Selection of aluminum alloys for use on Advanced LIGO UK parts.

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1 Issues

This note aims to address the issues of material availability and suitability for use on Advanced LIGO, following an action placed during the Glasgow meeting in January 2005 (see T050010 action 30 and subsequent discussion during weekly SUS meetings).

The principal concern was not that some grades of aluminium might not be vacuum compatible. Rather, the concern was that the vacuum bakeout might damage the alloy or its hardness, especially after welding. See the correspondence in addendum 1. During the course of writing this note, a second issue arose which was directly concerned with vacuum compatibility. This issue was whether or not it would be acceptable to use a cast aluminium plate ("tooling plate") in the LIGO vacuum systems. This is covered in section 7 below.

The latest version of the vacuum compatible materials list is E900050-B-E of March 2004. It gives "Aluminium and alloys (e.g.6061 2024)" as being acceptable for both LIGO and Advanced LIGO. The cleaning document, E960022-B-E of March 2003 requires that (page 16) aluminium parts are backed at 120C for 48 hours as part of the cleaning process.

This suggests that any grade of aluminium alloy will be acceptable provided it's properties are not rendered unsuitable by the bake-out.

2 References

1. Vacuum compatible materials list is E900050-B-E Of March 2004.
2. Vacuum cleaning document, E960022-B-E of March 2003
3. EN 485-2: 1994 (European standard for wrought aluminium alloys)
4. "The properties of Aluminium and its alloys" Aluminium Federation, UK, 2000. Standard UK reference work.
5. "The effect of post-weld heat-treatment on the mechanical properties on AA6082 T6 welds" F Feng and Z Li, Aluminium 2001 – proceedings of the TMS 2001 Aluminium Automotive and Joining sessions.

3 Grades of aluminum under consideration

Three grades are being considered, for reasons of availability or familiarity. In all cases properties given here are extracted from (ref 3).

The T6 condition is reached by heat-treatment in alloys that can be heat treated.

6061-T6

This is mentioned in the vacuum compatibility document and is in common usage in the USA. Its properties are:

State	yield	UTS	Elongation in sections up to 25mm
0	85 MPa max	150 MPa max	16%
T6 (up to 12.5 mm only given)	240 MPa min	290 MPa min	9%

6082

This was suggested as a "European equivalent" to 6061, but since both are in the European standard, and the composition and properties differ, this may be a misapprehension. The table in the front of the AlFed book (ref 4) suggests that 6082 is available in a wider selection of forms than 6061. Its properties are:

State	yield	UTS	Elongation in sections up to 25mm
0	85 MPa max	150 MPa max	16%
T6 (up to 12.5 mm only given)	255 MPa min	300 Mpa min	9%

5083
This is a very basic grade of aluminium which benefits from having reasonable properties in the soft condition and therefore is strong even after welding. It cannot be heat treated but it can be hardened by work-hardening. It is widely available in the UK.

State	yield	UTS	Elongation in sections up to 25mm
0	125 MPa min	275-350 MPa	15%
H14 (half-hard)	280 MPa min	340-400 MPa	9%

4 Effect of heat treatment on properties

The question remains as to what the effect of the vacuum heat-treatment will be on the properties of a hardened aluminium. Hardening regimes (ref 4) are:

	Heat to	Quench in	Age at	For
6061-T6	525C	water	165-195C	3-12 hours
6082-T6	530	water	175-185	7-12 hours

The Alfed book (ref 4) referred to above says of ageing: "heat-treatable alloys such as 6082 harden very slowly at normal temperatures: hardening can, however, be accelerated by heating the solution-treated alloy in the range 100-200C for a suitable period". We infer that you cannot "overdo" the ageing and so the 120C bake will have no effect.

To anneal 5083 it recommended heating it to 360C for 20 minutes, so even work-hardened 5083 would be unlikely to be affected by the vacuum bake.

5 Properties after welding

We have not been able to find much data on strength after welding. We assume that 5083 will basically have the same strength as given for the "O" condition, albeit with the caveat that the material quality is likely to lower in a weld than in the wrought alloy. For 6082 we have reference 5 which gives, strengths for T6 alloy after welding with various heat-treatment regimes. They are:

State	Yield, MPa	UTS, MPa	Elongation, %
Parent material	314	337	12.4
As welded	165	220	4.5
Aged 150C for 32 hours	242	254	3.1
Aged 175C for 8 hours	240	245	4.2

The 150C/32hours was the closest they came to 120C/48 hours. This suggests that ageing the material increases the strength with little effect on the ductility. Note that with no solution treatment after welding it is not possible to recover the full initial strength.

6 Conclusions - heating

We conclude that any of the above alloys may be used on Advanced LIGO with no particular concerns about heat treatment or properties other than those normally applied in engineering design. Any areas subject to particularly high stresses should be subject to real tests, perhaps on test pieces.

7 Vacuum compatibility of cast plate

Concern was expressed that during manufacture of the “face plates” that form part of the lower structure for the quadruple suspensions, there may be significant distortion during machining due to the relief of internal stresses. The standard solution to this problem is to use a cast aluminium “tooling plate” whch has been formulating to minimise this tendency. Several emails were exchanged (addendum 2) and the conclusions were:

1. The face plates for the controls prototype were not made from cast plate and did not give any particular machining problems. We are in the process of getting the written details of the material used.

2. A significant quantity of cast plate was used in LIGO without any apparent ill-effects on the vacuum.

3. Notwithstanding (2), it is not recommended to use any cast material in a vacuum, and we should not do so without getting it cleared by the vacuum review board.

Addendum 1: emails between Russell Jones and Larry Jones

-----Original Message-----
From: Larry Jones [mailto:ljones@ligo.caltech.edu]
Sent: 28 April 2004 18:51
To: Russell Jones
Cc: ctorrie; c.cantley@physics.gla.ac.uk; janeen@ligo.caltech.edu; Wilmut, I (Ian); Greenhalgh, RJS (Justin); nornar@stanford.edu; m.perreurlloyd@physics.gla.ac.uk; m.plissi@physics.gla.ac.uk; coyne@ligo.caltech.edu; smith_m@ligo.caltech.edu; mailand_k@ligo.caltech.edu; ljones@ligo.caltech.edu
Subject: Re: reference required

Russell,

Thank you for the added information. I especially appreciate the quote from Mondolfo that reheat effects are cumulative, which will help us to evaluate repeated reheat effects. I'm surprised by his statement, "fairly insensitive to long exposure to temperature slightly above normal or to short exposure to temperatures in the range 350 - 600 degrees K", where he doesn't specify what "slightly above normal" or "short exposure" mean. This could be disastrous for some applications.

I agree with you that further investigation/testing would be beneficial. The effects of reheat that are reported in the Metals Handbook are so precipitous (sharp drop-off in strength) that we don't want to make assumptions in this area.

I'm beginning to think that while 6061-T6 may be worth recommending as an aluminum for LIGO components, it shouldn't be singled out as acceptable. All aluminum alloys and tempers are susceptible to reheat effects, and all applications should be reviewed to confirm that an acceptable strength remains after whatever reheats planned are performed. This would include potential reheats, such as repeating vacuum bakes in the event of failed RGA scans; we should probably plan on at least 4 repeats. Our current vacuum bake is 120C for 48 hours. We would like to extend this to 150C for 100 hours for Advanced LIGO, to allow for more stringent outgassing requirements. These limits are selected for 6061-T6 particulars, resulting in less than a 5% reduction in yield strength for a single cycle.

Fortunately, most of the LIGO applications for aluminum are not stressed to high levels. Here's the most simple outcome, which may apply in many LIGO applications: ask the following: assuming the worst, would Type 1060, fully annealed aluminum suffice for this component? If so, no testing or further research is required. If not, the literature should be reviewed to see if the remaining strength after reheat effects is adequate. If no data exists, tests should be performed on that alloy and temper, putting sample coupons through the expected and potential (worst case) reheats. Most applications would probably be handled by torque tests of fasteners in tapped holes and tensile tests of coupons to measure the effects of bending stresses.

I talked with metallurgist Cheng Hsieh at JPL about weldments of tempered aluminum. To be conservative, he suggests that we assume the weld bead and the heat effected zones are fully annealed by the welding process. If a subsequent analysis results in unacceptable material strength for the particular application, we need to have the weldment heat treated to the proper temper prior to final machining.

Larry

At 04:41 AM 4/28/2004, Russell Jones wrote:
>Dear Larry,
>
>Mike and I have spent a little time looking for the information you
>requested. As we said during the SUS Telecon, we have not been able to
>obtain a to a copy of Metals Handbook (vol. 4) in the University
>Library, and furthermore we have found little reference to the reheat
>effects on Yield strength (of 6082-T6) in other texts.
>
>However, the mechanical properties of 6082-T6 and 6061-T6 given by
>"matweb.com" do appear to be very similar.
>
>One text that gave a useful general summary of Al Mg Si Alloys, which
>we
>believe covers both 6061-T6 and 6082-T6, was "Aluminium Alloys: Structure
>and Properties" (L. Mondolfo, 1976, pp 787-797), and we shall fax you

>through photocopies of these pages.
>Mondolfo states that Al Mg Si alloys are "fairly insensitive to long
>exposure to temperature slightly above normal or to short exposure to
>temperatures in the range 350 - 600 degrees K" but goes on to say
>"However, intermittent high-temperature exposures are cumulative and
>eventually lead to softening", (both quotes from the last paragraph of p.790).
>Later on in this passage reference is made to heat treatment. "Heat
>treatment of the alloys is not too critical.........Repeated heat
>treatments have no substantial effects on properties"(p.795-796).
>Assuming both are indeed Al Mg Si Alloys, these statements perhaps give
>some confidence that reheating of 6082 will be no more problematic than
>that of 6061, however the fact that effects on properties are not
>quantified may mean that further investigation/testing would be beneficial.
>
>What form would these tests take?
>
>We hope this information is of interest - let us know if we can be of
>any
>more help,
>
>regards,
>
>Russell and Mike.
>
>Larry Jones wrote:
>
>>
>>Dear Mike and Russell
>>
>>Would you be able to find information regarding the reheat effects on
>>yield strength for the 6082-T6-Al material?
>>
>>Specifically, we plan to (at least) put the components through a
>>vacuum
>>bake after cleaning that would be at least 120C for 48 hours, and may be
>>150C for 100-200 hours. The 6061-T6 material will have its yield strength
>>decreased by no more than 5% through the latter cycle, and it's very
>>possible that the 6082-T6 is similar. Other aluminum alloys and tempers
>>are much worse, with some have advice given of "reheating not
>>recommended". We would like to have some confidence that this is not
>>going to be a problem area.
>>
>>Depending upon the component, there may be additional reasons to go
>>through reheats. For instance, the Advanced LIGO SEI actuators use a
>>polyimide (Kapton) paint as an adhesive on the coil, which must be cured
>>at 175C for 4 hours.
>>
>>For reference, check out Metals Handbook, Vol 4, 10th Edition, p. 869.
>>If
>>specific data for 6082-T6 cannot be found, it's fairly straightforward to
>>run some tests.
>>
>>Larry
>
>

Addendum 2: emails concerning cast plate

-----Original Message-----
From: aligo_sus-admin@ligo.caltech.edu [mailto:aligo_sus-admin@ligo.caltech.edu] **On Behalf Of** Dennis Coyne
Sent: 22 September 2005 23:02
To: aligo_sus@ligo.caltech.edu
Cc: aligo_sys@ligo.caltech.edu
Subject: Re: [Aligo_sus] Fwd: Re: tooling plate in vacuum?

I did not look carefully enough in O'Hanlon, "A User's Guide to Vacuum Technology". Upon a second look, I find that he states:

"Cast tool and jig plate is readily available. It cannot be welded and should never be used in a vacuum system, because it is porous."

Section 16.1.4, 3rd edition, 2003. So our default guidance is not to use cast tool or jig plate in the LIGO vacuum system. O'Hanlon is silent on rolled tool plate.

Perhaps this is the definitive word. However, I'm not entirely convinced that all "cast" tooling plate is not usable, nor that all rolled or wrought tooling plate is usable in UHV systems. According to the Aluminum Association, commercially available cast plate products (with producers listed in parentheses) include Alca Plus, a 7xxx base alloy (Pechiney), Alca Max, which meets 2618 specifications for composition (Pechiney), MIC-6 (Alcoa), and M-1 (Alpase). I have seen references from SLAC to other producers and products, but perhaps these are no longer available. The Pechiney web site (http://www.castplate.com/home.html) reveals no process information details except "horizontally cast". References to Alpase M-1 plate include "molded" in the description. The Alcoa MIC-6 plate is made by a continuous sheet/plate casting technique, not a mold casting process. See for example:
http://www.alcoa.com/mill_products/north_america/en/product.asp?cat_id=1481&prod_id=619
http://www.alcoa.com/mill_products/catalog/pdf/mic-6.pdf
The molten metal is continuously fed, eliminating defects from lapses and seams. Thermal gradients are stabilized since heat is removed from both plate surfaces at a balanced rate. The employment of a SNIF filtering and degassing system ensures an end product free of voids and impurities.They actually cast it from a slot between two cooled cylinders that define the shape when hot and there is no stress buildup in the material as in cold rolled plates. Then it is ground between two opposite grinders to take away the oxydation layer and finish the surface. The material is outgassed in the electric oven melt. This provides exceptional dimensional stability during machining which we need for some close toleranced parts. (Not exceptional stability to changes in environmental temperature in the final application, which as you point out we do not need.)

Given the "dirty" process in plate rolling, I actually wonder if cast tooling plate is in fact better for UHV applications. As Mike Zucker noted, any porosity/virtual leak issue may be more than compensated by the fact that the voids should not contain any volatile HC oil (as they do in rolled and extruded alloy). Given the description of the Alcoa process above, I can't see why this would be any more porous than slabs that are subsequently rolled or wrought to dimension.

BTW Ken Mailand points out that we used cast tooling plate for the large arm cavity baffle (black glass support plates). Some of the COS pickoff telescope structures were made from tooling plate as well, though perhaps rolled tooling plate. From one oblique reference on the web, it seems that at least some rolled tooling plate starts as cast plate.

I've done some literature searching and have not found any mention of outgassing rates for aluminum tooling plate, or use in UHV systems.

So, if we *need* to use tooling plate, then we can perform some outgassing tests. To be representative and meaningful we would have to test plate of the selected formulation and source (all tooling plate alloys are proprietary as are their production processes). We would need to subject these plates to processing with representative (and permitted) machining fluids (so that they have an opportunity to diffuse/migrate into the porous substrate) and we would need to fill a large bake oven with a lot of surface area to make sure that we have sufficient mass spectrometer signal (above the chamber wall outgassing). We do not intend to embark upon these tests unless use of tooling plate is needed.
Dennis

At 04:49 AM 9/21/2005, Dennis Coyne wrote:

At yesterday's weekly SUS meeting a question about the suitability of cast aluminum tooling plate in vacuum was brought up by Ian. Curiously this question had not arisen before to my knowledge. I wonder if (even suspect that) we have used cast aluminum tooling plate in initial LIGO; something to check.

O'Hanlon's book, "A User's Guide to Vacuum Technology" does not address this concern. Nor could I find anything in the SLAC document, "*Technical Specification for Vacuum Systems", SLAC-TN-86-6* :
http://www.slac.stanford.edu/pubs/slactns/slac-tn-86-006.html
The LIGO vacuum engineering expert, John Worden, indiactes that it is probably acceptable if

the virtual leak rate is not too high. (His reply to the question is included below.) We should explore an answer to this question further since cast tooling plate is a good choice for many of our parts due to its dimensional stability.
Dennis

Date: Tue, 20 Sep 2005 12:14:01 -0700
To: Dennis Coyne <coyne@ligo.caltech.edu>
From: John Worden <worden_j@ligo-wa.caltech.edu>
Subject: Re: tooling plate in vacuum?

My experience is limited to rolled material with voids which can bridge a knife edge seal. If the casting can be cleaned and if it is not a barrier to atmosphere we may be able to handle it since our o-rings already behave like a virtual leak. It all depends on the extent of the virtual leaks I guess.

Sorry I can't help more.

John

At 10:37 AM 9/20/2005 -0700, you wrote:

Hi John,
A question came up that you might be able to help answer. In general our understanding is that one does not use casting in vacuum since they can be porous and have voids and act as virtual leaks. Tooling plate can be cast as well. It's nice plate to work with since residual strains are low. Alcoa claims a maximum void size & density which is apparently low (not sure how low). Do you know if tooling plate is acceptable in UHV applications like LIGO?
Dennis

____ Aligo_sus mailing list
Aligo_sus@ligo.caltech.edu http://mm.ligo.caltech.edu/mailman/listinfo/aligo_sus
____ Aligo_sus mailing list
Aligo_sus@ligo.caltech.edu http://mm.ligo.caltech.edu/mailman/listinfo/aligo_sus

-----Original Message-----
From: Rainer Weiss [mailto:weiss@ligo.mit.edu]
Sent: 22 September 2005 16:15
To: Greenhalgh, RJS (Justin)
Cc: Dennis Coyne; Wilmut, I (Ian)
Subject: RE: [Aligo_systems] Fwd: Re: tooling plate in vacuum?

Justin,
I know that cast stock is used for long term dimensional stability and for its relative "deadness" in springing back after machining but I still worry about it in the vacuum near the optics. If you find that you really have to have it for your application I would advise two things. 1) make sure that it is vacuum cast and 2) LIGO will need to test it in one of its vacuum bakeout ovens with an RGA used in SEM or counter mode set to look for hydrocarbons. The cost and schedule delays of these tests should be included in your planning and may offset the advantages the cast material offers.

I do wonder where it is that you have these unusual demands for dimensional stability. We do not regulate the temperature of the LIGO buildings to better than a degree C and in most critical places we use servo systems to maintain an instrument at the "correct" place for operation.

RW

On Thu, 22 Sep 2005, Greenhalgh, RJS (Justin) wrote:

> Hi Ray,
>
> Thanks for this input - the query came originally from us in the UK. I
> just want to check with you that I understood your response. There are
> two reasons we might want to use cast material. One is making things
> cheaply to shape without machining. The second is having a stable
> material which won't move when you machine it. The cast material we
> had in mind comes as a plate just like rolled material; we won't get
> any of the forming benefits of casting but when you machine it, it
> doesn't move around due to relief of internal stresses like rolled
> material does. My understanding of your reply was that you were
> talking about the first reason and not the stability issue; unless
> there's some neat trick that CNC machines can do that I have missed?
>
> Thanks - Justin.

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>
> Justin Greenhalgh
> Advanced Materials Group leader
> +44 1235 445297
>
>
> -----Original Message-----
> From: aligo_systems-admin@ligo.caltech.edu
> [mailto:aligo_systems-admin@ligo.caltech.edu] On Behalf Of Rainer
> Weiss
> Sent: 21 September 2005 17:52
> To: Dennis Coyne
> Cc: aligo_sus@ligo.caltech.edu; aligo_sys@ligo.caltech.edu
> Subject: Re: [Aligo_systems] Fwd: Re: tooling plate in vacuum?
>
>
> Dennis,
> Cast material has been a no/no for vacuum systems for ever. My first
> experience was with cast bronze which had to be tinned to avoid
> outgassing by the voids in the material. Vacuum casting was invented
> in part to reduce the voids and may be all right. But there should be
> no need to use cast material in this day of computer controlled
> milling machines and lathes. RW
>
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