Aluminium Heat Exchanger Technologies for HVAC&R
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Lectures of the 6th International Congress taking place in Düsseldorf on 7 to 8 May 2019

Organiser:
DVS – German Welding Society, Düsseldorf
Welcome to the 6th International Congress on Aluminium Heat Exchanger Technologies for HVAC&R

The 6th International Congress on Aluminium Heat Exchanger Technologies for HVAC&R is hosted in Düsseldorf, Germany, from 7 to 8 May 2019. We are looking forward to meeting participants from all over the world gathered here to exchange information about current processes and innovation in this industrial sector.

Not only with regard to the climate change it is becoming more important to use energy efficiently and reduce emissions. Stringent environmental requirements are the greatest challenges the heating, ventilation, air conditioning and refrigeration industry faces. This international congress is dedicated to these aspects and will be organised for the fourth time by DVS – German Welding Society.

DVS is proud to support this congress, which is in fact one of the best ways to transfer knowledge in different directions. Joining and brazing are complex technologies, applications of those technologies must be based on continuous activities in research, development, guidelines, rules, standards and training – the DVS concept of joining and brazing combines all those activities, thus we are ready to contribute to the further success of this congress.

We deeply thank all authors and session chairs for their valuable contributions to the congress and we welcome all participants!

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Ultra-High Pressure Laminated Aluminium Heat Exchangers for Jet Engines

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Fuel/Oil Heat Exchangers (FOHE) are critical components of modern jet engines. Their primary function is to cool the hot engine lubrication oil while heating the cold fuel coming from the fuel tank before it enters the combustion chamber. The fuel heating increases the engine efficiency substantially by recuperating the waste heat from the oil into the fuel. The fuel/oil pressures and temperatures required are increasing with the development of more efficient jet engines. "Gallium-Assisted Diffusion Bonding" is used to join stacks of aluminium plates containing fluid flow channels; without the weaknesses and limitations inherent in traditional brazing. The article describes a new technology for manufacturing more efficient and lighter Fuel/Oil Heat Exchangers than conventional shell and tube ones.

1 Aluminium-based Laminated Heat Exchangers

Laminated heat exchangers have vast applications in oil & gas, aerospace, and transport sectors. Fig. 1 shows the core section of a laminated heat exchanger made of stainless-steel plates containing fluid flow channels. The steel plates, with chemically-etched channels, are stacked in a certain order and then joined by diffusion bonding. Aluminium is an attractive material for aero heat exchangers due its higher thermal conductivity and strength to weight ratio than those of stainless steels. However, joining aluminium plates containing narrow fluid flow channels is not a straightforward process.

Conventional brazing of aluminium alloys requires heating the faying surfaces to the brazing temperature in the presence of a chloride/fluoride-based flux to remove the surface oxide layers [1]. This process has been extensively used to manufacture aluminium car radiators, where the Al/Si-based molten braze metal readily fills the joint gap by capillary action. However, brazing tens of aluminium plates to fabricate one laminated heat exchanger, similar to the steel one shown in Fig. 1, is very difficult, if not impossible. For instance, a precise and uniform amount of braze metal must be applied meticulously on thousands of faying surfaces. Any blockage of the channels caused by excessive amount of the braze metal will not be rectifiable. Besides, most available brazing fluxes are corrosive so must be removed entirely after brazing in order to minimise subsequent corrosion in service. Therefore, solid-state diffusion bonding remains the only viable option to manufacture aluminium-based laminated heat exchangers.

The presence of a tenacious surface oxide film on aluminium alloys, mostly alumina, makes solid-state diffusion bonding of these alloys very difficult and in most cases unreliable [2]. This article describes the results of a R&D project with an aim to develop aluminium-based laminated heat exchangers. The final outcome of this project is expected to be a number of prototype fuel/oil heat exchangers used in jet engines. The project had a budget of just over £1M from the UK Government (Innovate-UK) and several aircraft components manufactures in the UK.

2 Bonding & Testing Procedures

Preliminary experiments were carried out on aluminium alloys. The faying surfaces were prepared for diffusion bonding using a proprietary gallium-assisted process [3]. A k-type thermocouple was attached to one of the discs and used to control the bonding temperature. The bonding was carried out in vacuum (10^-4 mbar) using the diffusion bonding apparatus shown in Fig. 2. All samples were bonded at a temperature between 200 to 620 °C in 1 to 3 hours under a variable pressure of about 1 to 20 MPa.

Bond line microstructures were examined by optical and scanning electron microscopy (SEM). Energy Dispersive X-ray (EDX) analysis was used to
measure the concentrations of gallium at and around the bond lines. Bond strengths were determined by conducting tensile tests on “Top-hat” shape samples – see Fig. 3. A conventional Instron mechanical testing machine was used to apply a compressive load on the plunger. No post-bonding heat treatment was carried prior to tensile testing. The test was aborted if the sample showed signs of plastic deformation, e.g. drop in the load.

Having completed the initial bonding trials on the samples with flat faying surfaces, a new set of samples containing fluid flow channels were prepared for bonding. The channels were cut by wire Electrical Discharge Machining (EDM) process. Each bonded sample was consisted of a flat-face disc and a channel-face disc.

The bonding conditions were similar to those used in the flat-face samples except the bonding load which was reduced to compensate for the loss of joint cross section on the channel-face disc. The effective joint area in a channel-interface sample was estimated to be 15% of that in a flat-interface sample. Since it was not possible to machine a Top-hat tensile sample out of the channelled-interface samples, a new test set up was used, which is shown in Fig. 4.

Fractography was carried out on the fractured samples to determine the failure mechanism. More recently, some larger samples were bonded by stacking up and diffusion bonding 4 to 6 aluminium plates containing chemically etched channels. The dimensions of the plates are 100x100x2 mm with 3 mm wide channels across the entire plates. A proprietary rig, designed by Cambridge Joining Technology (CJT), was used for bonding these plate samples in a conventional vacuum furnace (10^-4 mbar) and without a need for a large vacuum press. The rig relies on differential thermal expansions to exert a compressive load on the plates being joined. The bonded plates were examined and tested rigorously. A number of slices were cut from each sample and subjected to severe bending tests.

Fig. 5 shows examples of the various multi-layer samples made in this work. The bonding parameters were optimised based on the outcomes of mechanical tests and microscopic examination carried out on the large multi-layer samples.
3 Results and Discussion

**Flat-interface samples**: The initial objective of this work was to assess the capability of gallium-assessed bonding to produce bonds with tensile strength comparable to that of the parent aluminium alloy. The samples with flat-face interface had a tensile strength above the yield strength of the alloy, judged by the reduction in the cross section of tested sample (e.g. necking) which suggested the material has gone through a permanent plastic deformation. A flat-interface sample withstood 166 MPa tensile stress before the test was aborted due to its excessive deformation.

**Channel-interface samples**: It was expected that the channel-interface samples to have lower bond strengths due to stress concentration around the bonded ridges. Nevertheless, the channel-interface sample withstood 115 to 137 MPa. To put these values in context, the yield strength of parent alloy (i.e. un-bonded) is around 125 MPa.

The SEM micrographs in Fig. 6 shows two bond-lines in a channel-interface sample. Despite some minor defects, the ridges appear to be fully bonded to the flat side. The microstructure of the bond-line is consistent with the high tensile strengths observed. Despite these promising results, it is expected that bonding larger samples will be more challenging due to the difficulties in bringing all faying surfaces in a close contact with each other. Also, it might not be possible to apply high bonding pressures, which otherwise may result in excessive deformation of the stacked plates with numerous fluid flow channels. The concentration of residual gallium on and around the joint interface was measured in the samples made using different bonding conditions. In all EDX analyses the concentration of gallium proved to be below the reliable detection limit of the EDX analyser used.

One of the small-scale laminated samples made in this work is shown in Fig. 7. Some of the laminated samples were subject to bending tests. In all samples, de-bonding occurred after the part was substantially deformed under the applied load.

4 Summary

The outcome of this work on aluminium alloys clearly shows that the gallium-assessed diffusion bonding is capable of producing joints with tensile strengths comparable to that of the parent alloy. Therefore, this process can be considered for fabricating prototype aluminium-based laminated heat exchangers.

Acknowledgement

The diffusion bonding part of this project was funded by Innovate-UK. The etched plates were provided by Precision Micro Co. (UK) and the experimental work was carried out in The Open University. The IP rights of the patented processes and the use of Thermal Expansion Rig (TER) for bonding large aluminium plates belong to Cambridge Joining Technology Ltd. (UK). Further development of diffusion-bonded heat exchangers is being funded by Guangdong Innovative and Entrepreneurial Research Team Program (Project No. 2016ZT06G025).

5 References

