Layer Manufacturing of Heat Exchange Elements using Photochemical Machining with Diffusion Brazing

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Abstract.

A number of heat exchanger elements for a Stirling engine were designed but found to be very difficult to manufacture using conventional technology. Each element required 1800 <1mm oval holes through a 70 mm length of the cooler. The elements were produced by repeated photochemical machining of 185 copper sheets of 0.455 mm thickness and joining them using a process known as diffusion brazing. This paper describes the science and process of manufacturing these components. The procedure was complicated by the need to integrate spigots at each end of the cooler, which meant that some layers required *selective* diffusion soldering.

Introduction.

Sustainable Engine Systems (SES) is a company that is designing and building a high efficiency Stirling engine. A Stirling engine is a device that makes use of an external source of heat, which is used to heat a closed volume of gas. This drives a piston, which converts the heat into useful work. After the gas has expended work, the remaining heat needs to be removed from the gas in readiness for the next cycle. This is achieved by passing the gas through a series of cooler elements. In order to maximise the thermal transfer efficiency of the engine, some components have been designed in a novel or radical fashion. This includes the cooler elements.

The design of the cooler elements required 1800 oval tubes 0.7 mm 0.9 mm x 68 mm in a finned copper cylinder. The tubes carry the gas to be cooled. The central core region carries coolant water. These were arranged in an annular ring within the copper block as can be seen in plan view in Figure 1. However, the manufacture of the coolers presented severe problems in machining the oval holes. Even circular holes would be impossible to drill conventionally. Alternatively, the cooler assembly could be manufactured by machining a series of notched annular rings of increasing diameter that would have to be shrink fitted together. This was deemed to be a very expensive process. The solution was to fabricate the coolers using a layer manufacturing process in combination with photochemical etching and diffusion soldering. This paper describes the manufacturing stages of the process.

Manufacturing Process

Design Concept

The cooler design can be broken down into three main regions.

1. The main cooler block containing the cooling channels.
2. The top spigot for location into the engine.
3. The bottom spigot for location.

Figure 2 shows a cross section profile of the required design. The spigot regions are indicated. Both spigot sections were identical in size and shape.

This design presented serious difficulties in manufacturing the cooler. It was possible to fabricate the cooler by machining a series of concentric cylinders with notches cut into one side and shrink fitting the cylinders together. However, the cost of setting up jigs and the machining was prohibitive with no guarantee that the cylinders, of 1 mm thickness could be adequately machined.

An alternative approach was to manufacture the coolers using layers of copper sheet. The layers had to be machined in some way to introduce the oval holes and the rest of the layer detail. It was decided that the most effective way of doing this was to use photochemical etching/machining. The layers then had to be bonded together. It was essential that there was a free flow of heat through the exchanger and so adhesives were discounted. Conventional soldering or brazing would be difficult to control in terms of maintaining the layer thickness'. Diffusion bonding was ruled out as extremely high pressures and temperatures would be required. Hot Isostatic Pressing (HIP) was not possible due to the enclosed gas volumes as well as the difficulty in "boxing" the finned shape of the cooler.

The only remaining option to bond the layers was to make use of a relatively new process known as diffusion soldering.

Processes details

1. Photochemical Machining.

Photochemical machining is a chemical milling process extremely well suited to the detailed cutting of thin sheets. The process comprises of five stages. A photographic mask is prepared based on the design detail of each layer. A layer of photoresist is applied to both sides of the individual sheets. The mask is placed over the sheet and the underlying resist is exposed through the mask using ultra violet light. Depending on the type of resist, areas exposed will either become fully cross linked and resistant to development (negative resist) or will become capable of dissolution in the developer (positive resist).

The resist is then developed, exposing the underlying metal in the regions that are to be milled. Finally, a spray etch is used to dissolve the exposed metal, thus defining the pattern detail. The resist is then chemically removed and the sheets are ready for further processing.

The smallest size of feature that can be milled is related to the thickness of the sheet in a direct proportion of 1:1, i.e. a 0.5 mm hole is the smallest feature that can be created in a 0.5mm thick sheet.

2. *Diffusion soldering/brazing.*

Diffusion brazing and soldering are processes that may join layers of metal by a relatively low melting point phase that after the process is complete, provides a much higher melting point joint - often with the same melting point as the parent metal. The process used in this work is the copper/tin system and will be described in detail.

Diffusion brazing and diffusion soldering, its lower temperature analogue, use a molten filler metal to initially fill a joint clearance between components, but during the heating stage the filler diffuses into the material of the components to form solid phases, generally raising the remelt temperature of the joint. This process is essentially a hybrid between liquid-phase joining (brazing and soldering) and solid-state diffusion bonding and it has the beneficial features of both techniques [1].

The steps involved in making a diffusion-brazed or diffusion-soldered joint are shown in Figure 3. This process provides the ready means to fill joints that are not perfectly smooth or flat (a feature of liquid-phase joining), while offering greater flexibility with regard to service temperature, in the sense that the joint will not remelt at the original joining temperature. Further consequential advantages of diffusion-brazing and diffusion-soldering are:

- Facilitating the achievement of exceptionally good joint filling in large area joints.
- Allowing edge spillage from the joints to be tightly controlled and kept to a minimum.
- Attaining high thermal conductivity with copper, silver and gold alloy systems because the joint produced is composed of the primary metal.

An alloy system suitable for diffusion brazing should have the following characteristics:

- Preferably is a binary alloy, to keep the joint design and joining process as simple as possible.
- Has a phase constitution that includes a relatively low melting point eutectic reaction to initiate the melting process.

Examples of alloy systems that satisfy these conditions and lend themselves to viable diffusion brazing and soldering processes are copper-tin, silver-tin, gold-tin, and nickel-boron [1,2].

The choice of the copper-tin diffusion brazing process in this application was based on the need to provide hermetic joints and to prevent leakage's from the multiple cooling channels, while minimising the risk of the channels being blocked by molten filler squeezed out of the joints. Copper was chosen in preference to silver and gold for financial reasons.

Crucial parameters governing the copper-tin diffusion are temperature, thickness of the tin layer, the upper limit on the tin-to-copper thickness ratio and the pressure applied to the joint. To achieve mechanically sound joints by copper-tin diffusion brazing, it is vital that all the tin is sufficiently dispersed and incorporated within the copper primary phase – not left as unreacted tin or combined with copper in brittle intermetallic phases.

In the development work, which led to the establishment of the copper-tin diffusion brazing process, it was shown that joints could be made under the following conditions:

Tin layer thickness: > 1.5 µm and < 5 µm
Minimum copper layer thickness = 8 µm
Minimum heating temperature = 690°C
Minimum time at the brazing temperature = 5 mins to 10 hours (depending on the thermal mass being bonded)
Minimum compressive loading = 3.5 MPa
Atmosphere = vacuum (< 10^{-3} mPa residual pressure)

The joints have typical shear strengths exceeding 130 MPa are consistently produced. The tin and copper layers are usually electroplated onto the substrate although it is possible to use preformed foils.

A temperature of 690°C is higher than melting point of the intermetallic Cu_3Sn phase (660°C). Heating below 660°C will result in a continuous layer of this stable brittle phase being formed, which will compromise the mechanical integrity of the joints. In fact, it is preferable to carry out the joining operation above 765°C, the melting point of the γ-copper-tin phase, and use heating times longer than 5 minutes in order to drive the diffusion process to equilibrium, at which stage all the tin will be uniformly dispersed in copper solution and the risk of residual hard copper-tin phases persisting will be diminished.

In this application, as the sheets were made from copper, only a layer of tin needed to be electroplated onto the sheets.

Manufacturing stages

Two different masks were required to carry out the photochemical machining - one for the bulk of the cooler and one for the spigots at each end. As six coolers were required, all six were positioned on the individual sheets. The sheets were Oxygen-Free High Conductivity (OFHC) copper, with a thickness of 0.455 mm. Figure 4a shows an etched cooler sheet whilst Figure 4b shows an etched spigot sheet.

The photochemical etching was subcontracted to a specialist company, Photofabrication Ltd in St Neots, Cambridge UK. Details of the etching are company confidential but there are a number of processes that may be used to etch copper and these can be found in the literature.

The sheets were then electroplated on both sides with between 1.5 and 2.5 microns of tin using a stannate tin bath. This type of electrolyte was used as it produces a very pure, organic free tin deposit. Organic inclusions in many commercial tin baths can cause joint degradation due to vaporisation of the organic material that often becomes included with the deposit. This can undermine the joint.

Whilst there were different sheets for the body and spigots, the interface between the two types presented a problem. If the last sheet with the cooler holes were bonded to the first spigot sheet, problems would be experienced when machining the spigot to final size as the milling cutter would produce burrs over the 1800 holes. To avoid this, the cooler sheets making up the last elements in the cooler stack were masked before plating in the region of the holes at both ends of the assembly. The first spigot sheet at either end was also masked in the same places thus avoiding the formation of a bond over the holes. Masking was carried out using an elastomeric masking paint.

To facilitate the diffusion soldering process, a pressure of around 3 MPa is needed on the sheets. A pressure jig was designed that facilitated this. It comprised of an upper and lower tool steel plate, both 8 mm thick. The jig included three pins to align the layers, ensuring that excellent alignment over the holes was obtained. The exact number of sheets required was calculated, including the thickness of the electroplated layers. Each sheet was placed onto the jig in the correct order until the stack was completed. Figure 5 shows the assembly procedure. The pressure was applied by means of six 16 mm tensile steel bolts positioned at the central cavity in the coolers. An appropriate torque was applied to give a downward force of ~90 kN on each bolt. This force gave a total pressure of around 2 MPa. The remaining pressure requirement was provided by the difference in expansion rates between the tool steel jig and the copper, the copper expanding at a greater rate than the steel bolts at temperatures below 500°C.

The assembly was placed in a vacuum oven, with a residual pressure of 10^{-5} MPa and heated at a rate of 5°C/minute. The assembly was taken to a temperature of 820° C and maintained there for ten hours. This was to ensure that the maximum diffusion of tin occurred but also took into account the high thermal mass of the block. Long heating periods are required to obtain full equilibrium heating of the whole block. The oven was then allowed to cool before the assembly was removed. Figure 6 shows the block after the removal of the top plate. Note that the tin layer has completely diffused into the copper.

The fused copper block was removed from the jig and the individual cooler elements were removed using a slit cutter. Dimensional measurements were taken prior to machining the coolers. These showed that the final dimensions were of the correct size, within ± 0.1 mm.

The cooler blocks were then given the final machining operation to form the external fins and to produce the spigots. Figures 7 and 8 show examples of the finished coolers. Hermetic testing showed that four of the six coolers were fully hermetically joined. The other two had very slight leaks, which were both traced to one of the layers that had the masking applied to it. It is likely that the handling involved in the masking operation may have allowed passive films to form on the tin that subsequently interfered with the bonding process. These were sealed using a standard soldering operation on the internal fins.

Conclusions

This is the first reported example of a method of joining a large stack of layer manufactured sheets and metallurgically bonding them using diffusion soldering. Such a system can enable the manufacture of objects with very complex internal features. The project showed that care must be taken in handling the tin plated layers to avoid the danger of introducing passive oxide or other layers that may interfere with the bonding process. However, if handled carefully, the process shows great promise for the production of components that would be extremely difficult to fabricate conventionally.

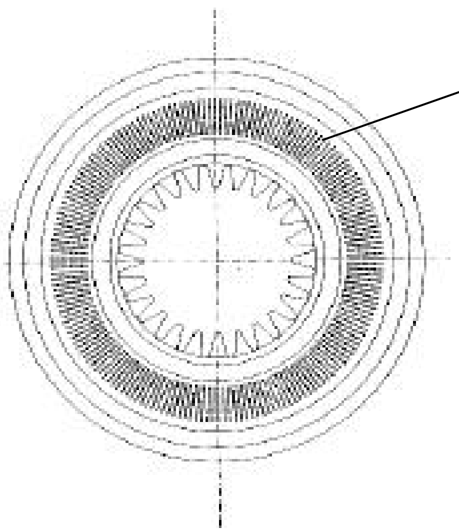

Figure 1. Plan of the cooler design

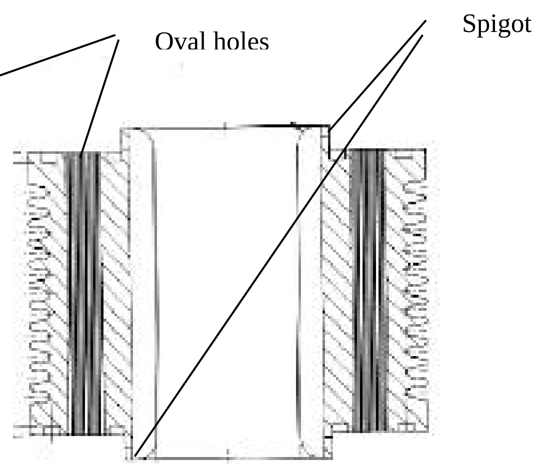

Figure 2. Cross-section of the cooler block

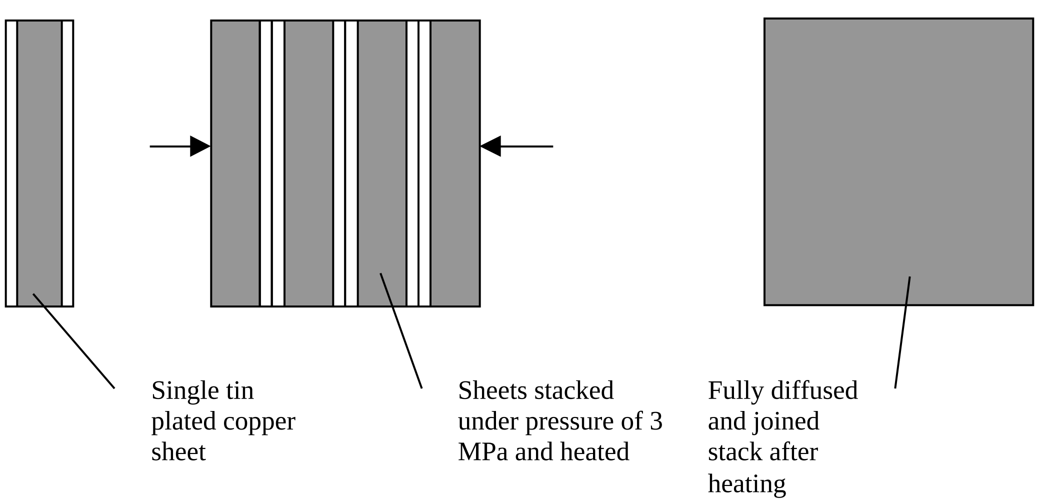

Figure 3. Outline of the diffusion soldering process

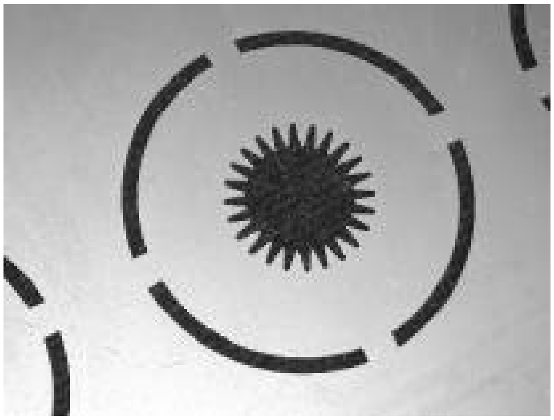

Figure 4a. Element of an etched cooler plate.

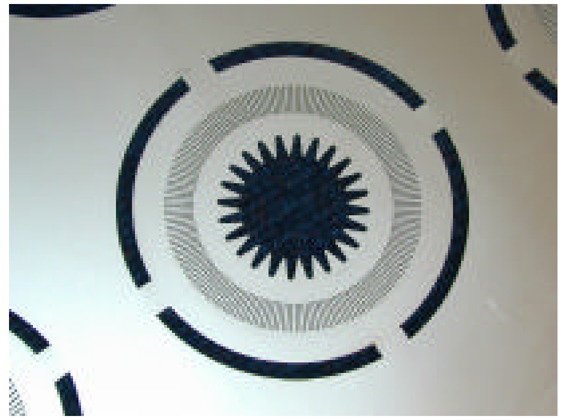

Figure 4b. Element of an etched spigot plate.

Figure 5. Stacking the sheets.

Figure 6. After heat treatment and removal of the top plate of the pressure jig.

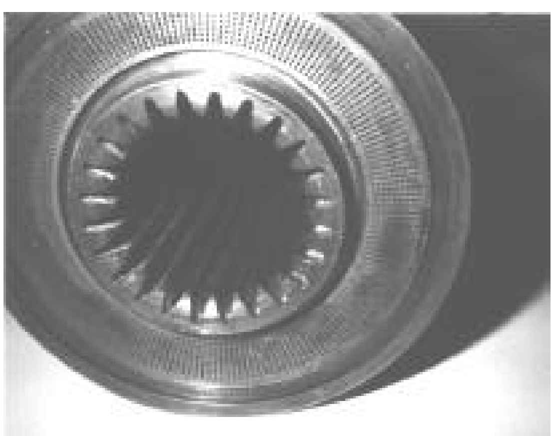

Figure 7. Cooler after final machining.

Figure 8. Two coolers after final machining.

References

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2. Sangha, S.P.S., Jacobson, D.M., and Peacock, A.T., 1998. ‘Development of the Copper-Tin Diffusion-Brazing Process,’ *Welding J.*, Oct., pp. 432-s – 438-s.