An Analysis of Induction Brazed Beryllium on Copper Alloy Substrates

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ABSTRACT

A long pulse JET Divertor requires the production of beryllium clad copper alloy hypervapotron target plates. Vacuum brazing of beryllium poses a number of problems relating to the stable beryllium oxide and ready formation of brittle intermetallics. Induction brazing offers some advantages and a rig has been developed for producing vapotron test target plates for power load testing in the Neutral Beam Test Bed. The brazed components have survived over 1000 shots at 13 MW/m^2 with an ultimate power loading capability up to 17 MW/m^2.

These results have been interpreted with respect to both localised stresses and thermal fatigue at the interface. This study analyses the power handling capability with respect to instantaneous heat flux failure, localised hot spots from target plate deflections and high cycle fatigue with a view to establishing an optimum unit size.

INTRODUCTION

Beryllium is favoured as a First Wall material, both for its low-z characteristics and its pronounced ability for gettering oxygen. Unfortunately this affinity for oxygen, together with its readiness to form intermetallic compounds, creates special difficulties in bonding it to substrates for heat removal.

The design of the JET Divertor for long pulse operation called for a study of brazing beryllium tiles on to a copper-chromium-zirconium substrate. JET has many years experience in working with this material for the manufacture of hyper-vapotron target plates [1], especially for the ease with which it can be machined, electron-beam welded and precipitation hardened.

Standard methods of beryllium brazing are based an aluminium or copper/silver brazes [2]. Aluminium brazes have the advantage of not forming brittle intermetallic compounds with beryllium but are not compatible with copper substrates and have lower strengths than copper/silver brazes. The most commonly used braze for structural purposes is Cusiltin, also known as BAg-18, with solidus and liquidus of 602°C and 718°C respectively. Vacuum oven brazing above the liquidus leads to unacceptable thick CuBe intermetallic layers so that a standard brazing cycle consists of the brazed joint being held under medium pressure at 650°C - 680°C for 30 minutes. Initial trials with this method led to widely scattered strength results (50 - 170MPa) and power loading failures of 2mm thick tiles at 7 to $12MW/m^2$.

Induction brazing offers the advantages of high heating rates and short, accurately controlled dwell times. This allows the brazed joint temperature to be raised above the liquidus while the short dwell time minimises the formation of intermetallics. An active braze Incusil ABA (containing 1.25% titanium) with solidus and liquidus of 605°C and 715°C was investigated during the vacuum oven brazing program to check for any beneficial effects from the active titanium content. It appeared to be ineffective at the sub-liquidus temperatures, but was identified as a suitable candidate for induction brazing where the titanium could getter the outgassing products from the brazed joint.

EXPERIMENTAL PROGRAM

Initial trials with a 50kHz RF generator and a solenoid coil showed both that heating rates above 6°C/second were possible and that joint strengths better than those for oven brazing were possible. Consequently a development program was established to investigate the following parameters:

- dwell time above liquidus between 10 and 300 seconds,
- different brazing materials such as

a) Cusiltin - Ag (60%) Cu (30%) Sn (10%), sol. 602°C, liq. 718°C.
b) Incusil - Ag (61.5%) Cu (24%) In (14.5%), sol. 630°C, liq. 705°C.
c) Incusil ABA - Ag (59%) Cu (27.25%) In (12.5%) Ti (1.25%), sol. 605°C, liq. 715°C.

All other parameters were to be fixed as follows:

- pressure on brazed joint at 0.3MPa,
- vacuum pressure at 5 x 10^{-5}mbar,
- temperature rise rate at 8°C/second,
- temperature cooldown rate at 4°C/second,
- braze thickness at 0.1mm and O_2 content < 50ppm.

The program would be carried out in two stages. The optimum parameters would be established through a series of brazes between 30 x 100mm tiles of 3mm thick beryllium and 6mm thick CuCrZr. The second stage would use the optimum cycle to bond Be tiles of different thicknesses on to vapotron test targets for power load testing in the JET Neutral Injection Test Bed.

APPARATUS

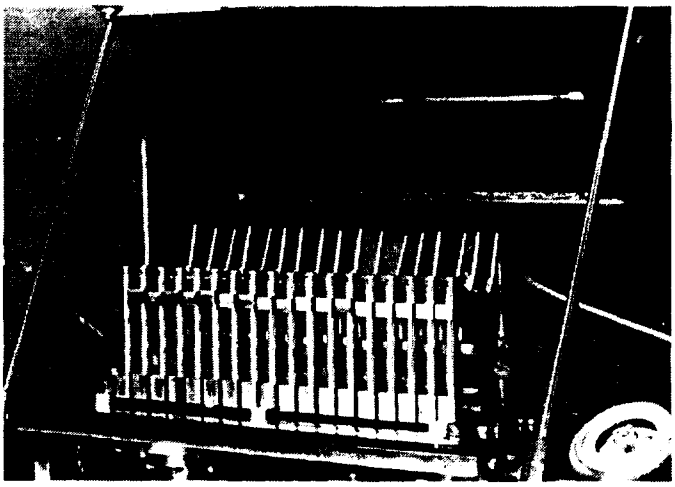

Fig.1A: Induction brazing rig.

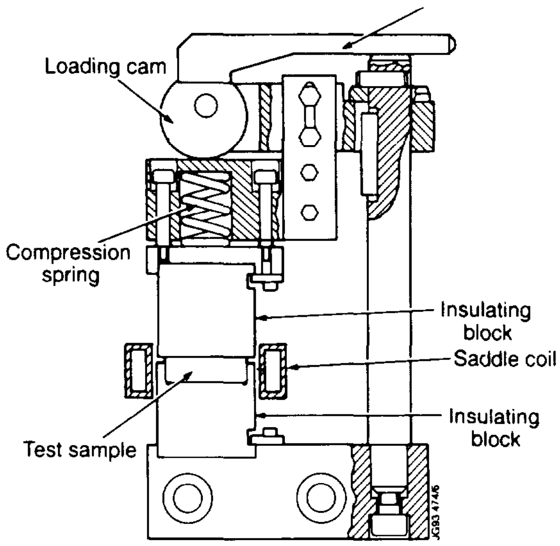

Fig.1B: Cross-section of sample loading rig.

A saddle coil design was chosen for the induction coil, both for its compatibility with the long rectangular vapotron shape and a joint clamping jig. The jig used insulating ceramic blocks to support the samples and compress the joint to 0.3MPa via lever-operated cams on to coil springs (Figure 1). A 600kW high frequency (4kHz) generator via an 18:2 matching transformer was required to achieve the heating rates. Three features were installed to achieve a rapid cooling rate, i.e. a water-cooled copper plate inside the vacuum chamber, helium backfilling to 100mbar pressure and an internal circulating fan.

Diagnostics consisted of six thermocouples, three in the beryllium tile and three in the substrate, arc-percussion welded at different depths into the sides of the tiles to monitor temperatures. The vacuum conditions were measured by a Penning gauge and RGA.

EXPERIMENTAL PROCEDURE FOR BRAZING QUALIFICATION

Each braze alloy was tested with five samples at dwell times of 10, 30, 60, 150 and 300 seconds. The standard cycle was:

a) Slow heating to 450°C,
b) Holding at 450°C for two minutes to stabilise temperatures,
c) Rapid heating (8°C/second) to 5 - 10°C above liquidus,
d) Dwell time,
e) Rapid cooling (4°C/second) down to 450°C.

A typical cycle is shown in Figure 2 where the temperature, chamber pressure and RGA were monitored throughout the cycle. The RGA scans repetitively between masses 3 and 18.

Each sample was scanned ultrasonically at 15MHz for joint defects. Thereafter they were cut-up to produce three micrographs, one from each end and centre of the specimen, plus twelve shear test specimens. Shear testing was carried out at 20°C, 250°C, 350°C and 400°C.

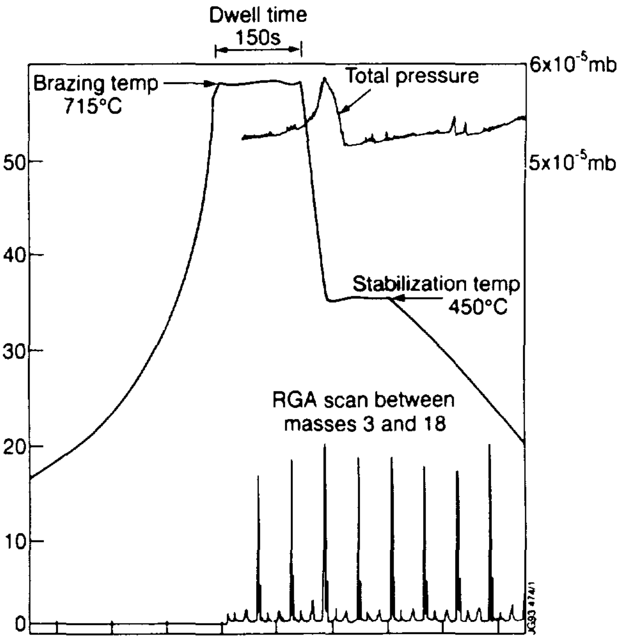

Fig.2: Measured parameters during brazing cycle

RESULTS OF BRAZING QUALIFICATION

A. *Incusil*

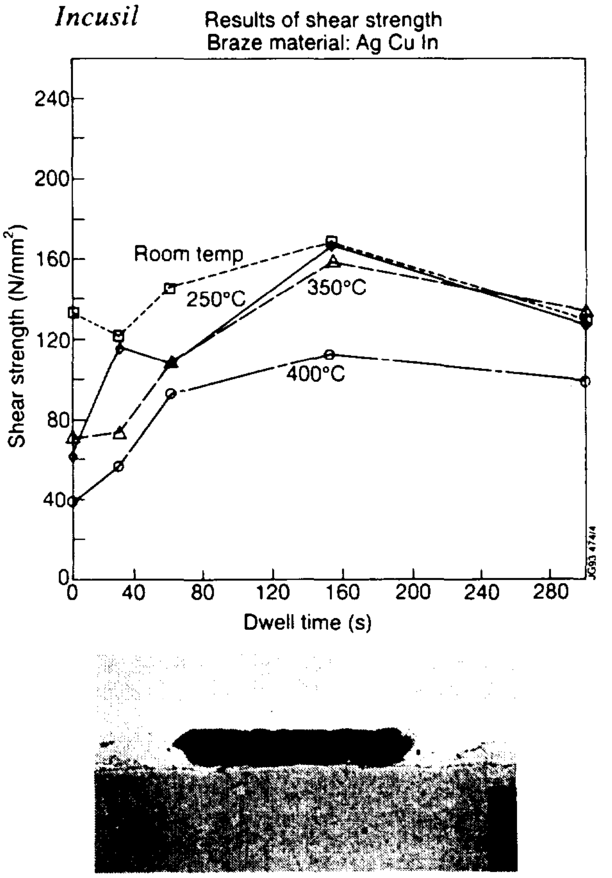

Fig.3: Micrograph and shear strength for Incusil braze.

Figure 3 shows the average shear strength versus dwell time and typical micrograph. From the shear strengths it is clear that maximum band strength is reached only after 150 seconds dwell time. All the micrographs show voids in the braze arising from the outgassing at the joint during the rapid heating phase. The average ambient shear strength is typically 150MPa but with a wide scatter, possibly arising from the voids.

B. *Cusiltin*

These results are similar to those for Cusiltin with average ambient shear strength of 150MPa. Both sets of samples had globules of braze along the edges of the joint, consistent with sputtering from gas bubbles in the liquid braze.

C. *Incusil ABA*

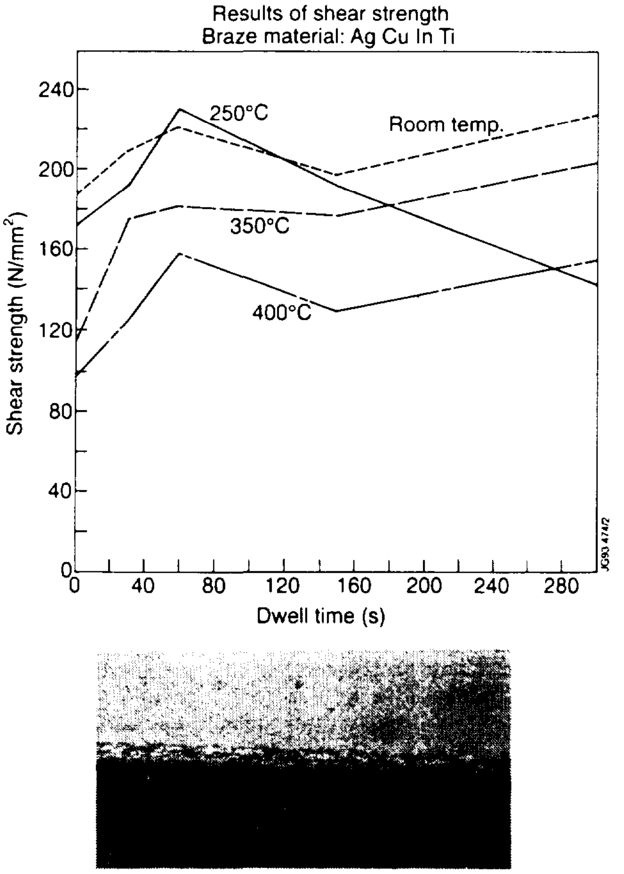

Fig.4: Micrograph and shear strength for Incusil ABA.

The results in Figure 4 show the superior performance of this braze with the average strength of 220MPa at ambient occurring after 60 seconds dwell time. The micrographs show no sign of voids and less wide scatter in shear strength. The active titanium was considered to be gettering the desorbed gas. A further five specimens were brazed at 60 seconds dwell to check for repeatibility. The shear strengths remained within a band of ± 10% as shown in figure 5.

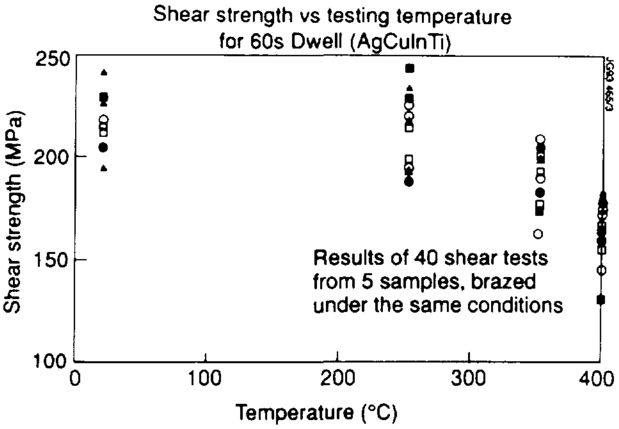

Fig.5: Repeatibility of shear strength for Incusil ABA.

POWER DENSITY TRIALS

The Incusil ABA at a dwell time of 60 seconds was identified as the optimum cycle. The brazing rig was modified to accept 500mm long vapotron test targets. Four sets of Beryllium tiles of thickness 1.5mm, 2mm (two off) and 3mm were prepared with castellated surfaces to relieve the thermal stresses under high power loading. The castellations were machined with 0.5mm wide slits down to a remaining thickness of 0.5mm in a 6mm square matrix (Fig. 6). A production proof sample was included in each brazing run.

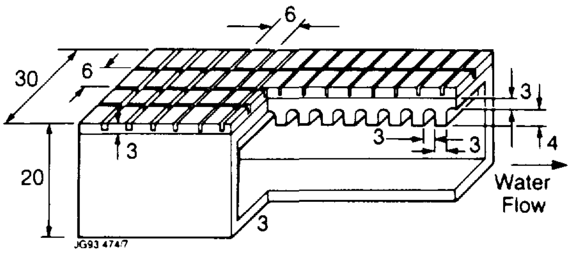

Fig.6: Sectioned Vapotron with beryllium tiles brazed to top surface.

The test program covered two phases. The first phase was chosen to determine the maximum power density to failure of each Be thickness, i.e. 1.5mm, 2mm, 3mm. The second phase was intended to check for durability by subjecting the 2mm thick Be tiles to 75% of the maximum power density for 1000 pulses. Reference [3] gives details of the Neutral Injection Test Bed facility. A dedicated beryllium test rig is used with a modified Positive Ion Neutral Injector to provide a power loading up to 50MW/m^2. Diagnostics consist of an inertial calorimeter to calibrate the beam power, an infrared camera to monitor the beryllium surface temperature and thermocouples to measure the substrate temperature.

MAXIMUM POWER DENSITY TEST

The procedure for this test was to increase the power level in small steps up to the maximum expected level, delivering 250 pulses of one second duration followed by one second off time at each level. The tests were stopped when melting of individual castellations as shown by the IR camera started to follow in rapid succession .

The different tile thickness performed as follows:

a) 1.5mm

The first failure occurred at a power density of 14.5MW/m^2 with the next two failures within a few cycles of each other at 18 - 20MW/m^2.

b) 2.0mm

The first failure took place soon after the start of the test at 12.5MW/m^2 with the second and third failures at 17MW/m^2.

c) 3.0mm

A number of failures occurred in rapid succession at 14 - 15MW/m^2.

The initial failures in the 1.5 and 2.0mm tiles were formed on central castellations but the later defects occurred at the tile edges where the stresses are the highest. This suggests that individual castellations can melt prematurely from a local low quality brazed area but that eventual failure at the tile edge represents the overall bond strength.

FATIGUE TEST

This was carried out on the second test target with 2mm tiles at a power density of 13.5MW/m^2 compared to the maximum of 17MW/m^2 from the previous tests. The load was applied for 1000 cycles at pulse lengths from one to five seconds. No beryllium melting occurred although the IR camera did indicate high surface temperatures in a relatively low power density region.

FURTHER STUDIES

The program to carry this study further will investigate:

- the effect of a thin, ductile OFHC layer between the beryllium and copper alloy substrate,
- the optimum % of titanium in the brazing fail,
- the relevance and desirability of tile castellations,
- ion plating of the beryllium surface with different materials before brazing.

ELASTO-PLASTIC ANALYSIS OF SANDWICH STRUCTURES

The thermo-mechanical analysis of bi-metallic structures can be done analytically only for materials with temperature independent properties. The properties of both beryllium and copper show strong temperature dependence, in particular the beryllium - part of the sandwich structure would be brittle at room temperature but ductile at elected temperatures. Finite-element analysis is mandatory to assess the response of a clad structure to both thermal shock, e.g. disruptions and differential thermal expansion under steady-state loading.

A model of a vapotron with both 2 and 3mm beryllium tiles has been analysed with ABAQUS [4, 5]. It has been found that, under JET relevant conditions, there is no plastic deformation in the beryllium layers for disruptive - type loading (duration <1ms) that may vaporize part of the plasma-facing layer. No substantial loads are exerted on the beryllium-copper interface as a result.

Steady-state heat fluxes of 5 - 15MW/m^2 have been analyzed with the finite element results predicting beryllium surface temperature of 300-750°C in a 2mm thick layer. Plastic strain in the beryllium appears for fluxes approaching 7MW/m^2 with a maximum value of 0.17% at 15MW/m^2. Plasticity is found in approximately 1/3 of the beryllium thickness over almost 90% of a typical vapotron width (30 - 50mm). If the beryllium is machined right through to the substrate in a 6 x 6mm matrix, no plasticity is to be found in the beryllium for fluxes up to 15MW/m^2.

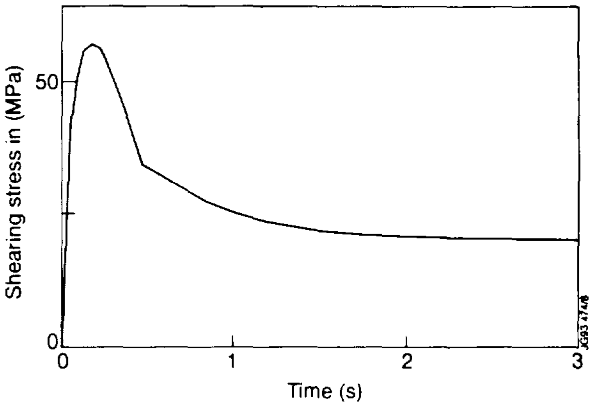

Fig.7: Computed shearing force on Cu-Be interface.

Fig.7 indicates that the stress reaches a maximum near the beginning of the pulse and later falls to a steady value. Melting of the beryllium castellations at the start of the pulse supports this analysis.

The singular stress condition at the free edge of a bi-metallic strip implies that residual micro-cracks are present in any brazed component. A non-linear code such as ABAQUS is however not capable of resolving this singularity since the range of the initial crack is only 10^{-5} - 10^{-6}mm for a copper-beryllium joint [6]. The results of the FEA for delamination loading from thermal cycling indicate that the joint shearing force on a beryllium-clad vapotron is greater for a full width uncastellated tile than for 6 x 6mm castellated tile. This has not, however, been supported by the experimental results.

REFERENCES

[1] R. Tivey, et al., "Testing of beam stopping elements using hypervapotron cooling". Proc. SOFE, Monteray (1987).

[2] D.R. Floyd and J.N. Lowe, "Beryllium Science and Technology" volume 2, 1979, Plenum Press, New York, pp 252-273.

[3] H.D. Falter, et al., "Thermal test results of the JET Divertor Plates", SPIE Vol. 1739, High Heat Flux Engineering (1992), pp 162-172.

[4] ABAQUS Users manual, Hibbit, Karlson and Svenson Inc.

[5] E. Deksnis et al., "Design of High Heat Flux Components for the JET Pumped Divertors", 16th SOFT, London 1990, pp478

[6] R. Viola, "Singular Stress Fields in Beryllium Copper Components, JET paper to be published.