Comments on blade references from VIRGO

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1. SOURCES

The sources I now have from VIRGO are:

a bibliography at http://mcvirgo.roma1.infn.it/~ricci/Virgo.htm

another one at

http://virmap.unipi.it/cgibin/virmap/vmibo?docenti:8134850;listapubblicazioni;anchor

(links point to descriptive pages not documents)

Norna's link from the summit:

www.ligo.caltech.edu/~veronica/Aspen2000/transparencies/Puppo.pdf

The documents I have gleaned are linked here:

http://www.eng-external.rl.ac.uk/advligo/blade_papers

Plus one more document, not linked here: Cordero et al "Acoustic emission in mechanical vertical filters for GW antennas" in Gravitational Wave Detection II (2nd TAMA conference) 1999.

2. COMMENTARY

beccaria1998 (Nucl inst + methods)

Lots of discussion of creep. Concludes that AISI 1070 creeps too much and that maraging C250 is OK especially if baked at 150C for a week. States that C250 was chosen for its "good characteristics and its availability" (section 7, first paragraph).

braccini2000 (meas sci + tech)

Microstructure and the effect of full heat treatment on C250. The graph showing that a longer, lower ageing treatment gives higher strength. Q measurements (I had overlooked earlier) between 1.2e3 (first mode in a small bar) and 1.5e4 (fifth mode in a small bar). Even a nice graph of Q vs temperature. BUT NOTE a second q graph (figure9) with higher Q numbers. E is given as 187 GPa with temperature coefficients.

braccini2000a (Amaldi 2000)

A very short note with some AE data. Cites the above paper.

braccini2002 (Phys lett A)

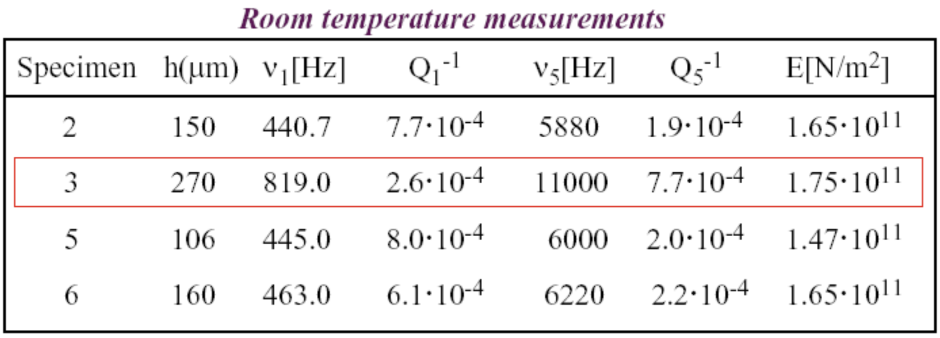
AE experiments. Conclude that applying a few stress cycles reduces the AE rate. Use fractal analysis on the data. Propose implementing an AE-based real-time veto monitor on VIRGO.

cordero2000 (J alloys + compounds)

Distilled from braccini2000. BUT GIVES 196 GPa for E. The value cited for G is identical to braccini2000 as are the temperature coefficients. Surely a misprint - but which is wrong? Gives the same Q measurements.

puppo (aspen 2000)

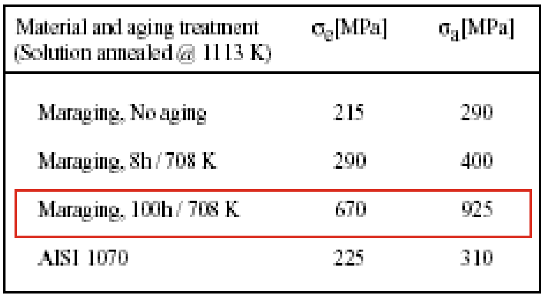
Distilled from beccaria1998 1998, braccini2000 and braccini2002, with extra AE results. Interestingly, concludes that the best ageing treatment is 16h at 753K. Presumably this is because of the better Q given in the table on page 10:



Room temperature measurements

Specimen	h(μm)	ν_1[Hz]	Q_1^{-1}	ν_5[Hz]	Q_5^{-1}	E[N/m^2]
2	150	440.7	$7.7\cdot10^{-4}$	5880	$1.9\cdot10^{-4}$	$1.65\cdot10^{11}$
3	270	819.0	$2.6\cdot10^{-4}$	11000	$7.7\cdot10^{-4}$	$1.75\cdot10^{11}$
5	106	445.0	$8.0\cdot10^{-4}$	6000	$2.0\cdot10^{-4}$	$1.47\cdot10^{11}$
6	160	463.0	$6.1\cdot10^{-4}$	6220	$2.2\cdot10^{-4}$	$1.65\cdot10^{11}$

Rather than the better strength given on page 7:



Material and aging treatment (Solution annealed @ 1113 K)	σ_e[MPa]	σ_a[MPa]
Maraging, No aging	215	290
Maraging, 8h / 708 K	290	400
Maraging, 100h / 708 K	670	925
AISI 1070	225	310

The TAMA paper briefly reviews some of the above.

3. WHAT AGEING TREATMENT TO USE?

I propose, from the results in Braccini2000, and the recommendations of Riccardo De Salvo, to use the longer, slower heat treatment 100h at 708K (435C).

4. WHAT IS THE MODULUS OF MARAGING STEEL?

Braccini2000 gives moduli found from resonant frequencies of bars. In table 5, values are given from 147 to 175 GPa for thin specimens (150 to 270 micron think). In section 4 they give 187 GPa for a thicker specimen 55 long by 3.6mm by 3.5mm. Cordero2000 gives 196 GPa citing the same tests – I could find no errata for the Cordero paper (I can't search Meas Sci & Tech online). Hopefully we will have our own results soon.

5. WHAT ANTI-CREEP TREATMENT TO USE?

Beccaria1998, titled "The creep problem in the VIRGO suspensions…", looks at the effect of various heat treatments on creep. Early in the paper (Section 3) they try to work out what creep rates will mean for detector performance:

> " The order of magnitude of the energy released in these events (hundreds of picoJoule) and the induced creep step length of the payload (picometers) can be calculated from the applied stress and from the grain dimensions [13]. The amplitude of these steps is extremely large if compared with the small displacement of the mirror induced by gravitational waves (typically lo-" m). A creep of just 1 urn per day would correspond to about ten of these steps per second. In Ref. [131, we describe a simple model to evaluate the mechanical shot-noise induced by creep events in the last stage of the superattenuator, in proximity of the mirror.5 In order to keep the creep shot-noise well below the VIRGO sensitivity, the vertical position of the blade tips of the last filter of the chain must be very stable. Only a creep yielding of the blade tips less than one nanometer per day can be allowed in our interferometer."

Concludes that (end of section 8) they will bake at 150C for a week (under load) – even though the paper does not report any tests at that temperature. A key paragraph is the penultimate one in section 8:

> "From Eq. (3), one can also deduce that a reduction of the temperature from 80°C to 30°C induces a reduction of the creep speed of about three orders of magnitude. This means that a creep rate of one micron per day at 80°C should be acceptable for VIRGO. The residual creep after baking can be further quenched by longer or warmer baking. Warmer baking is beneficial until it starts generating new kinds of dislocation processes or transitions in the metal. In Maraging steel, this is not expected below 200°C."

which suggests that measuring creep at an elevated temperature may be a way to predict creep at the operating temperature.

Braccini2002 has many of the same authors but by this time their thoughts seem to have moved on to overstressing as a way to reduce creep and to AE as a way to measure it. They offer no attempt to tie in the AE results to detector performance – this is the closest I found (section 1):

> "We can compute the energy involved in the process ΔE in a realistic case of d = 7 μm, b = 2.3 × 10.10 m and a mobile dislocation density ρm = 5 × 1012 m.2. According to the Tetelman model when a stress level of t = 200 MN/m2 is reached, we have an energy release
> ΔE ~ 5 ×10.10 J.
> Sensors for the AE detection are mechanically coupled to the sample surface and are sensitive to mechanical displacements or velocities. The output signal, proportional to ΔE1/2, depends on the source distance, the mean velocity of the dislocations and on their extension; as a consequence an accurate estimation of the output signal is far to be straightforward. Whenever a sufficient energy is released, microscopic changes can be detected using bandwidth limited piezoelectric sensors, at a level of 10.15–10.16 m of the displacement on the sample surface, while the source location can be inferred by the use of multiple transducers [3–5]."

They analyse their results using a "fractal" analysis and conclude that the event rate drops as the number of stress cycles is increased (they only report a few cycles). They do not in fact report directly on what happens when you overstress a blade but they give one result (Fig 7c) which shows that a blade previously loaded to 500N does not show much emission when subsequently reloaded until it is loaded beyond 500N.

The evidence in braccini2002 in favour of using overloading as an anti-creep method is indicative but much less clear than the evidence given in beccaria1998 for thermal treatment.

For now, we should go for thermal treatment.

6. WHAT TYPE OF MARAGING STEEL TO USE?

The earliest paper, beccaria1998, says (section7):

> "A search of the available literature and lore guided the choice of best candidate to Maraging C250, a steel of the Maraging family of precipitation-hardened steel alloys. Maraging C250 was chosen for its good characteristics and its availability"

I saw no other reference to any other grade of maraging in any of the other papers.

7. WHAT VALUE OF Q?

Beccaria1998 gives two tables and two graphs with Q values:

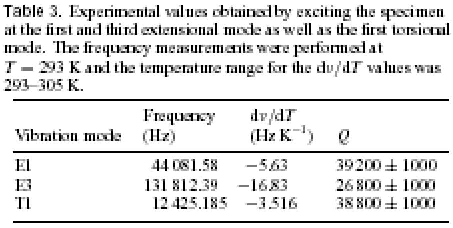


Table 3. Experimental values obtained by exciting the specimen at the first and third extensional mode as well as the first torsional mode. The frequency measurements were performed at $T = 293$ K and the temperature range for the $\mathrm{d}\nu/\mathrm{d}T$ values was 293–305 K.

Vibration mode	Frequency (Hz)	$\mathrm{d}\nu/\mathrm{d}T$ (Hz K^{-1})	Q
E1	44 081.58	−5.63	39 200 ± 1000
E3	131 812.39	−16.83	26 800 ± 1000
T1	12 425.185	−3.516	38 800 ± 1000

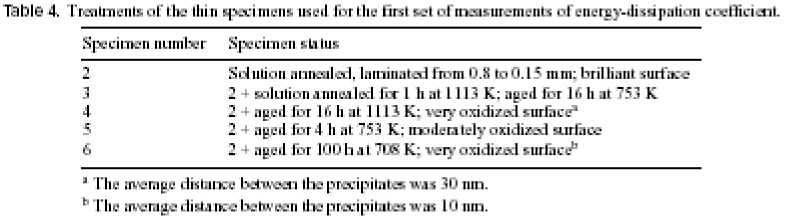


Table 4. Treatments of the thin specimens used for the first set of measurements of energy-dissipation coefficient.

Specimen number	Specimen status
2	Solution annealed, laminated from 0.8 to 0.15 mm; brilliant surface
3	2 + solution annealed for 1 h at 1113 K; aged for 16 h at 753 K
4	2 + aged for 16 h at 1113 K; very oxidized surface[a]
5	2 + aged for 4 h at 753 K; moderately oxidized surface
6	2 + aged for 100 h at 708 K; very oxidized surface[b]

[a] The average distance between the precipitates was 30 nm.

[b] The average distance between the precipitates was 10 nm.

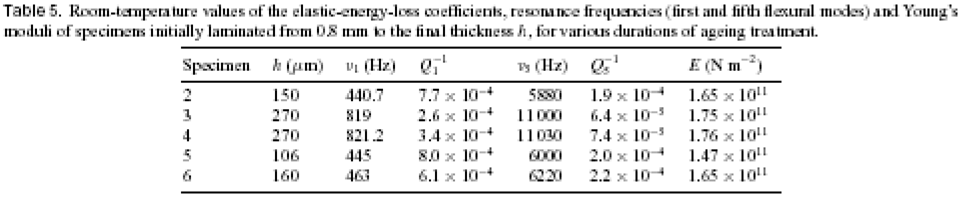


Table 5. Room-temperature values of the elastic-energy-loss coefficients, resonance frequencies (first and fifth flexural modes) and Young's moduli of specimens initially laminated from 0.8 mm to the final thickness h, for various durations of ageing treatment.

Specimen	h (μm)	ν_1 (Hz)	Q_1^{-1}	ν_5 (Hz)	Q_5^{-1}	E (N m^{-2})
2	150	440.7	7.7×10^{-4}	5880	1.9×10^{-4}	1.65×10^{11}
3	270	819	2.6×10^{-4}	11 000	6.4×10^{-5}	1.75×10^{11}
4	270	821.2	3.4×10^{-4}	11 030	7.4×10^{-5}	1.76×10^{11}
5	106	445	8.0×10^{-4}	6000	2.0×10^{-4}	1.47×10^{11}
6	160	463	6.1×10^{-4}	6220	2.2×10^{-4}	1.65×10^{11}

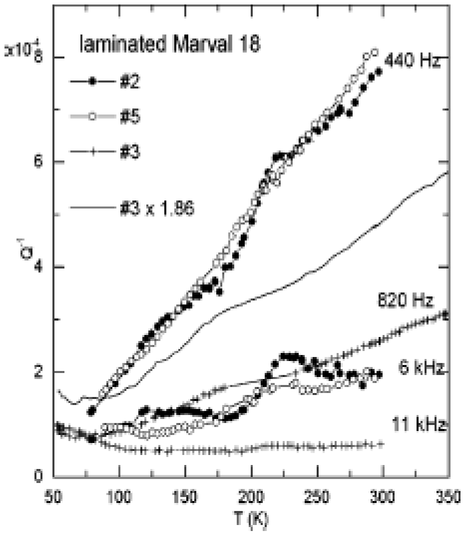


Figure 8. The elastic-energy-dissipation coefficient of Marval 18 after lamination and after the additional thermal treatments specified in the figure and in table 4. For each sample, both the first and the fifth vibrational modes are shown. The full line is the first mode of sample 3 multiplied by the ratio of its frequency and the frequency of the first mode of the other samples, in order to compare the curves.

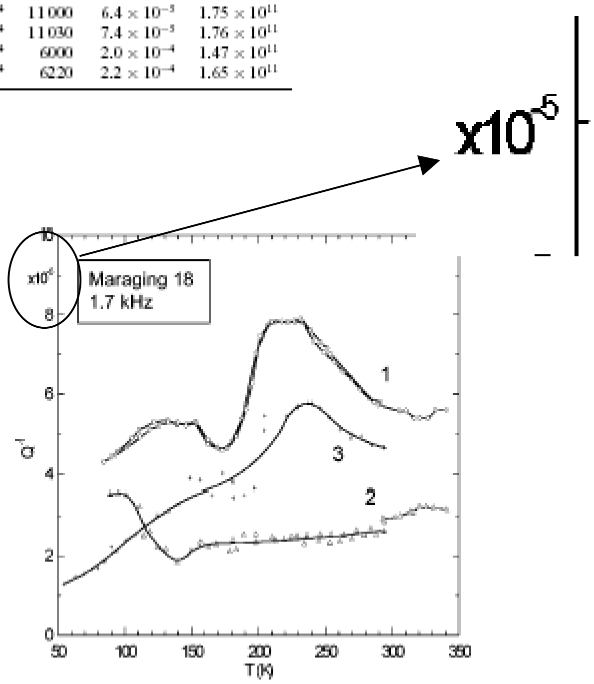


Figure 9. The elastic-energy-dissipation coefficient of a bar of maraging steel under the following conditions: 1, as cut from the central portion of a sample for tensile tests; 2, after solution annealing at 1093 K for 1 h and ageing at 808 K for 100 h; and 3, after the removal of the black oxidized surface with emery paper.

The second graph has numbers an order of magnitude different form the first but there is no comment made in the text. For the time being we will assume Q values of order 1E4.