An Effective Cooling Arrangement for an Infrared Mirror Subject to High Heat Loads at the SRS

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Abstract

The primary mirror of beamline 13.3 is located inside the main storage ring of the SRS, at less than 1m from the synchrotron radiation source tangent point. The mirror is designed to reflect only in the infrared, so that virtually all the thermal power of the SR beam is absorbed. Because of its proximity to the source, heat fluxes are higher than on any other component at the SRS, with peak power densities greater than $40W/mm^2$, presenting significant problems in engineering cooling systems to avoid yielding or failure due to thermal strain. This paper describes a new primary mirror configuration incorporating a cooled thermal shield. The arrangement is of particular interest in that localised RF vacuum brazing techniques are used to ensure that work hardened regions of the shield, made from conventional OFHC copper tube, retain their characteristic yield strength. The technique has general applicability to other vacuum brazed components that are required to withstand high thermal or mechanical stresses in or around modern high brilliance electron storage rings

1. INTRODUCTION

The primary mirror of BL13.3 is located at 1.08m from the tangent point of dipole 13 and accepts 60mrad (h) of SR beam. The mirror is not intentionally designed to reflect light shorter than IR wavelengths and therefore will absorb virtually all of the thermal power in the SR beam. Because of its proximity to the source, the distance from the mirror surface to the tangent point of the dipole's radiating arc varies considerably and at its closest is less than 660mm. At this point the on axis power densities are higher than on any other beam line component at the SRS, with a peak value of $44W/mm^2$, at 350mA [1] and a linear power density [2] of 21Watts per horizontal mm. The total absorbed heat load averaged over the full 130mm width of the mirror is approximately 1.8kW and is contained within a vertical full width half maximum of less than 0.46mm.

Such heat loads present a severe problem in limiting the thermal stresses and temperatures to avoid catastrophic failure by fracture and/or local melting, as evidenced by the history of failure associated with this mirror. Furthermore, the demanding design specification requires that the total out of plane distortion of the optical face, due to thermal strain, must amount to no more than 2 μm.

[1] Power densities calculated using in-house software and include effects of finite beam emittance

[2] The total incident heat flux vertically integrated above and below the orbit plane

2. PRESENT DESIGN

Flexibility in design has been restricted by the need to work with the existing layout of the dipole vessel and mirror mount feedthroughs. Working within these constraints, the design incorporates a thermal shield in front of the mirror to absorb the highly collimated X–ray beam which is associated with the bulk of the thermal load, whilst allowing most of the more divergent IR beam to pass onto the optic. Although this shield will cause a considerable umbra on the face of the mirror the loss of light is small in comparison to the advantages gained in removing the thermal load from the optic.

The mirror and cooled thermal shield are shown on fig 1 , and are described below.

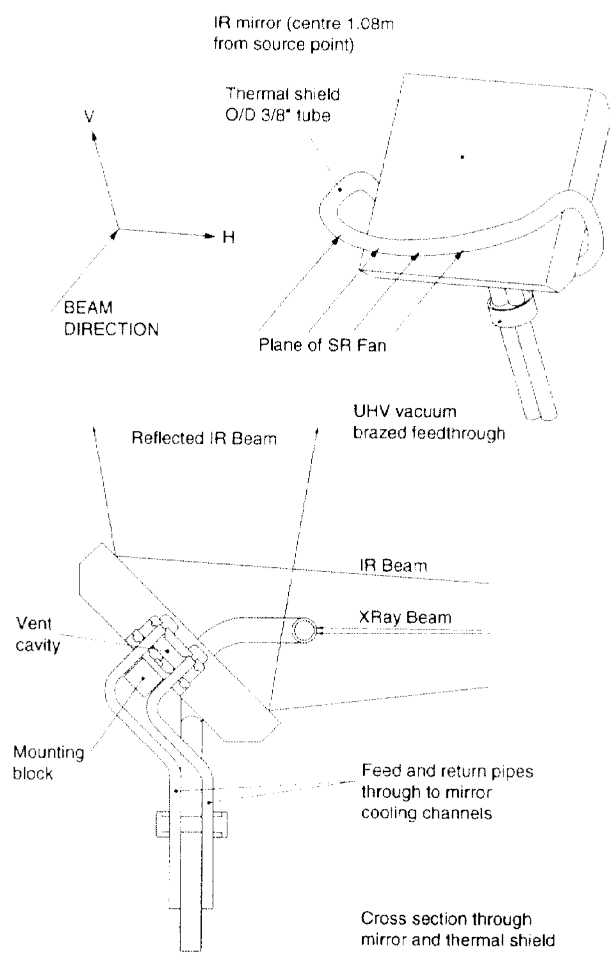


Fig 1: Mirror/shield arrangement

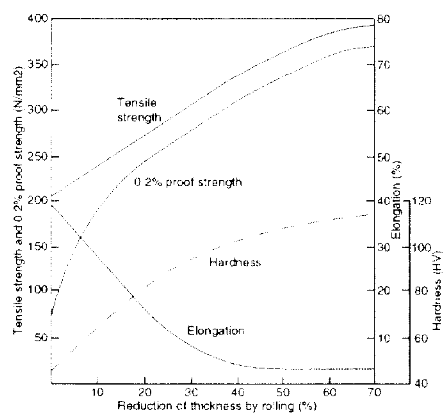
(a) Thermal shield

Design constraints and UHV requirements (i.e. no water to vacuum joints) limited the arrangement of the thermal shield to the form of a continuous 3m length pipe to and from the feedthrough with a maximum OD of 3/8" and nominal working ID of 5/16".

Preliminary calculations immediately precluded the use of pipe materials with relatively low thermal conductivity such as stainless steel because of the very large temperatures and thermal stresses that would result. After further consideration the only candidates that were found to maintain temperature and thermal stresses within material limits appeared to be dispersion strengthened copper (such as the proprietary alloy Glidcop), silver or chromium loaded copper alloys or conventional OFHC copper in a work hardened condition.

The first two options proved to be available in pipe form only as specially manufactured bulk orders at prohibitive cost. Standard OFHC copper tube was more readily available and if supplied in a suitable worked state would provide adequate proof strength for the calculated thermal stress.

Fig. 2.1 shows the effect of worked condition on the tensile strength and proof strength of high conductivity copper.



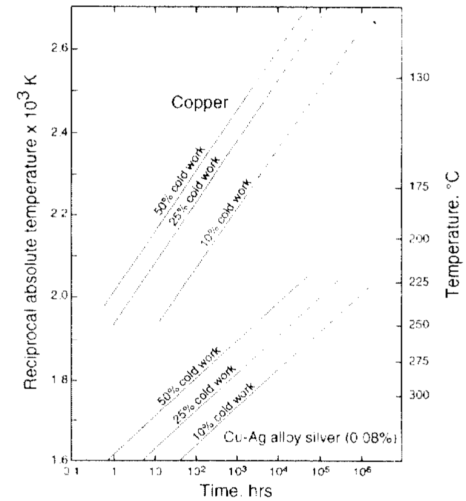
Effect of cold rolling on mechanical properties and hardness of high conductivity copper strip

Fig 2.1: Proof strength vs. worked state. Ref.. [1]

Standard engineering practice at Daresbury is to use 2/3 of the 0.2% proof strength as an upper working stress limit for components that are regarded as critical and therefore require a large safety factor. On the basis of finite element calculations we estimated that a copper with 25% reduction of cross section area from the fully annealed state (or 25% cold work) was required in order to provide a 2/3 proof strength of about 170N/mm^2

The worked condition of copper is highly dependent on the time spent at a given temperature, as shown in fig. 2.2

To maintain its proof strength and resistance to creep the part of the shield intercepting the SR beam must be maintained in a worked state throughout the brazing of the feedthrough and vacuum bakeout process – i.e. the copper must suffer only a minimum amount of annealing.



Relationship between time and reciprocal absolute annealing temperature to produce 50% softening of cold-worked Cu and Cu Ag 0.08.

Fig 2.2: Annealing times. Ref. [1]

To achieve this the thermal shield pipe, along with the feed/return and vent pipes from the mirror were vacuum brazed locally into the feedthrough at 800°C using RF heater coils whilst the critical part of the shield was cooled to 160°C for the duration of the braze.

The vacuum bakeout temperatures were also limited to a maximum of 170°C for 48 hours.

We selected an OFHC copper for use in the shield with a initial work of 50%. Keeping within the above criteria for brazing and bakeout ensured that the final condition would be at least equivalent to the desired 25% state.

Fig 3 shows a close–up view of a feedthrough test piece brazed using localised RF heating.

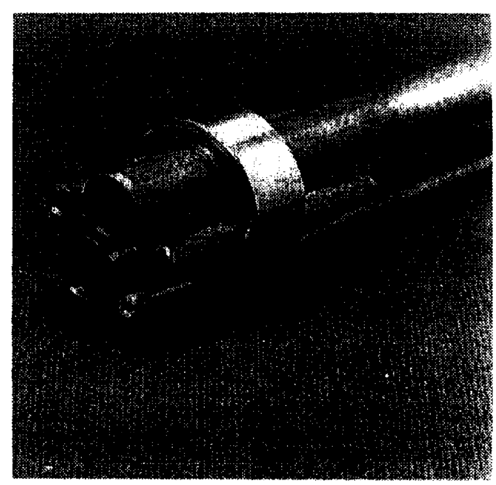


Fig 3: Locally brazed UHV feedthrough

A full 3D finite element analysis was carried out for the thermal shield under its normal operating conditions at 350mA beam current which predicted a peak temperature of

124°C at the point of maximum heat load. Fig. 4 shows the temperature contours through a cross section view of the pipe at this point.

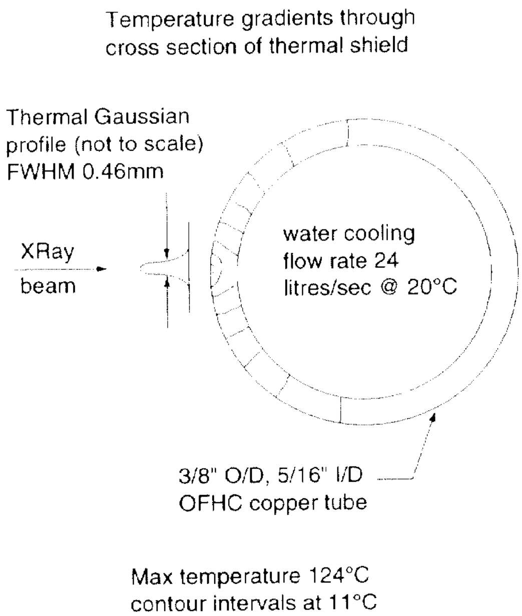


Fig 4: FEA contours of shield

A full thermal stress analysis of the heat shield was also performed with constraints fixed at the feedthrough. The large thermal gradients gave rise to a peak thermal stress[3] of 115N/mm^2. This is significantly below the copper's working stress limit of 170N/mm^2 and offers a comfortable safety margin for operating at even higher beam currents.

The lack of constraints on the thermal shield (except at the feedthrough) produces a lower peak thermal stress than might be expected by allowing thermal straining but introduces the possibility of failure due to long term creep or fatigue effects.

Experimental creep tests[2] on a 10% worked copper at 130°C have established total failure at a tensile stress of 140N/mm^2 after a duration of 1750 hours. For an annealed copper the failure occurs after only 170 hours. This indicates the marked improvement in resistance to creep offered by a worked copper. The operating stresses and temperatures in the thermal shield are less severe than those in the creep tests and the copper is in a greater worked state. We therefore assumed that the danger due to creep was not significant over several thousand hours of operation but checks should be made for signs of excessive straining thereafter.

Thermal straining of the shield will occur during each fill cycle of the SRS raising the possibility of failure due to fatigue.

Staying well within the proof strength of the shield precludes the possibility of failure at low endurance fatigue due to large plastic straining. Data for high cycle fatigue[3] predicts a fatigue strength of 117N/mm^2 @ 3 x 10^6 cycles. This is many orders higher than will be seen by the shield during an anticipated working lifetime of several years.

[3]Stress results were obtained as Von Mises (or equivalent strain energy stresses) generally recognised as a good conservative stress criteria for ductile metals.

(b) Mirror

In normal operation, i.e. with the SR beam incident on the thermal shield, cooling of the mirror is necessary only to accommodate the low energy light not reflected from the mirror and any scattered light from the shield. However, assuming a gross miss steer of the beam or misalignment of the thermal shield, cooling should also be sufficient to prevent catastrophic failure due to thermal stress.

The feedthrough allows for only 3/16" OD pipes to and from the mirror which restricts the maximum flow rates to about 6litres/min. The dimensions of the mirror channels (10mm x 4mm) have been optimised to give the best heat transfer coefficient for the available flow.

The mirror was fabricated from OFHC copper but was conventionally vacuum brazed and therefore installed in a fully annealed state, reducing 0.2% proof strength to about 75N/mm^2. A finite element thermal and stress analysis was also carried out for the mirror. Peak temperatures on the mirror were 140°C with related thermal stresses of 130N/mm^2. This is considerably higher than the proof strength of the annealed state. However there is some scope for strain hardening of the copper during thermal straining before longer term secondary stage creep acts to soften the metal, as evidenced by the ultimate tensile strength being relatively much greater for the annealed state than for any worked condition (see fig.) 2.Given the secondary role of the mirror, the highly unlikely event of a beam mis-steer for any length of time and therefore the absence of complicating factors such as creep it was concluded that the analysis results were secure enough to confirm its survivability to very short exposures of SR beam.

3. CONCLUSIONS

The IR13 mirror and shield arrangement was installed in March 1994 and to date has operated successfully over many beam cycles and up to 340mA beam currents.

The technique of localised brazing works very well and allows the use of work hardened standard OFHC copper in some higher mechanical or thermal stress applications where ordinarily, higher strength alloys might be required. These are often difficult to obtain and work with and a method which extends the use of standard OFHC copper into a high thermal stress environment will be of considerable advantage to the engineering of components in the front end of modern high brilliance storage rings

REFERENCE

[1] Publication TN29, High conductivity coppers, The Copper Development Association, UK

[2] Glen J, The Problem of the Creep of Metals, Kynoch Press, 1968

[3] Anderson A R and Smith, C S Fatigue Tests on Some Copper Alloys Proc ASTM Vol. 41 (1941) pp849–858