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Blade, wire and clamp process specification

J Greenhalgh, C Torrie, N Robertson, C. A. Cantley,
M Plissi, M Perreur-Lloyd, R Jones, I Wilmut, M Barton, J Romie

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This is an internal working note
of the Advanced LIGO Project, prepared by members of the UK team.

**Institute for Gravitational Research
University of Glasgow**

E-mail

**Technology Business Unit
CCLRC Rutherford Appleton Laboratory
Chilton, Didcot, Oxon OX12 0NA**
Phone +44 (0) 1235 44 5297
Fax +44 (0) 1235 445843

**Department of
University of Birmingham**

Phone

Fax

E-mail:

**Particle Physics and Astronomy Research
Council (PPARC)**

<http://www.ligo.caltech.edu/>

http://www.eng-external.rl.ac.uk/advligo/papers_public/ALUK_Homepage.htm

1 Introduction

This note sets out our current intentions and understanding about the optimum materials and processes to use for the blade springs of advanced LIGO. It arises from the work of the “blade committee” and others. In all cases we have tried to capture not only the decisions but also our reasoning.

The note was drafted in May 2004 but not released (with insertion of sections 9 and 10) at version 00 until January 2005.

At version 01 (June 2005) we have added comments on the wires and the clamps because we have realised that they form a system especially as regards the heat treatment steps.

Version 02 includes outcomes of discussion at blade committee of Nov 2005.

Version 03 includes comments on inert gas and the common rationale for design processes between SUS and SEI.

2 Background information

We have drawn on the experience of the GEO, LIGO and VIRGO groups; in particular, several papers of the VIRGO group and discussions with members of the group. See the list of references at the end of this note. An earlier note (T040083) described some of the references and what they contain.

3 Blade material

We have selected C250 type maraging steel.

Maraging steel has excellent performance as regards creep during use (see for example, [Beccaria 1998]). C300 is stronger than C250 but it has less Molybdenum than C250. Molybdenum is reported to be good at pinning dislocations thus discouraging creep [Plissi 2004]. It was said that there is some reference to C300 in the VIRGO literature, but we could not find it. There are also suggestions that C250 is more widely available and likely to be more uniform in properties than C300 or C350. Given the variation in properties:

we suggest that serious consideration be given to buying a single batch of material for all the blades in Advanced LIGO.

4 Wire material

For drum-ended wires, as currently recommended, the material is maraging steel; grade to be decided. A fallback, should adjustment issues defeat the use of drum-ends, is to use wires of “music wire” high-strength steel. See also email from Mike P-L in appendix re conversation with Geppo Cagnoli. The paper referred to is [Cagnoli 1997] in the references.

5 Clamp material

The default choice for the blade clamps (and wire clamps, if used) is stainless steel. The governing criteria are cost and creep concerns. Maraging steel is likely to be expensive but has the best guarantee of creep performance (suitably heat treated). Another possible solution would be to use a radius in the body of the blade by making the blade out of thick material and machining it down over all of its length except the clamped part, with a smooth transition. This would allow non-maraging steel clamps but still give the guaranteed anti-creep performance of

maraging steel where the stresses are high. Very simple FEA analyses have shown that a radius of the order of the blade thickness would remove the stress-raiser at the root. Having a blade made from thicker material raises the possibility of making a feature at the narrow end to house a drum-ended wire with no clamp – cost tradeoffs would need to be done.

6 Heat treatment – inert gas

Previous heat-treatment of some blades and wires has been done under Argon to avoid the surface being contaminated with oxygen or nitrogen. This issue should be explored more fully before the final specifications are written.

7 Heat treatment – annealing and ageing

The material should arrive in the annealed condition. For ageing,

the material should be aged after machining at 435 °C for 100 hours.

This will give a high yield strength (approaching 2 GPa) [Braccini 2000]. Because we will base our design stress on a percentage of yield, a high yield strength allows a higher working stress.

8 Hardness testing

Hardness tests should be used as a processes monitoring measure before and after the various heat-treatment stages. This has been found to be more fool-proof than, for example, relying on the temperature controls of furnaces.

9 Grinding

It was understood that the grinding process used on the blades would be exempt from the requirements of the E960050-B, the vacuum compatible materials list. At the time of writing (Nov 2005), Dennis Coyne is checking this.

10 Special treatment to prevent creep

Blades, clamps and wires will be heated, under load, to 120 °C for one week before use.

[Beccaria 1998] makes quite clear that heating under load will allow dislocations to move and thus relieve any tendency to creep on cooling back to room temperature. That paper also looks at the magnitude of the effect and compares it to the required noise levels for VIRGO. Curiously, the scheme proposed in the paper of 150 °C for a week is much higher temperature than any of the experiments they report in the paper. The idea was strongly supported by Riccardo [DeSalvo 2003]. We still need to check that this will not cause any unacceptable permanent deformation of the blades. We do not propose to do this for the controls prototype blades, although we might use some spares from that prototype to make trials of the process.

See [T050047-00.pdf](#). which shows that baking at 150C will accelerate creep by a factor of about $30^{((150-20)/15)} = 30^9 = 2E13$. Baking at 100C would give an acceleration of 30^5 or $25E6$, still quite large enough. However, the blade will be baked at 120C for 48 hours during cleaning and we should therefore treat to at least that temperature in order to avoid the possibility that the cleaning bake might interfere with the effects of the creep prevention bake.

This process will likely need to be carried out twice, at different stages in the assembly process; once before we characterize the blades and again later. In outline the bakes will be:

- Bake blades at 120C for a week under load to allow gross creep effects in the blades (“initial creep bake”)
- Blades do not need to be kept under load.
- Characterize blades, select matching pairs, decide on required clamp variants, etc.
- Clean and bake at 120C for 48 hours (“vacuum clean bake”).
- Assemble top stage and masses, preload blades, treat at 120C for a week to remove creep and creak effects (“Creep/creak bake”). The clamps must not be undone after this treatment, and ideally the blades should be kept under load.

For drum-ended wires, similar measures will be required. If drum-ended wires are used, and if the clamps depend upon the tension in the wires to keep faces in contact, then the wires would have to be kept under tension after the creep/creak bake. This could be avoided by suitable clamp design.

We will not use any overloading to ameliorate creep.

[Braccini 2002] and [Puppo 2000] suggest that overloading will reduce creep but they do not express that result in terms of detector performance, so it is not clear how much help it would be. In any case, we believe that the anti-creep heat treatment above will prevent creep from being a problem.

11 Design stress

The suggestion from VIRGO [Plissi 2004] was that we use 55% of yield, as they do. This, it was firmly asserted, “would avoid any problems with creep”. This is compatible with the requirements in E010613-01, the LIGO Generic requirements document, section 6.5.2, which calls for a factor of 1.8 on yield.

We propose to limit nominal stresses in the blades to 55% of yield, or around 1Gpa.

To some extent this measure, combined with the anti-creep heat treatment, is belt and braces. However we are not planning to do any experimental work ourselves and so a certain margin of safety seems prudent to us.

The idea of a uniform rationale for design stress between SUS and SEI was discussed at the LSC in March 2005. In deciding on the factor of safety the risk and consequences of failure must be balanced against the scientific payoff for raising the stress levels. This rationale should be applied uniformly throughout but may give different results in different places. The key observation is that if the SEI blades were to fail then the consequences for other subsystems could be dire; whereas if the SUS blades were to fail then the consequences would be limited to SUS and would be inconvenient rather than disastrous. Therefore it is acceptable to have a higher stress level in the SUS blades than the SEI ones.

12 Spare blades

See G050101-00 for reasoning. We will procure 12 as-drawn blades of each type (rejecting any that do not conform to the drawing) for every 8 that are needed; this will allow plenty of room for blade matching.

13 Quality factor “Q” of maraging steel

We propose that a value of $Q = 10^4$ be used (damping ratio = 5×10^{-5}) in calculations.

[Braccini 2000] gives various values of dissipation coefficient, but [Cagnoli 2004] note that these are at a variety of frequencies and under a variety of conditions. The value of Q relevant to internal blade modes will be no higher than around 10^4 even though figure 9 of [Braccini 2000] suggests measurements up to 10^5 . Measurements given in [Gammatoni 2000] and [Cagnoli 1999] give Q for maraging steel of around 10^4 .

14 In-vacuum bake temperature

The "Universal Suspension Subsystem Design Requirements Document": <http://www.ligo.caltech.edu/docs/T/T000053-03/T000053-03.pdf> gives temperature requirements in section 2.6.1.1 (pg. 11). The non-operating, low temperature, in-vacuum bake temperature is 46C. Experiments have been made by Riccardo de Salvo to determine what temperature the blades can take during bake-out without suffering from excessive creep. See [T050047-00.pdf](http://www.ligo.caltech.edu/docs/T/T050047-00/T050047-00.pdf) which showed that the creep rate is decreased by a factor of 30 for every 15 degrees of temperature change, so the creep we will see during the 47C bake will be slower than during the “Creep/creak bake” by a factor of $30^{((120-47)/15)} = 30^{4.8} = 12.3 \text{ E}6$. Since the vacuum bakeout will only last about as long as the Creep/creak bake, this is no problem.

15 Blade adjuster

There are good reasons for including in the design a facility to change the height of a blade tip by changing the angle at which it is clamped. The controls prototype design includes replaceable angle pieces to allow this to be done (the so-called “library of clamps”). An alternative design has been developed at RAL and is being prototyped (October 2005).

16 References

Many of the papers are available at the time of writing from http://www.eng-external.rl.ac.uk/advligo/blade_papers

[Cagnoli 1997] “Mechanical shot noise induced by creep in suspension devices”, Cagnoli et al, Phys Lett A 237 (1997) 21-27

[Beccaria 1998] Beccaria et al, “The creep problem in the VIRGO suspensions: A possible solution using maraging steel” Nucl Inst & methods A404 (1998) 455-469

[Cagnoli 1999] Cagnoli et al “Low-frequency internal friction in the clamped-free thin wires” Phys Lett A 255 (1999) 230-235

[Braccini 2000] Braccini et al, “The maraging-steel blades of the Virgo super-attenuator” Meas Sci Technol 1 (2000) 467-476 (Erratum in Meas. Sci. Technol. **15** (2004) 599)

[Braccini 2000a] Braccini et al “The Maraging steel blades of the Virgo super attenuator” 3rd Amaldi conference p437

[Cordero 2000] Cordero et al “Elastic and anelastic properties of Marval 18 Steel” J alloys and compounds 310 (2000) 400-404

[Puppo 2000] Braccini et al “Acoustic emission in the Virgo Suspension Blades” talk given at the 2000 Aspen conference.

[Gammaitoni 2000] “Virgo suspension R&D: fused silica and creep” Third Amaldi conference p 162.

[Braccini 2002] “Monitoring the acoustic emission of the blades of the mirror suspension for a gravitational wave interferometer” Phys Lett A 301 (2002) 389-397

[DeSalvo 2003] Riccardo’s talk to an aligo_sus (Tuesday morning/evening) meeting. Minuted at the sus meeting page http://www.ligo.caltech.edu/~ctorrie/SUS_MEETING/SUS_MEETING.html under [SUS Notes 03 12 09.pdf](#)

[Plissi 2004] Mike Plissi’s discussions with VIRGO in May 2004, and in particular with Franco Frasconi. See his email summary reproduced below.

[Cagnoli 2004] Geppo Cagnoli’s input at one of the blade committee teleconferences in May 2004.

[Plissi 2004]

Mike Plissi’s summary from discussions with Virgo team

Dear All,

Here is a list of answers to some questions concerning maraging steel and optimal heat treatment. I would like to acknowledge the help of Franco Frasconi and the rest of the VIRGO team for their assistance in answering these questions.

Qu: Why is C250 material used in preference to C300 or C350?

Ans: C250 Steel has a higher molybdenum content which creates pinning points stopping dislocation movement between the grains of the material. This leads to low creep even though the elastic limit is quoted to be higher with C300 and C350 material.

Qu: What is the preferred ageing treatment for the steel?

Ans: 435 deg. C for 100 hours is the preferred ageing treatment. The hardness is highest with this treatment and there is a strong correlation between tensile stress and hardness. Consequently the creep should again be reduced to a low level.

Qu: What stress limit is typically used?

Ans: Up to 55% of the elastic limit is used without any long term creep problems.

Qu: What other technique is used for creep prevention?

Ans: It was mentioned that applying a few stress cycles to the blade reduces acoustic emission.

Qu: Why is there a discrepancy, in the value for the Young's Modulus, between the Meas. Sci. Tech. paper and the Journ. Alloys and Compounds paper?

Ans: The Young's Modulus was determined directly from the Poisson Ratio of the maraging steel. It was thought that the value of 0.38 used in the Journ. Alloys and Compounds paper was too high. A more realistic value of ~0.35 would give a Young' Modulus value close to that quoted in the Meas. Sci. Tech. paper ie.~ 187 GPa.

It was also pointed out that the experimental determination of The Young's Modulus shows small variations depending on the type of machine used. It has been measured as low as 175 GPa (this is close to what was measured on our dog-bone samples of C250 material).

I think that this answers just about all of the questions we had on maraging steel and creep prevention in processed material.

Best regards
Mike

[Perreur 2005]:

-----Original Message-----

From: Michael Perreur-Lloyd [<mailto:m.perreur-lloyd@physics.gla.ac.uk>]

Sent: 13 May 2005 11:01

To: Caroline Cantley; Greenhalgh, RJS (Justin); Norna Robertson; Janeen Romie; Calum Torrie; Russell Jones; Wilmut, I (Ian); Mike Plissi; Michael Perreur-Lloyd; Ken Strain; Hayler, TM (Tim)

Cc: Geppo Cagnoli

Subject: A little information on Wires

Hi all,

I finally got hold of Geppo to ask a little information about the wires they used in Italy and what they did to erase its memory.

Wire Rusting:

Geppo suggested that the rusting of wires was down to the type of material chosen. In Perugia he remembers using either Maraging Steel or C85 steel (which is a very hard steel) for the wires. He was sure that the maraging steel didn't have problems with rusting and was fairly sure that there was no occurrences of this with C85 either.

Erasing the Wires Memory:

Geppo and his colleagues set up a home-made vacuum oven to perform the heating of the wires. There were two reasons for this:

- 1) to erase the wires memory
- 2) to minimise wire creep

The oven was heated to between 100 and 150 degrees and the wire was fixed around a jig resembling the suspension stage, in the oven.

A paper has been written about the creep in the wire (an experiment was done in a smaller oven where wires were heated to 100-150 degrees) but not specifically about the wire memory, although perhaps this was mentioned in the creep paper(?). Geppo is going to have a look for the paper and I will send it round later.

Thanks.
Mike P-L.