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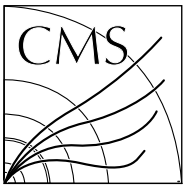

The Compact Muon Solenoid Experiment

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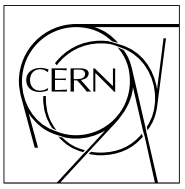

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An Unconventional Set-up for Fluxless Brazing of Aluminium

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Abstract

In order to successfully braze aluminium alloy assemblies without the use of oxide-removing fluxes, an environment with very low contaminant level is mandatory. This is mostly achieved by using a vacuum furnace. Brazing under inert gas of sufficient purity is also possible. The method reported upon here makes use of a stainless steel bag which can enter a traditional air furnace. The bag is evacuated, giving a well distributed mechanical pressure on the parts to join. The intrinsic handicap of poor vacuum is compensated by regular inert gas flushing, even at high temperatures. The set-up works rather well, and the idea is believed to yield a valuable strategic and economic option, for the realization of special equipment as well as for prototyping work. We intend to use the principle for the CMS Preshower cooling screens.

1 Motivation

Brazing is a prime joining technology for complicated aluminium assemblies, well-established in motor car and air-conditioning industry, less known in high-energy physics. Yet there are several potential applications: efficient cryogenic heat exchangers, cooling screens and environmental shields in detectors. We are currently trying to deploy the technology for the absorber coolers for the Preshower detector of the CMS experiment on CERN's Large Hadron Collider.

Reliability is at a premium in these high-energy physics applications. Corrosion resistance and mechanical strength and toughness are evident requirements. Complicating demands may be related to large temperature swings - cool down to cryogenic temperatures -, ionizing radiation resistance, cleanliness, the presence of unusual fluids like perfluorocarbons, or even a combination of them. Often designers prefer to avoid the so-called fluxes, which remove the oxide layer and enable metallic bonding on the aluminium workpieces during brazing. In that case they tend to use fluxless brazing. This latter technology is often judged difficult. It requires in any case quite some care and equipment. The Appendix contains a brief description.

2 Towards the Bag

The devices we would have to produce for CMS, are of large surface and fairly thin. There is a strong desire to braze them in horizontal, lying, position.

A stiff container, made out of austenitic stainless steel, entering a classical air furnace, and capable of mechanically withstanding the vacuum, would be costly. The workpieces would have to lie on a suitable "marble", and moreover they would have to be loaded with large weights. The total payload inside the container would represent a huge heat capacity. This would render swift brazing cycles impossible, at least when brazing under vacuum. On the other hand, it would be difficult to achieve the necessary purity when brazing under inert gas, because of the assembly's very unfavourable surface-to-conductance ratios.

Suppose now the assembly to braze would sustain[a)] the pressure due to the vacuum inside a floppy container, a bag. Not only would such a container be less complicated and costly than a stiff container, a less heavy marble would probably suffice. The payload would no longer have to contain weights: the consolidation pressure would simply be supplied by the furnace atmospheric pressure whilst evacuating the bag. The total payload inside the container would be greatly reduced, and consequently the heat capacity and the outgassing.

Traditional vacuum brazing in such a bag has not been considered. The pumping behaviour would undoubtedly be very poor, mainly due to the big surfaces firmly squeezed together by the outside pressure. The contaminant level would be far too high during brazing.

We have instead tried out regular argon flushing during the principal heating up part of the brazing cycle. The bag is filled with argon at ambient pressure or even a few mbar above, immediately after which it is again pumped. A multiple contaminant dilution is the result hoped for. One would expect an efficient outgassing, for two reasons. The first is that the argon flushing also takes place at high temperatures, the last operation typically at 500-520˚C. The second is that the surfaces which are pressed together when the bag is evacuated, become more or less loose upon argon admission.

We have performed a number of dedicated brazing tests on a small set-up, described in the next section.

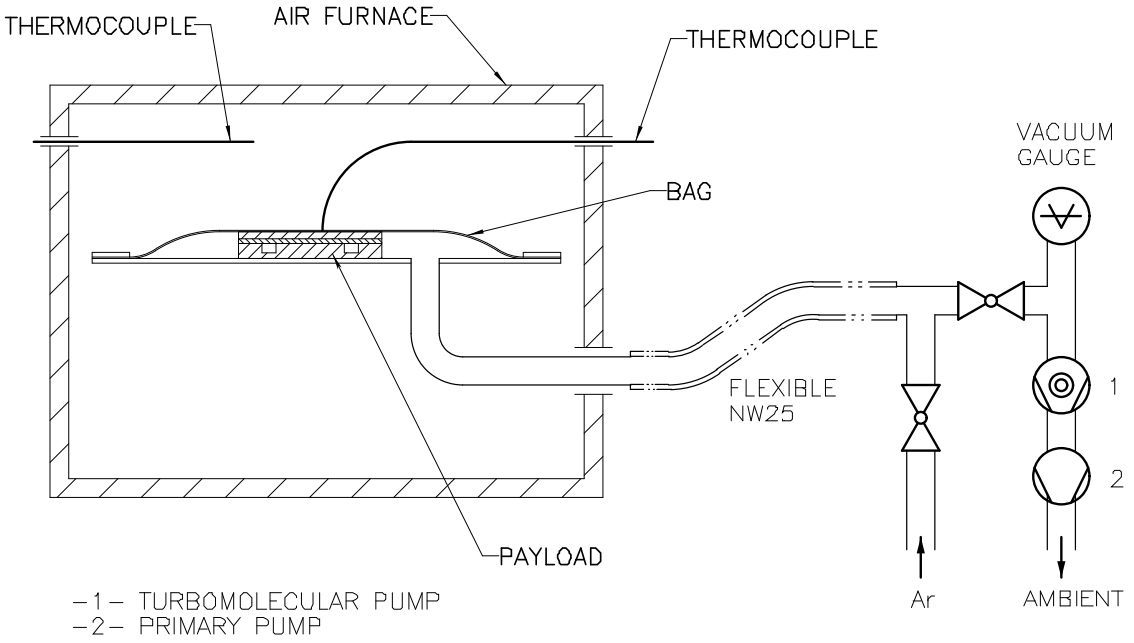
From Ref.[4] it can be inferred that the magnesium in the brazing filler metal starts to come out of solution and to disrupt the filler's own oxide layer as from 555˚C, the Al-Mg-Si ternary eutectic temperature.

It was therefore judged prudent to have vacuum rather than argon as from that point onwards, in order to better evacuate the excess magnesium.

An unsolved question is that of the minimum required heating rate from these 555˚C onwards. Successful surface activation and wetting means metallic bonding - at least to some extent -, and consequently: diffusion. Silicon would diffuse into the workpiece and erode the grain boundaries in the adjacent parent metal. This silicon would be lost for the brazing filler, rising the latter's liquidus temperature. These are undesirable phenomena, and they should not be given too much time. Heating rates of 10-20˚C/min. are typical in vacuum furnaces. Ref.[3] mentions even 35˚C/min. to be required for good results in gas. We could only obtain about 4 to 8˚C/min. in our big and small air furnaces, respectively.

a. The yield strength of common metals at temperatures very near the solidus is not great.

3 The Setup



4 Results and Outlook

In the small furnace, we could perform a brazing operation in about 80 minutes. In the first 60 minutes, argon is flushed typically 5 times. The first rinsing takes place at the beginning of the cycle at room temperature, the second soon after having reached 150˚C in order to eliminate moisture. The total brazing cycle time was determined by the maximum heating rate of the furnace. This consequently limited the available pumping time. A gauge reading of 0.4 to 1 $*10^{-4}$ mbar was achieved at the brazing temperature. The same order of magnitude was obtained in between two successive argon fillings, from which it can be inferred that the vacuum in the bag must therefore have been rather poor.

Right after having reached the desired brazing temperature, 615˚C in most cases, the furnace was partially opened to minimize the time spent in the 600˚C region. Once below some 550˚C, argon was again admitted, improving heat transfer to the payload, enabling to decrease the total throughput time.

Brazing tests with two different kinds of filler have been performed, see the Appendix for a description of the alloys. One is in the form of double-sided cladding, where the filler, alloy AA4104, 50 µm thick per side, is co-laminated onto a 0.3 mm thick AA3003 alloy (DIN shorthand AlMn1) substrate. The other is simply a foil, AA4004, 75 µm thick.

Part of the samples still have to be examined by optical microscopy, but so far the results are quite encouraging.

The present bag has to be cut open to retrieve the payload, and sealed by welding after another loading.

In the near future, and in view of Preshower cooler production, we want to investigate a more sophisticated bag. It would be sticking out of the furnace, and would have a cold, O-ring sealed and thus dismountable cover. The heat loss to ambience would be limited, because the bag would have thin walls and would be made out of a very poor heat conductor, and because internal convection losses are only present during the short flushes with inert gas.

Acknowledgements

S. Mathot and R.Kirner (EST) brazed the first samples, in vacuum as well as under inert gas, making the technology operational at CERN, before we started testing the bag. M. Caccioppoli and J.-P. Brachet (EST) were helpful in designing and realizing the bags. A. Braem (EP) and G. Juban (EP) made equipment available. G. Jesse and J.-P. Bacher (EST) and M.Gittos (The Welding Institute, UK) investigated the quality of the brazed samples.

We are kindly indebted to them all. We also thank the CMS experiment, Ph. Bloch in particular, for the support.

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Appendix: On Fluxless Brazing of Aluminium Alloys

Soldering and brazing are joining techniques which use a supply metal with a liquidus temperature lower than the solidus temperature of the workpieces. The obvious goal is to liquify the filler without melting the workpieces.

The term soldering is used for processes where the assembly is heated to only relatively low temperature, below 450˚C. The supply metal - the solder - is an alloy containing heavy metals, as Zn, Sn, Cd. The mechanical performance of the assembly is low. More important even are the poor corrosion properties. Soldering is not retained as a valid method.

The name brazing is reserved for process cycles peaking well above 450˚C, Ref.[1]. In this case, the supply metal - the brazing filler metal or hereafter simply filler - is itself an aluminium alloy.

Silicon is the main alloying element. It serves as a melting temperature depressant, and improves fluidity. The adverse affects on corrosion are modest, even if it is added in large quantities. This is the case for the brazing fillers: 9.75%[a)] Si is a typical content, only slightly below the Al-Si eutectic composition of 11.7%.

A fundamental problem is that of so-called wetting of the workpiece surface, which has to do with eliminating/transforming the ever-present oxide layer. Also the filler's oxide layer must be disrupted. Summarizing the research on this topic is beyond the scope of this note. Typical brazing alloys contain - on top of the Si - about 1.5% magnesium, in order to achieve the necessary surface activation. The alumina is reduced and MgO is formed.

Those brazing alloys are normalized[b)] as AA4004 and AA4104. The latter contains in addition 0.1% Bi, which, according to some authors, further enhances wetting, but its exact role remains unclear. We have carried out tests with both braze alloys. They are quoted to have a melting range of 555-590˚C, and would be used in brazing cycles with a peak temperature of 595-615˚C.

Establishing the right peak temperature is a matter of some fine-tuning. We have found the samples brazed at low temperatures, 595-605˚C, to have a very dry appearance. The typical feature of edge rounding off by the wet fillet was mostly absent. One would be tempted to say that there had never been liquid formation. Mechanical tenacity was low and sometimes very low. Very high temperatures, 620˚C and above, clearly brought about grain boundary erosion problems in the workpieces' heat affected zone. It is important to stay no longer than strictly necessary at high temperatures. Evidently, the higher the peak working temperature, the more restricted the choice of workpiece alloy. It has to have a very high solidus temperature, and consequently can only carry minor alloying fractions.

It is important that the parts be clean - grease and fingerprints are fatal - and carry only the minimal oxide layer. A proper etching, degreasing/cleaning and rinsing treatment was judged necessary, and has been carried out on all the samples we brazed.

It is equally important that the atmosphere be clean at the high temperatures, in order to avoid excessive oxide formation. Dangerous contaminants are oxygen and water.

Fluxless brazing is most often carried out in vacuum furnaces. Evacuating from ambient air, a vacuum of the order of 10^{-5} mbar is the typical value quoted for good brazing. Needless to mention that vacuum furnaces are much more exclusive than traditional ambient air devices, a significant problem when one has to braze assemblies with exotic dimensions. Moreover, prototyping work is never very welcome in such a vacuum furnace. Contamination due to condensation of MgO on the relatively cold furnace walls is a concern. The catastrophe in case the workpieces should accidentally melt is yet another.

A much less familiar way of performing fluxless brazing is under inert gas, Ref.[2]. Gas purity is of concern. Oxygen levels below 10-30 ppm and dew points below -60.-40˚C are quoted. Rather detailed research of more recent date, Ref.[3], has been carried out with Mg-containing filler alloys under inert gas. A Mg level significantly lower than the typical 1.5% found in the common alloys, was reported beneficial. The Mg-rich braze metals reportedly produced excess MgO in an imperfect atmosphere, and irregular and sometimes poor fillets. The extra difficulty of imperfect inert gas, compared to imperfect vacuum, would lie in the drastic difference in mean free path before collision of excess - unreacted - magnesium. Now the normalized 4004-4104 alloys are already difficult to get for a reasonable price in small quantities. We had no possibility to obtain special-tailored alloys, and EST/SM performed brazings in argon with the usual alloys. The resulting fillets were quite attractive. In fact, we were not really able to confirm the worries mentioned in Ref.[3]. However, the workpieces did came out with somewhat darkened surfaces.

We had to find out that a firm compression on the workpieces is very helpful in order to improve consolidation. With a traditional fluxless brazing strategy, in a vacuum or inert gas furnace, this would call for heavy loading weights or a troublesome compression jig. This handicap is absent when using a bag.

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a. By default, weight percentages are understood.

b. Aluminum Association numbering (USA).