Flame welding tests for monolithic suspensions of the mirrors of future GW interferometers.

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Introduction

The 40 kg mirrors of the Advanced LIGO interferometers [1] will be suspended on four circular silica fibres with diameter 400 μm. The fibres will be pulled and welded to ears on the sides of the mirrors using a 10.6 μm CO_2 laser beam. To gain experience, preliminary experiments have been under taken and these include fabrication, profiling, welding and breaking of flame pulled silica fibres rather than laser.

Fig 1. *The fibres were pulled and welded to the ball shaped rods using a H_2-O_2 burner.*

Fig 2. *The ball shaped rods enable us to mount the fibres on a strength test machines.*

The experiment

The fibres were pulled by hand from 1.5 or 3mm diameter circular Suprasil-Standard or Suprasil-2 stock material, in a *H_2-O_2* burner flame. The fibres were stretched until they broke on a tensile machine. To mount the fibres on the test machine 5 mm silica rods were flame welded to the ends of the fibres. To improve the surface of the silica we polished the stock with a flame. At the first stage the flame polishing was applied after welding stock to the ball shaped rods but before pulling the fibre. The strength of the fibres reached up to 6 GPa and does not depend on the fibre length for these “pristine” silica fibres [2]. However, the Advanced LIGO fibres will be welded after pulling, which can result in vapour deposition on the fibre surface. To investigate the strength in this case, fibres were welded to the ball shaped rods after pulling. The behaviour of these fibres in comparison with those welded before pulling is presented in this report.

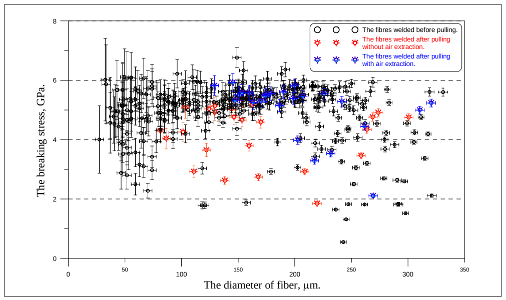

Fig 3. Plot of the breaking stress vs minimum diameter of fibre.
The blacks marks represent the data obtained for sequence **a** (see Figure 4), the red and blue marks correspond to sequence **b**.

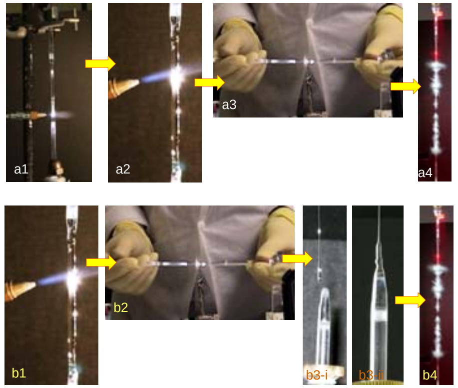

Fig 4. *Changing the order of fibre preparation has an effect on the distribution of the breaking stress of the fibres.* ***a1****- welding of thick rods to the stock,* ***a2*** *&* ***b1*** *– flame polishing of the stock,* ***a3*** *&* ***b2*** *– pulling the fibres,* ***a4*** *&* ***b4*** *– testing (breaking) of the silica fibre.* ***b3*** *– welding of the pulled fibre to the ball shaped rods.*

The statistical analysis of data

The breaking of the fibres is described using a so called Weibull distribution (WD). The model of this distribution is based on the idea of “weak link in the chain”. The fracture of the fibre will be fully predetermined by the weakest mechanism of a series. [2]

The cumulative probability of failure i.e. relative quantity of the fibres with breaking stress less or equal to S.

$$P(S) = 1 - \exp\left[-\left(\frac{S}{S_0}\right)^m\right]$$

The density function ***fs*=dP/dS**

$$f_s = \frac{m}{S_0}\left(\frac{S}{S_0}\right)^{m-1} \cdot \exp\left(\frac{S}{S_0}\right)^m$$

The Weibull plot and the peaks of density function

The expression for the cumulative probability can be transformed to give linear relationship with respect to *lnS*.

$$\ln\left[\ln\left(\frac{1}{1-P}\right)\right] = m \cdot (\ln S - \ln S_0)$$

Deriving parameters ***m*** and ***S_0*** one can calculate the density function as well as the average stress **<*S*>** and variance ***σ***. [3]. The data for breaking caused by one mechanism forms a straight line on the plot. The plot of fractures caused by a few different mechanisms is comprised of segments of straight lines, representing the modes of a multimodal WD or different peaks of a density function. The data for breaking of fibres welded before pulling can be described using a bi-modal distribution. The fibres with breaking stress smaller than 4 GPa relate to the second mode of WD or a lower peak of the density function.

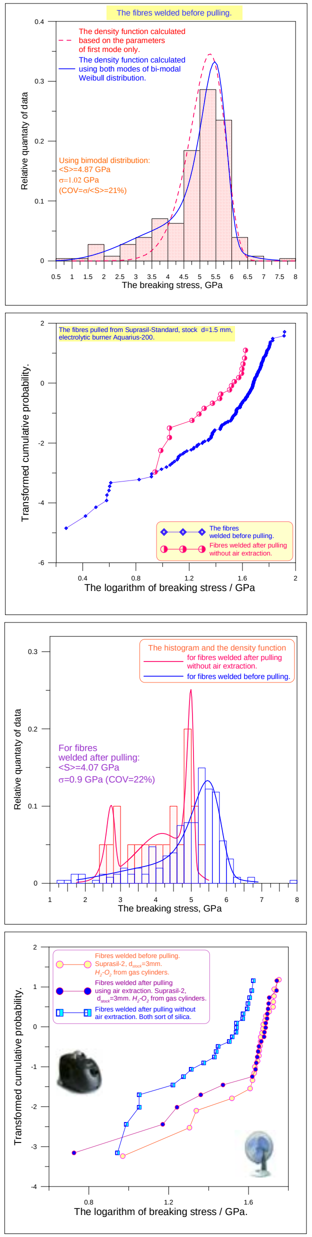

Fig.5-8. Plots of density function and Weibull plots for the fibres welded before and after pulling.

The high-speed video record of fracturing fibres

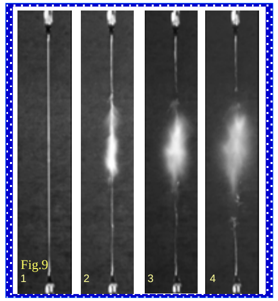

Fig. 9. Photo of breaking of the fibre welded after pulling without air extraction recorded at 30000 fps.

The 40 kg flame welded suspension

Fig 10. *The 40 kg steel mass suspended on 4 laser pulled silica fibres.*

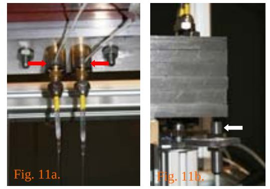

Fig 11. *To investigate the movement of the 40-kg suspension, additional sensors have been installed.* ***a*** *– strain gauge at the top of each fibre (red arrows),* ***b*** *– position sensor below each corner of the mass (white arrow).*

Conclusion

1. The density function of silica fibres is formed by two peaks. To select fibres appropriate to mirror suspension it reasonable to pre-test fibres and exclude the weakest fibres in the lowest peak of distribution.
2. The distribution of the breaking stresses of fibres flame welded to mounting rods shows a smaller average value. The reduction in strength of the flame welded fibres is probably caused by deposition of silica vapour on the surface of the fibres. This effect is attributable to decreasing of the energy of activation of crack formation.
3. When extraction of the welding vapour was carried out during welding, the distribution of breaking stress was fully restored.
4. A 40 kg steel mass suspension fabricated using flame welding technique was demonstrated.

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