was used
to braze mechanical testing specimens rather than full heat exchanger elements, however one element was brazed in this furnace as well to determine feasibility. Unlike the pure hydrogen furnace, there is very little cleaning effect from the gas, so good surface preparation is critical for a robust braze joint.

Figure 3.7: The tube furnace used for brazing test specimens in house. This unit is resistively heated and uses an argon/hydrogen mixture to shield the pieces during brazing.

### 3.4.1 Braze Alloy Selection

Selecting a suitable braze alloy is critical to ensure good performance of components. Alloys choices vary depending on the substrate materials, operating environments, and operating temperatures. Aluminum, zinc, and magnesium alloys are typically brazed using a zinc based braze system. Copper and its alloys are often brazed with alloyed copper based braze, as well as silver brazes. Low temperature soldering of copper is done with lead/tin solders. Ferrous materials have a wide variety of suitable
brazing alloys. Most common are copper and silver alloys, which are frequently brazed using a torch and flux, as well as controlled atmosphere furnace operation. Nickel alloys are very popular as high performance steel braze materials, as they exhibit high strength even at elevated temperature, and are generally exceptionally resistant to corrosion. Even more exotic systems use gold based braze as it is nearly impervious to most corrosive environments.

![Figure 3.8: Several braze alloys in different forms. From left to right, tin-based soft solder paste with flux, zinc-aluminum brazing rod, silver based brazing wire, copper-based brazing paste, and nickel-based amorphous foil.](image)

For our work, a nickel braze alloy was chosen. The nickel alloy was chosen for use in our application due to the high strength requirements at elevated temperature in a possibly corrosive environment. The specific alloy was chosen as recommended from a consultation with Prince and Izant Company. [26] Our alloy choice was Prince and Izant AMS4777, a nickel alloy with chromium, iron, boron, and silicon. Specific composition can be found in table 3.1. The braze is in an amorphous foil form, rolled...
in a strip 1.5in wide and .0015in thick. The amorphous nature allows the foil to be handled and maintain its shaped due to the high strength.

### 3.5 Pressure Testing

The design of the waste heat recovery system utilizes high pressure, supercritical carbon dioxide as a working fluid. The design of the heat exchanger unit has to be able to withstand fluid pressures in excess of 5000psi. A series of burst tests were performed on brazed heat exchanger plate elements to determine the maximum pressure attainable.

A special pressure test rig was developed to allow testing of the elements in house as can be seen in figure 3.9. The equipment consists of a high pressure fluid pump, able to develop 10,000psi of fluid pressure, a high pressure hose with appropriate AN type fittings to connect to the HX plate, and an 8900psi digital pressure gauge with maximum pressure readout, all mounted in a welded steel frame. The pump operates by using compressed air from a standard industrial air line to compress the working fluid, which was water in our experiments. The compressed air acts on a large piston which acts on a small piston to pressurize the fluid, developing a mechanical pressure advantage ratio of 100:1, so an air pressure of 100psi will produce a fluid pressure of 10,000psi.

### 3.6 Braze Strength Testing

Because the fabricated metal plates of the heat exchanger are brazed together, the strength of the braze has to be quantifiable to ensure acceptable performance in real world applications. The pressure test does provide excellent data on the failure pressure of the heat exchanger unit, but more carefully controlled and measured experiments to test the braze are necessary to develop a suitable model of brazed
joint failure that can be applied to the heat exchanger plates.

The failure mechanism of the heat exchanger elements is due to pressure causing the plates to separate and peel apart. The peeling failure is controlled by both geometry of the system components and the tensile strength of the braze material. Understanding the complete failure mechanism of the system requires testing the braze strength in simple tension and applying that data to the peel geometry. To analyze the braze strength, a model for the stress distribution ahead of the crack must be developed through mechanical testing experiments.

### 3.6.1 Braze Peel Testing

The primary mechanism by which failure occurs in the heat exchanger plate is a peeling failure. As the pressure increases, the open sections balloon outwards, creating
a localized tensile load in the braze joint. To approximate this localized loading scenario, a series of peel tests are run to provide data on the performance of the joint as it separated.

Peel specimens are made by partially brazing coupons of sheet metal and then pulling them apart. The coupons are .5in wide, and made in various sheet thicknesses to compare performance based on substrate constraint. The brazed area was .5in X 1in in all the basic peel samples.

Figure 3.10: Brazed peel specimens. Note that the top specimens have been bent to allow gripping for peel test. Bottom specimens are unbent, in as-brazed condition. Inset is a diagram showing a magnified image of the T specimen, specifically indicating the braze joint.

A second type of peel test is developed to further understand the stress distribution at the crack tip. This is critical for fully developing and understanding the model of heat exchanger plate failure. This design incorporates a series of four brazed joints on two strips of 316 stainless steel substrate. The substrate was of the same thickness as
the final heat exchanger design (.020in X .0625in) and had plate dimensions of .75in X 6in. The joints are the width of the strips and .5in long, spaced evenly at .5in, as shown in figure 3.11. This geometry allowed the load and displacement data from the tensile machine to directly correlate to the crack tip location in the specimen throughout the test. This type of peel test is repeated with a second set of substrate geometries, both using the .0625in thickness material. The second set of the new peel samples are prepared in the same manner as the first. Figure 3.12 shows the new peel geometry during testing.

![New geometry peel samples masked with boron nitride, ready to be brazed.](image)

**3.6.2 Braze Tensile Testing**

Failure is ultimately controlled by the tensile strength of the braze. While the loading on the heat exchanger plates is not purely tensile in nature, the tensile strength
controls failure in the peel/crack opening loading case that is prevalent. A standard tensile test is utilized to determine the tensile strength. Two solid cylindrical bars of the substrate material are machined, with one end faced and ground flat, and brazed together with a butt joint. The samples have a diameter of .5in and an overall brazed length of 3in. This testing geometry offered suitable properties for testing.

A specially developed fixture is fabricated to allow the pieces to be aligned and held during brazing, and the process is carried out in the same hydrogen conveyor furnace as the majority of the heat exchanger brazing. The fixture allows for ten tensile samples to be brazed simultaneously, and is coated with Nicrobraz type II, an aluminum oxide braze stopoff compound to prevent accidental brazing of the sample to the fixture.

Braze processing of the tensile samples used a 316 stainless substrate and a total of
Figure 3.13: The fixture for brazing tensile test specimens. The fixture is constructed from 4130 steel tube welded together and coated internally with Nicrobraz type II aluminum oxide braze stopoff compound to prevent bonding the specimens to the fixture.

ten samples are brazed, five with a single layer of braze material, and five with two layers. Testing both one and two layers will allow data to be collected that can assist in development of a model for the plates. It is unlikely that the braze thickness will be perfectly consistent across the entire bonded area of the HX plate, so being able to account for varying thicknesses in the braze strength model could be important. After brazing, the round tensile samples were pulled in the Instron 1125 tensile machine until failure and separation, to demonstrate the characteristics of the braze failing in a purely tensile loading scenario.
Figure 3.14: The tensile test specimens after testing. The specimen without a seam is the baseline test specimen, and the surface shows signs of plastic flow.

3.7 Model of Stress Distribution in the Braze

To fully understand the behavior of the failure mode, a model is developed based on existing adhesive peel models and the experimental data. Previous models for peeling adhesives have been developed, but they are generally not accurate enough to be applied directly to the heat exchanger plates. For this, the model has to be developed and refined with the use of the experimental data from the peel and tensile specimens. Simple models of beam bending and deflection are used to provide boundary conditions for the system. Tensile loading within the braze can be calculated from these boundary conditions as well as the tensile and peel data acquired through mechanical testing of the brazed joints.

Generating a model for the stress distribution requires data on the tensile strength of the braze, the length over which the stress gradient acts, and the general form of
the stress gradient for this geometry.

3.8 Performance of Micro Channel Heat Exchangers

Early experimentation with a standard tube and fin heat exchanger utilizes a gas burner to provide heat energy to an air stream passing across the transfer surface, as shown in figure 3.15. Water is pumped at a constant flow rate through the unit and the temperature of the hot and cold side for both the water and the hot air are measured. While this setup allows simple collection of baseline performance data, a dedicated testing apparatus is necessary for continued testing of various heat exchangers to ensure consistent results.

Figure 3.15: Initial testing of a traditional tube and fin heat exchanger. After initial test results, this apparatus was repurposed for long term high temperature exposure testing.
A system is designed using a blower to force electrically heated air across the heat exchanger which is secured in an appropriately sized fixture within a ductwork. Thermocouples are used to measure the intake and exhaust temperature of both fluids, and the mass flow of water through the heat exchanger can be measured. These figures allow for efficiency and effectiveness calculations to be performed to determine the performance of each HX unit tested.
Chapter 4

Results and Discussion

4.1 Environmental Testing

The initial testing of common metal alloys indicated that 300 series, specifically 316, stainless steels are the best choice. They are limited by their relatively low thermal conductivity, but corrosion resistance and high temperature performance are excellent. The high conductivity alloys were found to be unsuitable for several reasons. Copper was found to oxidize rapidly at high temperatures, and also becomes annealed and soft, possibly leading to premature failure of the component. Aluminum was unable to withstand the test temperatures, rapidly degrading and creeping to the point of fracture, at which point the sample fell into the burner flame and melted. The lowest cost mild steel option was also found to be unsuitable as it oxidized rapidly and also had undesirable conductivity characteristics.

The results of this testing indicated that while copper could be utilized in some specific applications, 300 series stainless steel alloys are generally the best choices. This became the baseline material to test some of the more exotic alloys. While it is felt that stainless steel will be adequate for most applications, there exists the possibility for more extreme environments that require even more robust materials.
Because of this, a second, long term exposure test is currently being run to compare 316 stainless steel with nickel based superalloys.

4.2 Batch Brazing Experiments in a Vacuum

Initial elements are brazed by Solar Brazing in a vacuum furnace. Vacuum brazing is considered to be the cleanest, most reliable method available in the industry, as it operates in an environment without atmosphere to interact with the braze or substrate metals. The braze material is provided by Solar for these experiments, and limited data is provided regarding the process. The braze is a nickel based alloy, though it is unknown whether it was in powder, past, strip or some other form.

Solar’s vacuum brazing results are found to be unsatisfactory. Post process analysis by both visual and x-ray inspection indicates that the brazing process results in a low quality product. The braze has filled a number of the channels while coating a significant amount of the outer surface.

4.3 Continuous Belt Processing in a Hydrogen Atmosphere

Following the unsatisfactory results of the vacuum brazing process at Solar, a local company is sought to do brazing for this project. American Brazing agrees to provide brazing services on their hydrogen conveyor furnace. The conveyor furnace operates a slow belt that moves braze specimens from the loading point in a standard atmosphere into an atmosphere of pure hydrogen. After entering the hydrogen atmosphere, the parts are heated to the process temperature, and the hydrogen shields the metal and reduces any oxidation, leaving a clean bright surface. The process used takes approximately two hours and forty five minutes to complete, with a process temperature of
Initial testing with the hydrogen furnace utilizes a graphite fixture to locate and position the plates during processing as seen in figure 3.6. Unfortunately, during brazing the plates undergo substantially more thermal expansion than the fixture, so they become constrained in the fixture and buckle and warp during the process. The fixture is modified by machining a groove in the support pins to allow for full expansion of the plates without constraint. While this allows the plates to conform during brazing, warping still occurs in the plates. This was thought to be due to the different cooling rates experienced by the two plates, one being exposed to atmosphere while the other sitting on a large mass of heated graphite. Experimentation with brazing without the fixture indicated that better results could be had if the plates are simply placed on the steel mesh conveyor belt. This presents the problem of locating the plates relative to one-another, which is solved with a spot brazing process. The plates are resistively brazed at six to eight locations so they were fixed together and could be handled and placed on the conveyor belt. This process proves to be successful and became the standard fabrication procedure for the heat exchanger elements. The hydrogen conveyor furnace is also used to braze the tensile samples used to develop the braze strength model. The geometry of these samples required that they be brazed in the hydrogen furnace rather than the tube furnace.

4.4 Peel Testing of Brazed Joints

Because the heat exchanger elements fail by a peeling mechanism, a peel test is devised to test strength of a crack propagating through the braze due to a peeling load. Specimens are made from sheet stock and had a brazed area of 1in x .5in. These samples are brazed flat in the tube furnace with a protective atmosphere of hydrogen and argon. After brazing, tabs are bent off to allow the Instron 1125 to grip the
material for the peel test. The peel test is performed by the machine pulling the tabs in a tensile direction, which initiates peeling in the specimen. An approximation of the stresses in the peeling material can be seen in figure 4.12.

![Initial geometry peel test](image)

Figure 4.1: The maximum load achieved during the initial peel testing, in chronological order of the test. Each data point is the value from an individual peel sample. The range is varied, indicating inconsistencies within the brazing process. This data is used to verify the accuracy of the model developed for braze stress distribution, as seen in figure 4.14.

The results from the peel test are shown in figure 4.1, which are quite varied indicating that the braze joints are not consistently robust. Figure 4.2 shows the typical behavior of a peel sample. Visual analysis of the joints after failure shows locations of good braze bonding by a dull fracture surface with a shiny surface indicating locations where the braze does not bond the two substrates and instead smoothly coats them, as shown in figure 4.3. Upon closer examination with a microscope, it is noticed that the shiny surfaces are in fact heavily textured, with jagged facets that reflect light, providing the appearance of smoother and shinier. The surfaces that were bonded
are actually smoother, but don’t have the same reflectivity as the jagged unbonded surface. Examination under the SEM supports this conclusion, as the bonded surfaces are quite smooth and dull, but the exposed surfaces have an oxide film on them, and a jagged structure, as seen in figure 4.4.

![Graph](image)

Figure 4.2: The load vs displacement trace of peel sample number 3. This curve is typical with increasing stress to a flat plateau, and then rapid failure near the end. While the magnitude of the load was inconsistent between samples, the general shape and behavior during the test was quite similar.

The first set of the redesigned peel tests did not provide suitable results on the strength of the braze joint. These peel tests used the same plate geometries as the final design for the heat exchanger elements, .020in X .0625in plate thicknesses. During peel testing, these specimens fail almost immediately by fracture of the stainless steel substrate. While the results of this experiment fail to provide any useful quantitative data, it should be noted that this failure mechanism is a confirmation that the braze joints are of sufficient strength for the system in which they are being used. The joints
are strong enough that they are not the weakest part of the system, a fact corroborated by the failure mechanism of the heat exchanger elements during pressure testing. The second set of new geometry peel tests produce data that represented both the load carrying capacity and the depth of the stress distribution during peeling failure. The values measured during the test are displacement and load, which are then analyzed to calculate the stress distribution depth. The test itself is shown previously in figure 3.12 and the data produced is shown in figure 4.6. The fracture surface after testing is shown in figure 4.7.
Figure 4.4: The fracture surface under a scanning electron microscope. The bright, highly textured portions on the left and right side of the picture are the unbonded section. They are coated with an oxide layer, formed during the brazing process. SEM work courtesy of Dr. Xuejun Zhu.

4.5 Tensile Testing of Butted Brazed Joints

Tensile testing is carried out on a number of round tensile specimens. The specimens are .5in diameter and 3in long, machined from 316 stainless steel. These specimens are cut in half perpendicular to the axial direction, faced, and ground to provide a good flat surface to braze. Brazing is done in a special multi-tubular fixture that allowed ten samples to be processed at once. The fixture is coated with Nicrobraz stopoff to prevent bonding of the specimen to the fixture and brazing is carried out in the hydrogen conveyor furnace. The braze is cut from the amorphous foil using the Nd-YAG laser to form braze circles that accurately matched the diameter of the test bar. Initial testing includes different amounts of braze to test the strength relationship of varying joint thickness. Samples are made with both one and two layers of .0015in
Figure 4.5: The first set of peel tests with the redesigned braze geometry. These specimens utilize the same substrate thickness as the heat exchangers, with a .0625in front plate and a .020in backplate. These fail in the same manner as the heat exchangers, with the stainless steel fracturing prior to braze failure.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Layers</th>
<th>Strength(ksi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>101</td>
<td>1</td>
<td>38.352</td>
</tr>
<tr>
<td>102</td>
<td>1</td>
<td>33.98</td>
</tr>
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<td>103</td>
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<td>2</td>
<td>28.27</td>
</tr>
<tr>
<td>205</td>
<td>2</td>
<td>13.726</td>
</tr>
</tbody>
</table>

Table 4.1: Tensile test results. In the single layer specimens, the substrate yields prior to braze failure, at around 30ksi.

thick braze. The tensile test results are available in table 4.1.

After brazing, the tensile samples are pulled in the Instron 1125 tensile machine. One solid sample is also utilized as a baseline, to detect yield of the base stainless steel and compare it to the brazed samples. The results indicate that one layer is stronger than two layers, as expected due to the higher triaxiality of the tensile
Figure 4.6: Load vs displacement during testing of the second peel geometry. Analysis of the trailing edge of each maximum allowed for calculation of the stress distribution depth.

Figure 4.7: Fracture surface of the second peel geometry after testing.
stresses providing constraint in the joint. Of greater interest was the fact that the stainless steel substrate yields prior to braze failure. This indicates that the braze joints are robust enough to withstand the operating pressures of the heat exchangers, because the substrate will fail by yielding before the braze joint fails. This also gives insight into the mechanism of the failure, and allows for the development of the braze strength model in section 4.7.

4.6 High Pressure Testing

The high pressure test rig is used to burst test the initial HX elements after other analysis has been completed. For the system to be viable, it has to be able to withstand an operating pressure in excess of 5000psi, so the goal is to develop a unit that fails at a pressure significantly higher than 5000psi, and exhibited no deformation at that level. As the process was developed, a generally increasing trend in burst pressures was evident, as seen in table 4.2.

Element 1 is produced by Solar and brazed in a vacuum furnace. Visual examination reveals substantial excess braze on the surface, though the plates appeared to be bonded together properly. In depth inspection with x-ray shows that the center section is not well bonded, and that the braze has flowed into and blocked several of the micro channels. This first element is tested at a local facility prior to the acquisition of a pressure testing rig in house. Failure occurs at 768psi, well below the target minimum value of 5000psi.

Elements 2 and 3 are the initial attempts at brazing the plates at American Brazing. The graphite fixture is used on the early plates, to locate them as the passed through the furnace, as seen in figure 3.6. The plates experience substantial thermal expansion and are constrained by the fixture to the point that they buckled. Brazing is entirely unsuccessful and the fixture is modified to allow for reasonable expansion of the plates.
Element 4 is the first successfully brazed element. It is processed at American Brazing in the hydrogen furnace. Element 4 features a thinner backplate of .010in as opposed to the 1/32in (.03125in) plates previously used. This decision is made because it is hypothesized that the thickness of the backplate controls the ability for it to conform to the slight contours of the frontplate. Both the visual and x-ray inspection seem to confirm this, and the pressure testing results also favorably support it. A spot brazing process is first used on this element to located the frontplate and backplate in the correct orientation. The spot brazing process is utilized on all subsequent elements to simplify handling for processing. For the brazing process, the graphite fixture is not used. The graphite fixture has been acting as a heat source during the cooling phase after the brazing, causing distortion as the surfaces of the element cool at different rates. Because of the spot brazing, the element can be placed directly on the mesh conveyor belt which allows for more even cooling rates across the surface. Element 4 is able to withstand 3083psi in the burst test, and fails after significant deformation of the stainless steel backplate, as can be seen in figure 4.9. This indicates that the thinner backplate does help the brazing process, but it is concluded that an intermediate thickness is probably necessary to support the higher pressures required.

Element 5 is processed at American Brazing with the thicker 1/32in backplate again, in attempt to solve the brazing problems inherent in the more robust design. It is expected that the combination of the spot brazing and the lack of the fixture will allow the two plates to conform and braze properly. Unfortunately, this is not the case and inspection shows that the center section is again unbonded. Element 5 fails at just 476psi.

Element 6 is the second element brazed at Solar, and visual inspection reveals excess braze on the surface again. X-ray shows reasonably good bonding, but again several channels are blocked. The geometry of this sample incorporates the 1/32in backplate, as it had been delivered to Solar for processing prior to the successful test of the .010in
backplate element. Pressure testing of this element is successful, failing at a maximum pressure of 4079psi. However, due to the blocked channels, it is concluded that this element can not yet be considered a successfully fabricated plate.

Element 7 is the final element incorporating a 1/32in backplate. It is brazed by American Brazing, and it is hoped that careful flattening and preparation of the sample prior to brazing would allow it to bond well. Unfortunately, visual and x-ray inspection indicates poor bonding and pressure testing resulted in the lowest pressure attained during the tests of 461psi.

Based on the earlier result with a thin backplate, an intermediate thickness is chosen. The new backplates are .020in thick, twice as thick as the most successful element tested, but about .012in thinner than the 1/32in material typically used. Elements 8 and 9 show great success. Both are brazed at American Brazing, spot brazed prior
to processing. They are run through the conveyor furnace without any fixturing, and visual and x-ray inspection indicate that both elements are fully bonded and the channels are clear of obstruction. Pressure testing for element 8 results in a 4836psi burst pressure, very close to the 5000psi goal. Element 9 results in a burst pressure of 6467psi, well above our 5000psi goal. This indicates that the design is good and the processing steps utilized are capable of delivering a robust product. With the results of the initial series of burst tests, enough evidence is available to indicate that the heat exchangers can be fabricated to have the desired performance characteristics, so further development of the system can proceed.
<table>
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<tr>
<th>Sample</th>
<th>Date</th>
<th>Fabricator</th>
<th>Plate Geometry</th>
<th>Process</th>
<th>X-Ray</th>
<th>Pressure (psi)</th>
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<td>Vacuum</td>
<td>Unbonded</td>
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<td>Hydrogen</td>
<td>Fully bonded</td>
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Table 4.2: Initial pressure burst test results.

Figure 4.10: Elements 4 (top) and 5 after burst test.

4.7 Failure Mechanism of Brazed Joints

Quality control during production of heat exchangers will require methods for testing the braze strength. It is necessary to understand how the braze strength that can be easily measured relates to the burst pressure, a much more difficult and costly test to perform. The critical failure mode for brazed plate heat exchangers is peeling apart of the two plates. To correlate the quantitative data from mechanical testing of braze specimens with the pressure data from the burst testing of the brazed plates,
a model of braze failure was developed. The peel model is based on other models
developed for adhesive tests, using the same T peel geometry, [29, 30] but is enhanced
through development of an understanding of the deflection of the substrate material
and incorporates data from mechanical testing to provide accurate model results.
To correlate the burst pressure with a more readily measurable value, it is key to
understand the behavior of the heat exchanger plate during failure. Analysis of
videography taken during the burst experiments indicates that rupture is directly
preceded by severe expansion and plastic deformation of the heat exchanger plate.
This ballooning allows the pressure inside the heat exchanger to act on a much larger
surface area, creating the critical stress necessary to fracture the material. Typical
failure during the burst test occurs in the substrate material rather than the braze
itself. This is an indicator of good braze strength, and confirms that the process is
suitable for fabrication.
While it is reassuring to know that the current design is suitable, understanding the
stress distribution within the braze joint is important to optimize the design of the
plates for maximum heat transfer. To increase heat exchanger performance, the ratio
of internal surface area to fluid volume must be increased. This is done by increasing
the number of channels in the design, which is accomplished by reducing the channel
spacing. Unfortunately, this reduces the strength of the braze joint due to lower
bonded area being subjected to the same load.
The T peel test is a good representation of the stresses felt by the heat exchanger
during failure. The loading and stress distribution is very similar in both cases, as
the stress is offset and peels the two sides apart. Figure 4.11 shows the similarity
in geometries of the peel and the pressure test, and graphically describes the stress
distribution ahead of the crack tip as the braze is failing. By understanding the
stress distribution in a peel test, the strength of the braze joint in the heat exchanger
can be determined. The failure strength will allow determination of the theoretical
burst pressure for a heat exchanger. While maximizing the braze joint strength is important, it must be noted that during the experiments, it was seen that the stainless steel back plate is the weakest part of the system. In samples with robust braze joints, the stainless steel plastically deforms before the braze fails, with fracture typically occurring in the substrate rather than the joint.

Figure 4.11: The loading of the heat exchanger due to pressure compared to the geometry of the peel test. They are very similar, especially near the braze joint failure point. Inset is a graphical representation of the hyperbolic stress distribution felt ahead of the crack tip.

The ballooning failure that leads to substrate fracture initiates in the center section of the heat exchanger, where the channels and manifolds are located. There is less brazed surface area here, and this is the section where the working fluid exerts pressure. The weakest section is on the channel-side edge of the manifold area, as there is the largest surface area and the least brazed area in that location. As such, we focus on this area as the critical failure region. To model the stresses locally, we treat the heat
exchanger backplate as a cantilever beam, with a point load acting on it due to the internal pressure.

Figure 4.12: Rendering of stresses induced in the brazed joint area. Red indicates high stresses, blue indicates low stresses. Note that the general applied loading is tensile in nature.

Figure 4.13: Definition of the variables used in the model equations as applied to the rendering from figure 4.12.

Equation 4.1 shows the bending moment exerted on a cantilever beam loaded in this manner, and is an excellent approximation of the stresses in the substrate close to the joint. Equation 4.2 shows the applied stress during the peel test, and is the true
stress in the substrate near the grips of the Instron 1125. For equations 4.1 and 4.2, $M$ is bending moment (in-lbs), $P$ is load (lbs), $x$ is distance from the crack tip (in), $\theta$ is the effective angle (degrees), and $A$ is the cross sectional area (in$^2$) of one of the substrate pieces. Figure 4.13 shows what the different variables are measuring. In the portion of the substrate between the grips and the brazed joint, a combination of these two loading mechanisms acts on the system, applying both a tensile load and a bending deflection. Note that this equation loses accuracy in the center portion of the substrate between the grips and the joint, but as this section does not affect braze joint performance, it is of little consideration here. This method is also applicable to the peel specimens that were tested, so it provides the ability to directly compare the two tests, and apply the data from the inexpensive peel test to the costly burst test.

\begin{equation}
M = P \times x \times \cos(\theta) \tag{4.1}
\end{equation}

\begin{equation}
\sigma = \left(\frac{P}{A}\right) \times \frac{1}{\sin(\theta)} \tag{4.2}
\end{equation}

Using the cantilever beam model, the tensile stress value measured from the tensile tests is applied to the braze model at the crack tip. This is nominally the stress required to propagate a crack through the braze and initiate ballooning failure. The depth of the stress gradient is measured from the second peel test geometry. By measuring the crosshead displacement and the load as each brazed section failed, it is possible to determine that the depth of the stress gradient is on average .00949in, with a standard deviation of .0038in. These values do not include four outliers that were removed due to inconsistency with the data set. These were attributed to poor brazing conditions for the specific sample.

Combining these two values to develop the stress distribution requires the use of a stress distribution model. The Rice-Tracey relationship [31, 32] as shown in equa-
tion 4.3 describes the hyperbolic distribution of stresses that is common to triaxially constrained tensile stresses. By applying this hyperbolic model, the depth and shape of the stress distribution can be determined. Rice and Tracey developed their model to describe the behavior of ductile materials loaded in triaxial states, just as in a brazed joint. The hyperbolic form of this stress gradient is typical for systems with a continuous distributed load. Other work in adhesively bonded joints has resulted in similar stress distribution geometries. [29, 30] In the Rice-Tracey equation, $\dot{\epsilon}_{pc}$ is the critical plastic strain immediately ahead of the crack tip, $\bar{\epsilon}_{pc}$ is the global critical plastic strain, $\sigma_H$ is the hydrostatic stress, and $\sigma_e$ is the equivalent von Mises stress. [32] Hadavinia, et al. performed numerical analysis to verify that the Rice-Tracey equation accurately modeled the behavior of ductile materials in a triaxial stress field, ahead of a progressing crack tip.

$$\frac{\dot{\epsilon}_{pc}}{\epsilon_{pc}} = \frac{0.521 \binom{1.5\sigma_H}{\sigma_e}}{\sinh(\binom{1.5\sigma_H}{\sigma_e})}$$  \hspace{1cm} (4.3)

To apply the stress distribution to the brazed heat exchanger situation, equation 4.4 has been developed. It fits the load to the hyperbolic stress distribution for a perfectly brazed specimen. In equation 4.4, the multiplier terms come from the experimental data, with the scalar $8\times10^8$ applied to fit the maximum tensile stress to that measured from the tensile tests, and the value .00949 fitting the depth of the model stress distribution to the measured depth. To verify that this model works, the measured load on a perfect sample should equal the load predicted in the model. A rendering of the general stresses felt during braze failure via peel mechanism is shown in figure 4.12. In equations 4.4, 4.5, and 4.6, $\sigma$ is the stress (ksi), $\delta$ is the distance ahead of the crack tip (in), $F$ is the load (lbs), and $L$ is the length of the braze joint (in).

$$\sigma(\delta) = 8 \times 10^8 \cosh(-(.00949 - \delta) - 1)$$  \hspace{1cm} (4.4)
Equation 4.5 describes the total load a braze joint can support without failing. The total load carrying capacity of the braze joint is slightly higher in the model than measured, most likely due to local weak points in the joint caused by imperfect brazing. The model predicts the ideal situation, but the strength as measured during testing is slightly lower. The initial peel experiments demonstrate the accuracy of the model, as shown in figure 4.14. While there is a significant range of load values taken from the peel experiments, the well brazed specimens demonstrated strength approaching that predicted by the model, with the best sample carrying 97% of the load predicted by the model, 165.1lbs compared to the value of 171lbs predicted.

Figure 4.14: The results from the initial peel experiments in order of increasing load carrying capability. Fracture surface features for various samples can be seen in figure 4.15. The limit line indicates the maximum theoretical value predicted by the model. The best sample carried 97% of the load predicted by the model.

Applying this model to the heat exchanger requires accounting for the geometry of
the heat exchanger. The fact that the internal pressure exerts an equivalent stress on either side of the manifold, and that there is constraint of the plate on either side of the manifold, a correction factor of four must be applied. Equation 4.6 predicts the maximum pressure that the braze joint is capable of withstanding without failure. In equation 4.6 ρ is the pressure (ksi) and W is the width of the critical channel, in this case .1875in, the width of one of the manifolds.

\[ \rho = \frac{F \times 4}{(L \times W)} \]  

(4.6)

Figure 4.15: A series of peel specimen fracture surfaces, showing the macroscopic features that indicate poor braze strength. Note the unbonded sections on the weaker samples. The maximum peel load for each sample, from left to right, is: 48.1lbs, 81.6lbs, 104.6lbs, and 150.2lbs.

This equation predicts that for the .1875in wide manifolds, the maximum pressure before braze failure is 7200psi, demonstrating that the best experimental value of 6467psi is about 90% of the theoretical maximum for this geometry.
Figure 4.16: The first micro channel heat exchanger produced at Case Western Reserve University. This was composed of a stack of twenty heat exchanger plates, and used for heat transfer testing.
Chapter 5

Conclusions

Due to their high theoretical efficiency, microchannel heat exchangers are likely to become more widely used throughout various industries. With lower cost, higher efficiency heat exchanger units for waste heat recovery will be a viable option for more applications where size restrictions or low heat quality currently make it unfeasible. Development of low cost and reliable fabrication methods are key in expanding the use of microchannel heat exchangers.

Fabricating heat exchangers from two machined halves that are subsequently joined by brazing is a promising technology for several reasons. Compared to many other technologies, it can be done at a much lower cost. It also is easy to increase production for commercial output volumes. Brazing is a commonplace manufacturing technique and the equipment needed to use the process is readily available. High throughputs on belt furnaces make it especially attractive for high volume production runs.

Laser machined heat exchanger plates work well for prototyping and small scale production for research purposes. Alternate solutions are probably better suited to production. The most cost effective way to produce the plates is most likely to use a stamping process. Such a process would allow the fastest throughput and lowest production costs, though there would be a significant initial investment to acquire the
tooling.

In this project, testing of several different stainless steel plate geometries led to the decision to use a machined .0625in thick frontplate and the .020in thick backplate. Burst strength in a pressure test was found to be directly related to backplate thickness as it prevented excessive plastic deformation in the plate. Braze quality and bond strength were however inversely related to backplate thickness. This originates from the more compliant nature of thin plates that ensure good contact during brazing. For this reason, the intermediate .020in plate was chosen over the .010in or the .03125in thick plates.

Our experiments demonstrate brazing to be a suitable option for manufacture of heat exchanger elements. After some development, plates could be fabricated to hold well in excess of the 5000psi internal water pressure requirement. While ultimately best to ensure satisfactory performance, the water pressure test is costly, as it employs machined and brazed elements. Two mechanical testing methods of brazed joints, a tensile and a peel test, were designed and evaluated to assist the development of the brazing process. These tests allow to optimize the strength of the brazed bond by utilizing inexpensive sample configurations. They allow understanding of the failure mechanism of the heat exchanger elements and provide experimental method for predicting the strength of the joint without running a full battery of expensive internal water pressure tests. A correlation between the tensile and peel tests and the pressure tests was developed. This correlation predicts ideal maximum values for load carrying capability of the heat exchanger based on the results of the peel test. This is especially important for optimizing the heat exchanger design, as there is now an understanding of the strength limits. These limits can be applied to the design to allow for incorporation of more channels with smaller spacing for more efficient heat transfer without dropping below the critical strength level.

Based on the geometries utilized, we experimentally found the most load per specimen
width that a peel sample could endure is 330.2lbs/in. The model developed predicted a slightly higher ideal condition capable of supporting 342lbs/in. The experimental result was 97% of the theoretical value for the peel test. The experimental results from the pressure test resulted in a failure pressure of 90% of the theoretical, 6467psi compared to 7200psi. This is likely due to the added complexity of brazing the machined heat exchanger elements, and is considered a good result.
Bibliography


